Non-Gaussian diffusion weighted imaging for assessing diurnal changes in intervertebral disc composition

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Introduction: It has been known that the spine becomes shorter during the day and recovers during the night. This phenomenon has been thought to result from a decrease in disc hydration with daily compression. Diffusion weighted imaging (DWI) has been applied to measure intervertebral disc (IVD) diurnal changes of molecular water diffusion, as the apparent diffusion coefficient (ADC) [1], and is expected to reflect microstructural changes such as matrix composition (water, proteoglycan, and collagen) and matrix integrity [2]. Conventional DWI analysis is based on an assumption that the water molecules follow a Gaussian distribution. However, human tissue including the IVD is a complex and restricted environment that hinders the distribution of water molecules, resulting in distributions that are far from Gaussian. The recently proposed q-space imaging (QSI) analysis does not assume a Gaussian shape for the underlying probability density function (PDF) of water molecule diffusion. It has shown promise for evaluating the microstructure and pathology of tissues in vivo [3] because it can provide additional diffusion metrics, namely the root mean square displacement (RMSD) and apparent kurtosis coefficient (AKC), which give in vivo microstructural information that complements the ADC values [4, 5]. We therefore hypothesized that QSI analysis would be able to provide more information about IVD diurnal microstructural changes in vivo.

Purpose: To investigate the use of RMSD and AKC metrics of QSI data to estimate diurnal changes in IVD composition.

Methods: We investigated five male subjects (mean age, 27.2 years; mean BMI, 22.69 kg/m^2) who had no episodes of lower back pain or radicular pain in the last 6 months. Subjects were investigated once in the morning less than 30 min after rising and a second time in the evening after at least 10 h of normal physical activity. Images were acquired using a 3T Signa HDx MR system (General Electric). QSI and T2 mapping data were acquired in the axial plane of the IVD between L4 and L5. Parameters used for QSI were as follows: TR: 5000 [ms]; TE: 99.6 [ms]; NEX: 3; FOV: 25.6 [cm]; matrix size: 128 × 128; slice thickness: 4.0 [mm]; imaging time approximately 7.5 min; and eleven b values (0, 40, 160, 360, 640, 1000, 1440, 1960, 2560, 3240, 4000 [s/mm^2]) with diffusion encoding in three directions for every b value. Gradient length (δ) and time between the two leading edges of the diffusion gradient (Δ) were 33.9 and 39.9 ms, respectively. T2 mapping data were acquired with a multiecho spin echo sequence using the following parameters: TR: 1200 [ms]; TE: 7.9, 15.8, 23.8, 31.7, 39.6, 47.5, 55.4, 63.4 [ms]; NEX: 0.5; FOV: 22 [cm]; matrix size: 256 x 256; slice thickness: 5.0 [mm]. For the post-processing, QSI analyses were performed using the free software dTV II FZR and Volume-One 1.72 (The University of Tokyo, Tokyo, Japan). T2 maps were created with Functool software (Advantage Windows Workstation, General Electric), and T2 values were measured using the free software Image J (/rsbweb.nih.gov/ij/). Five equally sized circular regions of interest (ROIs) on the central slice of the axial plane (Fig. 1) were manually drawn. Each ROI (4 - 6 mm) measured 20% of the midline disc diameter in the axial plane. The most anterior and most posterior ROIs (ROI 1 and ROI 5) were interpreted as anterior and posterior annulus fibrosus (AF), respectively. The ROIs in between were interpreted as nucleus pulposis (NP) (ROI 2, anterior NP; ROI 3, middle NP; ROI 4, posterior NP). Paired t-tests were applied for testing significant changes in T2 values and diffusion values (apparent diffusion coefficient [ADC], RMSD, and AKC) between the morning and evening evaluations. A P value < 0.05 was seen as significant.

