Accurate Measurement of Cartilaginous Endplate of the Intervertebral Disc of In Vivo MRI Data

Sung M. Moon[1,2], Jon H. Yoder[2], Ed J. Vresilovic[3], Dawn M. Elliott[2], and Alexander C. Wright[1]

[1]*Laboratory for Structural NMR Imaging, Department of Radiology, University of Pennsylvania, Philadelphia, PA, United States,* [2]*Department of Orthopaedic Surgery, University of Pennsylvania, Philadelphia, PA, United States,* [3]*3Department of Orthopaedics and Rehabilatation, Penn State University, Hershey, PA, United States*

INTRODUCTION: The intervertebral disc has three major structural components: nucleus pulposus, annulus fibrosus, and cartilaginous endplates (CEP). Many studies have reported on anatomy, mechanics, and chemistry of the nucleus and annulus [1-4] while very little is known about the MR characteristics of the CEP because it is very thin (~600μm) and difficult to visualize on routine MR exams (Fig.1b). Functionally, the CEP is considered a gateway for nutrient transport from vertebral blood into the central disc [2]. As degeneration progresses, the CEP becomes sclerotic and loses contact with blood vessels, providing less nutrition to the disc as well as to the CEP itself. As a result, proteoglycan content decreases within the disc, which in turn, causes a loss of hydration and osmotic pressure of the disc matrix [3,4]. The loss of the CEP is also believed to be associated with calcification and rupture. Therefore, visualizing CEP and/or measuring water content of the CEP are important for the evaluation of disc degeneration. Recently, a new method based on an optimized FLASH sequence has allowed visualizing CEP at high resolution (0.2mm^3 isotropic ex vivo and 0.4mm^2 in-plane in vivo), and CEP morphology such as thickness, area, and volume was reported [5]. However, since CEP thickness is 0.4~1.4mm, MRI thickness measurement in vivo might not be accurate enough at 0.4mm^2 resolution due to partial volume averaging. In addition, measurements made on FLASH images tend to be thicker than those made on IR-TSE images due to higher signal level in the nucleus pulposus, although FLASH is generally faster than IR-TSE. In this study, accuracy of CEP thickness measurement was analyzed, using both ex vivo and in vivo data. Partial volume artifacts were assessed, and a semi-automated method was developed to overcome measurement bias from different imaging sequences. Ex vivo and in vivo measurements were evaluated at different voxel sizes and CEP thicknesses.

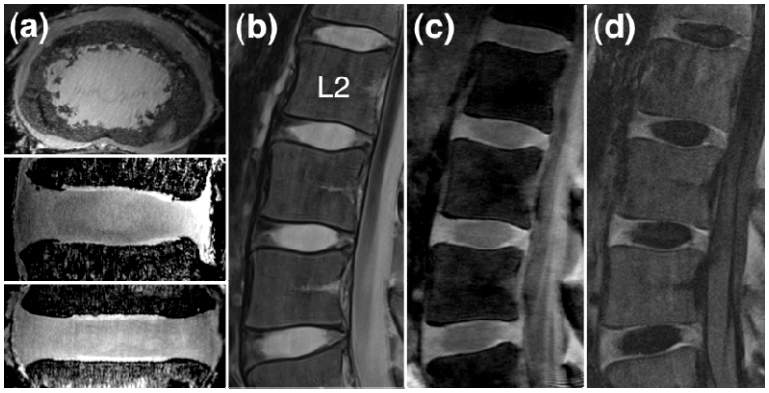

Fig. 1. Ex vivo (a) and in vivo (b-d) MRI of the disc. (a) Axial, sagittal, and coronal views highlighting the CEP of the disc. (b-d) mid-sagittal images: T2w for grading, FLASH, and IR-TSE images of the same person and at the same resolution.

METHODS

MR Imaging: For ex vivo, a human cadaveric lumbar spine segment (L3L4) was imaged using a FLASH sequence with 0.2mm^3 isotropic resolution on a Siemens 7T scanner (Fig1a). Sequence parameters for optimal nucleus-CEP contrast were described in ref [5]. For in vivo, a male volunteer (32yo) was imaged in a Siemens 3T MRI with three different sequences: T2w-TSE(Fig1b), FLASH(Fig1c), IR-TSE(Fig1d)), at the same resolution (0.49x0.49x5mm^3) and slice-position. TE/TR was 41/2000ms, 3.7/9.2ms, 14/2000ms (w/ TI=700ms), respectively.

