High-Resolution DTI of Human Articular Cartilage with Long Diffusion Time: Preliminary Findings

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NTRODUCTION

The articular cartilage has a matrix structure of three layers - superficial zone, middle zone and deep zone, which are divided by the different orientations of collagens. Recent publications have shown fractional anisotropy (FA) can reflect the orientation of the collagen fibers using diffusion tensor imaging (DTI) in MRI [1-3]. However, the FA contrasts were low especially between the superficial zone and middle zone in those literatures. This was possibly because they selected the short diffusion time (Δ < 10 ms) [1-3]. In our study, we chose both Δ = 10 ms and Δ = 30 ms and kept the same b = 500 s/mm^2 in six directions of diffusion gradients. The FA contrast between superficial zone and middle zone in Δ = 30 ms increased by about 4 times of the FA contrast in Δ = 10 ms. After increasing Δ, the mean diffusivity (MD) in each zone decreased because MD depended not only on the self diffusion of fluid in cartilage but also on the pore size [4], while the maximum diffusivity (MaxD) kept almost unchanged since MaxD was along the principal diffusion direction and experienced less restricted diffusion. Our preliminary data shows the MaxD has the potential to be used as a marker of the proteoglycans (PGs) concentration. Future development of this approach may be important for detecting the early degeneration of cartilage.

THEORY

With the use of diffusion weighted images (DWI) in the six directions, the apparent diffusion coefficient (ADC) can be estimated and constructed into a symmetric tensor matrix. After diagonalizing the diffusion tensor matrix, MD, MaxD and FA can be calculated.

$$\mathbf{D}=\begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{pmatrix} \longrightarrow \mathbf{D'}=\begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

$$MD=\bar{\lambda}=\frac{\lambda_1+\lambda_2+\lambda_3}{3},\ MaxD=\max(\lambda_1,\lambda_2,\lambda_3),\ FA=\sqrt{\frac{3}{2}}\sqrt{\frac{(\lambda_1-\bar{\lambda})^2+(\lambda_2-\bar{\lambda})^2+(\lambda_3-\bar{\lambda})^2}{\lambda_1^{\,2}+\lambda_2^{\,2}+\lambda_3^{\,2}}}$$

MATERIALS AND METHODS

Three specimens of Human tali were obtained within 24 hours of death of the donor through the Gift of Hope Organ and Tissue Donor Network (with Rush University IRB approval). The cartilages with Grade 0 were cut into small pieces and inserted in a 5 mm wide NMR tube filled with 0.9% Saline.

All diffusion experiments were conducted at 11.74 T (500 MHz for protons) using a Bruker DRX Avance spectrometer. The diffusion measurements were carried out using a stimulated echo pulse sequence with diffusion gradients. For the DTI experiment, TR/TE = 2000/13 ms, slice thickness = 1 mm, matrix 128 x 128, FOV = 6 x 6 mm^2. and b = 500 s/mm^2. The six directions of the gradients are as follows (x, y, z): (1, 0, 0), (0, 1, 0), (0, 0, 1), (1, 1, 0), (1, 0, 1) and (0, 1, 1).

RESULTS

Region of interests (ROIs) were selected in superficial zone, middle zone, deep zone and the whole cartilage.

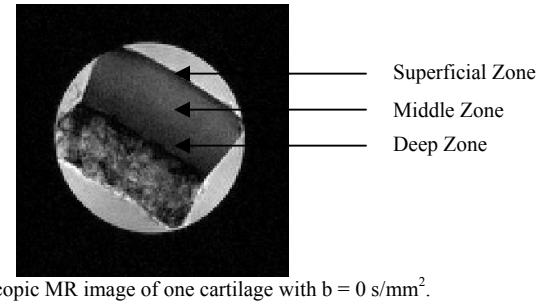


Fig. 1 Microscopic MR image of one cartilage with b = 0 s/mm^2.

Table 1 FA, MD and MaxD of superficial zone, middle zone, deep zone and bulk of the

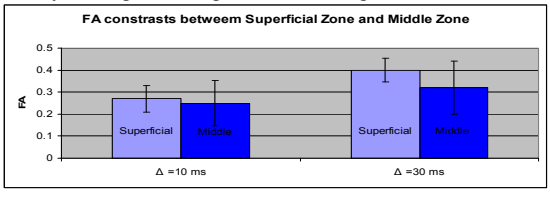
	FA		MD ($\times 10^{-3}$ mm^2/s)		MaxD ($\times 10^{-3}$ mm^2/s)	
	Δ =10 ms	Δ =30 ms	Δ =10 ms	Δ =30 ms	Δ =10 ms	Δ =30 ms
Superficial	0.27±0.06	0.40±0.05	1.39±0.19	1.18±0.14	1.72±0.16	1.68±0.17
Middle	0.25±0.10	0.32±0.10	1.11±0.22	1.02±0.20	1.38±0.16	1.35±0.16
Deep	0.47±0.13	0.52±0.18	0.77±0.11	0.78±0.12	1.27±0.10	1.25±0.10
Bulk	0.33±0.13	0.41±0.14	1.06±0.19	0.99±0.18	1.40±0.10	1.40±0.10

DISCUSSIONS AND CONCLUSIONS

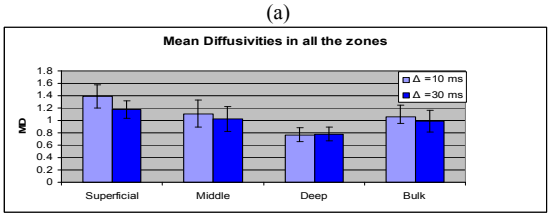
Collagen, the predominant extracellular matrix in cartilage, is broken and lost in osteoarthritis starting from the superficial zone. The collagen fibers are well organized in the superficial zone but randomly organized in the middle zone. Only given enough diffusion time, it will improve FA contrast between the superficial zone and middle zone and thus increase the FA sensitivity to the collagen structure.

Our preliminary data also shows that MD values decreased in the superficial and middle zone in the long diffusion time due to the effect of restricted diffusion. However, MaxD values didn't change obviously because it was along the principal diffusion direction. MaxD was close to the self diffusion coefficient which is related to the content of free water. Thus, MaxD might have the potential to be used as a marker of hydration or PG loss, which is the entry point of cartilage degeneration.

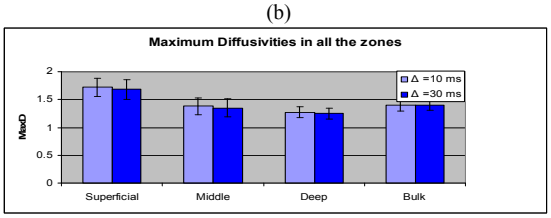
Further establishment of this method can be applied to the comparison of each zone between healthy cartilages and degenerative cartilages in the future.



(a)



(b)



(c)

Fig. 2 (a) FA contrasts between Δ=10 ms and Δ=30 ms in superficial and middle zone; (b) MD difference in all the zones between Δ=10 ms and Δ=30 ms; (c) MaxD difference in all the zones between Δ=10 ms and Δ=30 ms

REFERENCES

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