THE EFFECTS OF PARTIAL NUCLEOTOMY AND REPETITIVE LOADING ON INTERVERTEBRAL DISC MECHANICS

Wade Johannessen, Edward J. Vresilovic, Alexander C. Wright, Heather A. Lynch, Dawn M. Elliott

McKay Orthopaedic Research Laboratory
Department of Orthopaedic Surgery
University of Pennsylvania
Philadelphia, PA

INTRODUCTION

The earliest stages of intervertebral disc degeneration occur in the nucleus pulposus; degradation of proteoglycans and a decrease in total proteoglycan and water content in the nucleus pulposus reduce the swelling pressure of the nucleus and lead to an altered loading state in the disc. Later stages of degeneration are typically marked by the presence of cracks or fissures in the annulus fibrosus. It is unclear whether these early changes in the content of the nucleus pulposus act as a mechanism for further degeneration throughout the disc.

In this study we performed a partial nucleotomy in cadaveric sheep motion segments in order to study the early stages of degeneration. In addition to measuring the acute effects of partial nucleotomy, a repetitive loading and recovery protocol was used to gain insight into the chronic effects of the partial nucleotomy. We hypothesized that partial nucleotomy would alter the mechanical behavior of the motion segment by limiting the pressure developed in the nucleus in response to applied compressive loads. We also hypothesized that, when combined with physiologic cyclic compressive loading, partial nucleotomy would lead to degenerative fissures in the annulus fibrosus. A greater understanding of the pathway of degeneration will be important in developing and validating new treatment strategies.

MATERIALS AND METHODS

Twelve lumbar sheep spines were harvested from healthy adult sheep. The musculature and soft tissues were dissected away and the transverse processes and facets removed. The L3-L4 motion segments were then potted in PMMA bone cement.

Motion segments (n = 12) were mechanically tested in a phosphated buffer saline (PBS) bath using an Instron 5543. The mechanical "Loading Protocol" (Figure 1) was as follows: An initial compressive tare load of 15 N was applied to each sample. Samples were then subjected to 50 cycles of compressive preconditioning between 15 and 400 N, at a frequency of 1 Hz. Following preconditioning, a thirty-minute stress-relaxation experiment was performed at 20% compressive strain. A slow (1 N/sec) compressive ramp test from 15 to 400 N was then performed in order to determine elastic behavior of the tissue.

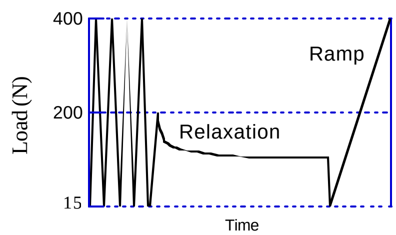

Figure 1. Loading Protocol

All samples were then subjected to repetitive loading. Samples were cycled at 1 Hz between 15 and 400 N for a total of 10,000 cycles. Samples were then placed in a refrigerated PBS bath for 18 hours to allow recovery and re-hydration. Following the recovery period, the twelve motion segments were randomly divided into two groups: samples in the treatment group (n = 6) were subjected to partial nucleotomy, the remaining samples were left as unaltered controls (n = 6). The partial nucleotomy was done by creating a 9.5 mm diameter perforation, approached parallel to the long axis of the spine, through the superior vertebra into the nucleus pulposus resulting in removal of approximately 40% of the nucleus material. The Loading Protocol as described previously was then repeated in its entirety for both groups; properties measured will be referred to as "Acute".

Both groups were then subjected to an additional 10,000 cycles of compression as described above. Properties measured at the conclusion of this repetitive loading will be referred to as "Fatigue". A second 18-hour recovery period was allowed, and properties, to be referred to as "Final", were measured again using the same Loading Protocol.

Elastic compressive stiffness was calculated as the slope of the load-displacement curve (in the linear region between 150 and 400 N) of the constant compressive ramp test. Data from the stress-relaxation tests were analyzed to determine percent relaxation and early-time relaxation behavior. Percent relaxation was defined as the total relaxation to occur during the thirty-minute relaxation period divided by the initial peak load of 200 N. Early-time relaxation behavior (during the first 100 seconds of relaxation) was calculated by computing the slope of the reduced relaxation curve with respect to logarithmic time.

Differences between control and partial nucleotomy groups were assessed using a two-way mixed-design ANOVA with independent measures on treatment group and repeated measures over loading history.

At the conclusion of the study, two representative discs from each group were imaged axially and sagitally using T2-weighted gradient echo (90°) and spin echo (300/10 and 3000/10) magnetic resonance (MR) imaging. Images were examined for changes in disc structure and water content by an orthopaedic surgeon.

RESULTS

Partial nucleotomy resulted in significant changes in total relaxation and early-time relaxation (Table). Samples in the partial nucleotomy group exhibited a 17% greater percent relaxation (Figure 2) and a 32% greater slope of the early-time logarithmic relaxation curve than control. These changes remained significant after cyclic loading and recovery. Axial compressive stiffness was not significantly affected by the nucleotomy procedure (Table, Figure 3).

