Investigation of fluid movement in intervertebral discs under compression using magnetic resonance imaging

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I. INTRODUCTION

The intervertebral disc's nutrient supply, waste removal and homeostasis rely on diffusion and fluid flow, which contribute to disc health and function. Several factors can change the disc's fluid flow, including injuries, dynamic load environments and prolonged forces acting upon the spine. Capturing the hydration level of a discs can be an indicator of degeneration and related to lower back pain [1]. Biphasic modeling has been investigated to capture the interaction of the physiological structures and fluid flow in human body models (HBMs) [2-3]. To inform an intervertebral disc biphasic model, experimental data are needed to help quantify the interplay of hydration level and stress input. The goal of this work is to describe a method to quantify fluid movement throughout the disc under force-controlled axial compression. These data could be used in validation studies for biphasic constitutive models. Initial findings for porcine and human lumbar discs are presented.

II. METHODS

Bone-disc-bone segments were isolated from the lumbar spine of porcine and human fresh-frozen specimens (human specimen protocol followed UVA IRB-HSU 2021-06). Excess soft tissue was removed from the specimen, as well as the posterior elements (posterior/lateral processes and facet joints). Each vertebral body was potted to approximately half its height in high-density urethane resin, with the midline of the disc parallel to the potting surfaces. Prior to testing, the specimen was preconditioned by submerging it in 37° C USP normal saline (0.9% sodium chloride) and loading to 200 N compression for 2 hours. After preconditioning, the specimen was wrapped in saline-soaked gauze surrounded by plastic wrap and transferred to a magnetic resonance (MR) compatible compression device for scanning. A vial of water was placed next to the specimen in the compression device for normalization of signal intensity values in post-processing analysis.

The MR compatible pneumatic compression device was designed to load the segment to various stress levels. The enclosed portion of the device consisted of two chambers, one pressurized and one containing the specimen, separated by a sliding piston. The force applied to the second chamber of the cylinder was calibrated using a load cell (Denton Implantable Tibia Load Cell Model No. 2886) to correlate the input pressure to the applied axial load.

MR images were acquired with a Siemens 3T Prisma MR Scanner using a knee coil as the transmitter/receiver. High resolution proton density (PD) images were acquired prior to and after applied compression using the Siemens SPACE pulse sequence to obtain the initial and final geometry of the specimen. Planar multi-echo spin echo (SE) images were acquired at approximately 15-minute intervals before and after load was applied. Acquisition times varied due to minor adjustments between scans based on intermediate scout scans. SE images were primarily acquired in the axial plane at the mid-disc; supplemental images in the sagittal plane were acquired for the human specimen. Localizer scans were acquired between each SE scan to verify or adjust the current slice position to the appropriate region of interest. Critical scanning parameters are listed in Table I.

TABLE I

	FOV (mmxmm)	Matrix size	TR/TE (ms/ms)	Slice thickness (mm)	Bandwidth (Hz/pixel)
PD	102x70	512x352	2000/7.2	0.4	280
SE*	102x102	512x512	3000/12.7	1.5	195

*Echo train length = 16.

The SE images were segmented, then analyzed in MATLAB on a voxel-by-voxel basis. Analyses to determine the distribution of water content in the disc included normalizing signal intensity values to the water vial, optimizing the T2 relaxation constant to fit a decay model to the signal decay of the experimental SE images, correlating the T2 relaxation constant to water content [4], and summing the water content across the disc volume.

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III. INITIAL FINDINGS

Two porcine specimens (P1, P2) and one human specimen (H1) were analyzed. Testing parameters and segmented volumes from PD images for each specimen can be seen in Table II. The volume for all specimens decreased between the initial and final scan (determined from PD scans), indicating that material was compressing, or fluid was exiting the segmented region of the disc. The images of the water content determined from the SE images are in Figs 1–4 for specimens P1, P2 and H1 (axial and sagittal views). For all figures, the scale is 0–100% water content (blue to red). For P1 and P2, the fluid from the nucleus redistributed throughout the annulus under load, with a relatively higher allocation to the posterior portion of the disc relative to the anterior portion. The porcine SE images likely captured part of the endplate in addition to the disc, as the disc became thin during compression. For H1, the largest change was between the pre-compressed and start of compression scans.

TABLE II

	Load (N)	Time under load (min)	# time points acquired	$V_{initial}$ (mm^3)	V_{final} (mm^3)
P1	400	70	4	2745	2226
P2	535	135	8	2845	1887
H1	535	135	4	17062	15429

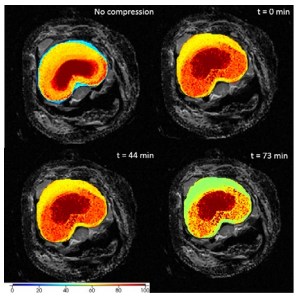

Fig. 1. P1 water content.

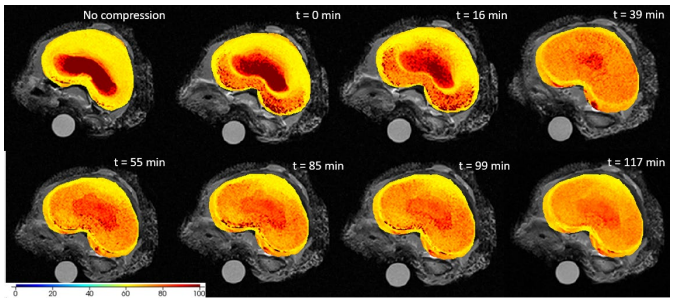

Fig. 2. P2 water content.

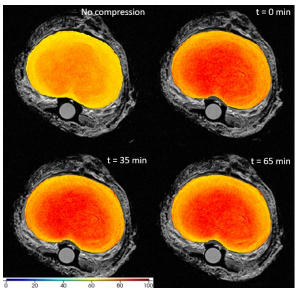

Fig. 3. H1 water content, axial view.

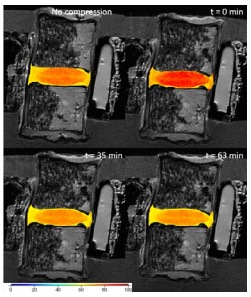

Fig. 4. H1 water content, sagittal view.

IV. DISCUSSION

The porcine discs had a wider range of water content distribution in various regions of the disc compared to the more homogenous water content distribution throughout the human discs. This could have been due to several factors, including the condition of the specimen or the magnitude of the load relative to specimen size (equivalent forces were applied, not equivalent stresses).

Limitations of this study included the relatively thin disc of the porcine specimens (may have captured endplate as well as disc in SE slices) and the reliance on the T2 relaxation constant and water content correlation provided by [4]. Additional work should be performed to validate the normalization techniques and correlation used. The preliminary values presented in this study should only be considered relative to each other and not as absolute.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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