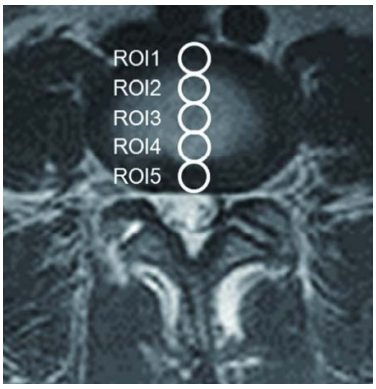

Fig.1: Positioning of the regions of interest (ROIs).

Results: T2, ADC, and RMSD values showed a significant decrease in the evening (167.0 +/- 039.9, 1.94 +/- 0.14 and 41.9 +/- 1.8, respectively; P < 0.05 for all values), when compared to those in the morning (247.5 +/- 64.7, 2.05 +/- 0.11 and 45.7 +/- 1.9, respectively) in the ROI representing the middle of the nucleus pulposus. In contrast, the AKC value showed a significant increase in the evening (0.63 +/- 0.03), compared to that in the morning (0.57 +/- 0.03) for the same ROI. No significant differences were observed between the morning and evening for other ROIs (Tables 1-4).

Table1: T2 values (msec)

	Morning	Evening	p
ROI 1	71.6 ± 11.5	71.0 ± 14.4	0.87
ROI 2	120.2 ± 14.1	115.7 ± 25.0	0.57
ROI 3	247.5 ± 64.7	167.1 ± 39.9	0.02 *
ROI 4	144.5 ± 30.9	119.8 ± 13.6	0.20
ROI 5	62.6 ± 12.7	57.2 ± 17.9	0.49

Table 2: ADC values (10^{-3}mm^2/s)

	Morning	Evening	p
ROI 1	0.90 ± 0.14	1.01 ± 0.29	0.58
ROI 2	1.78 ± 0.13	1.67 ± 0.20	0.27
ROI 3	2.05 ± 0.11	1.94 ± 0.14	0.04 *
ROI 4	1.71 ± 0.26	1.75 ± 0.20	0.48
ROI 5	1.15 ± 0.09	0.96 ± 0.28	0.22

Table 3: RMSD values (μm)

	Morning	Evening	p
ROI 1	24.7 ± 1.6	24.8 ± 1.5	0.78
ROI 2	36.1 ± 7.2	36.3 ± 6.3	0.93
ROI 3	45.7 ± 1.9	41.9 ± 1.8	0.03 *
ROI 4	39.4 ± 2.6	38.8 ± 3.3	0.50
ROI 5	27.7 ± 5.0	26.7 ± 1.7	0.75

Table 4: AKC values

	Morning	Evening	p
ROI 1	3.18 ± 0.99	2.94 ± 1.04	0.36
ROI 2	0.77 ± 0.22	0.84 ± 0.31	0.69
ROI 3	0.57 ± 0.03	0.63 ± 0.03	0.04 *
ROI 4	0.72 ± 0.07	0.70 ± 0.07	0.33
ROI 5	3.19 ± 1.03	2.76 ± 0.96	0.12

Discussion: Water molecule diffusion is restricted in a complex manner by several factors such as the cell membrane and extracellular matrix (e.g. collagen fibers and proteoglycan) in the IVDs. In general, RMSD is not influenced by the viscosity of water, but by the space for free water movement. Our results suggest that compressive forces occurring during the day causes narrowing of the space for free water movement within the NP, which we are unable to assess with conventional quantitative MR measurements such as T2 or ADC.

Conclusion: The RMSD and AKC values obtained from QSI analysis may provide additional information regarding IVD diurnal microstructural changes. These diffusion metrics are also expected to provide insights into the pathophysiology of various IVD pathologies, such as infection and sports-related injuries.

References: [1] Ludescher B et al. J Magn Reson Imaging 2008:28:252-257. [2] Niu G et al. AJNR Am J Neuroradiol 2011:32:1617-1623. [3] Hori M et al. Eur Radiol 2012:22:1797-1802. [4] Jensen JH et al. Magn Reson Med 2005:53:1432-1440. [5] Farrell JAet al. Magn Reson Med 2008:59:1079-1089