CEP Measurements: CEP thickness, defined by the full-width-half-maximum (FWHM) of the CEP intensity profile, was measured semi-automatically using a custom Matlab program. The program was used to acquire CEP intensity profiles at five locations along the mid-sagittal AP direction (center, 5mm, 10mm off-center towards anterior and posterior). To each of these a Gaussian curve was fitted, with the FWHM used as the CEP thickness.

RESULTS

To see the difference in CEP thickness measurements and the effects of partial volume averaging due to low resolution in vivo, the high-res (0.2mm^3) image data was down-sampled to match In vivo resolution, and CEP thicknesses were measured using the custom software (Fig.2). CEP thickness ranged 0.44-1.26mm, and there were significant effects of anterior-posterior location on CEP thickness, where the minimum thickness was at the center of the disc, resulting in a "V" shaped pattern across the disc, which corresponds well to previous literature [6]. The CEP thicknesses measured from the simulated (down-sampled) in vivo data tended to be thicker than the high-res ex vivo data, over-estimated by 18.5%. CEP thicknesses measured in vivo (Fig.1c-1d) using the custom software resulted in a similar trend (Fig.3). To further assess the amount of over-estimation, a digital phantom was created to theoretically predict the error. To do this, a top-hat function (representing the CEP) with SNR corresponding to that of the in vivo data, was Fourier transformed to simulate k-space data (sinc-function), and then a truncation window was applied to simulate a low-resolution image acquisition. Next, the truncated sinc-function was zero-filled and inverse Fourier transformed and the FWHM was measured (Fig.4). The results show a theoretical overestimation of 19% for an in-plane resolution of 0.4mm^2.

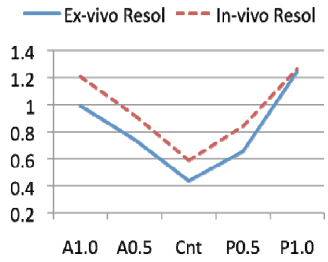

Fig. 2. Comparison of the CEP measurements from ex-vivo (0.2mm^3) and in-vivo (.49x.49x 5mm^3)

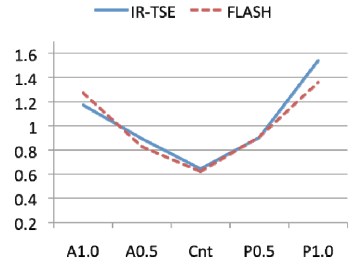

Fig 3. CEP measurements from FLASH and IR-TSE

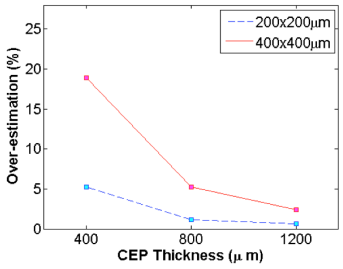

Fig4. Simulated error of over-estimation for in vivo measurements

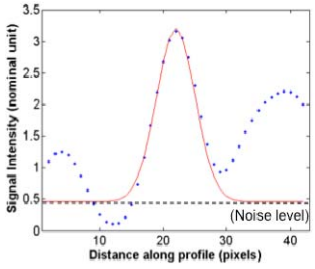

Fig.5. CEP signal profile (blue) and its Gaussian curve fitting (red)

DISCUSSION: The intensity profiles across the CEP had Gaussian-like shapes (Fig.5), which supports the use of a FWHM definition of CEP thickness. In any case, it is clear that due to both the thinness and curvature of the CEP, voxel size should be minimized to avoid partial volume averaging as much as possible.

ACKNOWLEDGEMENT: Funded by NIH grant RC1 AR058450.

REFERENCES: [1] Urban JPG et al., Arthritis Research & Therapy, 5(3):120-130, 2003. [2] Roberts S et al., J Ortho Res,11:747-757, 1993. [3] Lyons et al., Biochem Biophys Acta, 673:443-453, 1981. [4] Raj PP, Pain Practice, 8(1):18-44, 2007. [5] Moon SM et al., 57th ORS meeting: p.174, 2011. [6] Roberts S et al., Spine 14:166-174, 1989.