Table: Mechanics Results, mean (std dev)

	Acute		Fatigue		Final	
	Ctl	DeNuc	Ctl	DeNuc	Ctl	DeNuc
Stiffness (N/mm)	678.91 (101.48)	597.65 (151.26)	823.53 (127.19)	778.09 (153.35)	668.96 (132.09)	669.00 (83.96)
Total Relaxation%	40.19 (4.84)	47.10 (4.35)	16.35 (3.18)	18.24 (2.36)	44.06 (6.25)	52.38 (7.28)
Early-Time Logarithmic Slope	0.0348 (0.0034)	0.0460 (0.0018)	0.0186 (0.0039)	0.0226 (0.0027)	0.0370 (0.0060)	0.0451 (0.0045)

The initial 10,000 cycles of compressive loading caused a significant increase in compressive stiffness, a decrease in percent relaxation, and a decrease in the slope of the early time logarithmic relaxation curve. For *all* parameters measured, the 18-hour unloaded recovery period resulted in complete recovery back to initial values.

Magnetic resonance imaging did not reveal large differences between the initial and post-test conditions in either group (Figure 4). While there was some evidence of decreased hydration in the annulus fibrosus after testing, the sample size was not large enough to draw any definitive conclusions. Magnetic resonance images of the treated discs revealed that the original defect created by the nucleotomy procedure had been filled (Figure 4, arrow).

DISCUSSION

In this study, we found the effect of partial nucleotomy to be a change in the viscoelastic behavior of the motion segment. The viscoelastic behavior remained altered after cyclic compressive loading and recovery. These results supported our hypothesis that a partial nucleotomy would alter the mechanical behavior of the motion segment. There has been limited study of the effects of nucleotomy on viscoelastic behavior of the disc; the focus of previous studies has been primarily on elastic and kinematic behavior. Altered viscoelastic behavior may act as an important mechanism in disc degeneration by altering the cell-signaling and nutrient flow in the disc.

The effects of nucleotomy on motion segment kinematics, endplate deformation, and disc pressure have been previously investigated. In agreement with these earlier studies, the axial compressive stiffness of the motion segment was not affected by the partial nucleotomy procedure [1, 2], suggesting that the annulus plays

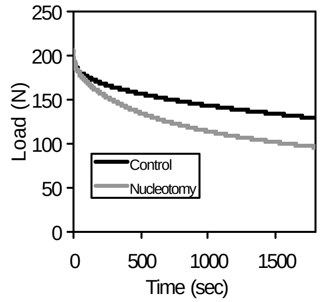

Figure 2. Stress-Relaxation

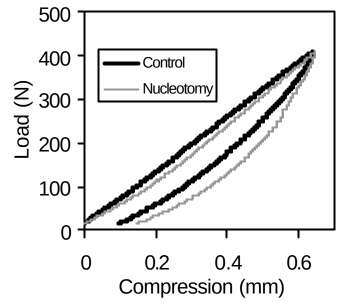

Figure 3. Slow Stiffness

Figure 4A. Control **4B. Partial Nucleotomy**

an important role in compressive load bearing. It has been suggested that the observed therapeutic effects of clinical discectomy procedures are largely due to perforation of the annulus fibrosus - the partial removal of the nucleus having little effect in comparison [3]. Importantly, in this study nucleotomy was performed while leaving the annulus fibrosus intact allowing new insight into the role of the annulus in load bearing.

Study of the internal deformations of denucleated discs has demonstrated inward bulge of the inner annulus fibrosus while the outer annulus continues to bulge outwardly [4, 5]. This condition may lead to increased shear stresses between lamellae inducing degenerative fissures in the annulus. In this study, however, neither gross inspection nor MR imaging revealed definitive signs of damage in the annulus fibrosus. It is possible that additional compressive loading cycles or higher loads may have been needed to induce degenerative changes. Alternatively, this lack of degenerative fissures may be due to the *in* vitro nature of the study, which is limited because there is no cellular response mechanism.

The study design also allowed for the study of the effects of cyclic compressive loading and recovery in the normal sheep disc. Repetitive loading caused an increase in stiffness and a decrease in percent relaxation, properties that returned to normal after a recovery period. This behavior can be attributed to dehydration of the disc tissue that occurred during cyclic loading [6].

This study of axial cyclic loading and recovery in the presence of partial nucleotomy provides information about the role of altered mechanics in disc degeneration. Further study on additional loading configurations, such as bending or flexion-extension, is still needed. To gain further insight into the effect of nucleotomy on the internal load distribution of the disc, finite element modeling will be necessary.

Supported by NIH and The Whitaker Foundation

REFERENCES

1. Shea, M., et al., J Spinal Disorders, 1994. **7**(4): p. 317-25.
2. Brinckmann, P. and R.W. Porter, Spine, 1994. **19**(2): p. 228-35.
3. Gunzburg, R., et al., Spine, 1993. **18**(2): p. 218-26.
4. Meakin, J.R., et al., Clinical Biomechanics, 2001. **16**(2): p. 121-8.
5. Seroussi, R.E., et al., J Orthopaedic Res 1989. **7**(1): p. 122-31.
6. Race, A., et al., Spine, 2000. **25**(6): p. 662-9.