Percutaneous Disc Decompression with Nucleoplasty—Volumetry of the Nucleus Pulposus Using Ultrahigh-Field MRI

Richard Kasch1, Birger Mensel2, Florian Schmidt1, Wolf Drescher3, Ralf Pfuhl4, Sebastian Ruetten5, Harry R. Merk1, Ralph Kayser1

1 Clinic and Outpatient Clinic for Orthopedics and Orthopedic Surgery, University Medicine Greifswald, Greifswald, Germany, 2 Department of Diagnostic Radiology and Neuroradiology, University Medicine Greifswald, Greifswald, Germany, 3 Department of Orthopedic and Trauma Surgery, RWTH Aachen University, Aachen, Germany, 4 Leibnitz Institute for Farm Animal Biology, Dummerstorf, Germany, 5 Department of Spine Surgery and Pain Therapy, Center for Orthopedics and Traumatology, St. Anna-Hospital Herne, Herne, Germany

Abstract

Purpose: To evaluate changes in nucleus pulposus volume as a potential parameter for the effects of disc decompression.

Methods: Fifty-two discs (T8 to L1) were extracted from 26 pigs and separated into thoracic (T8 to T11) and thoracolumbar discs (T12 to L1). The discs were imaged using 7.1 Tesla ultrahigh-field magnetic resonance imaging (MRI) with acquisition of axial T2-weighted turbo spin-echo sequences for determination of baseline and postinterventional nucleus pulposus volumes. Volumes were calculated using OsiriX® (http://www.osirix-viewer.com). After randomization, one group was treated with nucleoplasty, while the placebo group was treated with an identical procedure but without coblation current. The readers analyzing the MR images were blinded to the kind of procedure performed. Baseline and postinterventional volumes were compared between the nucleoplasty and placebo group.

Results: Average preinterventional nucleus volume was 0.799 (SD: 0.212) ml. Postinterventional volume reduction in the nucleoplasty group was significant at 0.052 (SD: 0.035) ml or 6.30% (p<0.0001) (thoracic discs) and 0.082 (SD: 0.042) ml or 7.25% (p=0.0078) (thoracolumbar discs). Nucleoplasty achieved volume reductions of 0.114 (SD: 0.054) ml or 14.72% (thoracic) and 0.093 (SD: 0.081) ml or 11.61% (thoracolumbar) compared with the placebo group.

Conclusions: Nucleoplasty significantly reduces thoracic and thoracolumbar nucleus pulposus volumes in porcine discs.

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Competing Interests: The authors have read the journal’s policy and have the following conflicts: AArthroCare Deutschland, Remscheid, provided the technical equipment needed for nucleoplasty. The authors received for their project the nucleoplasty Convenience Pack (DLR SpineWand and sterile 17-gauge Crawford needle (6’’)) from ArthroCare Germany. There are no further patents, products in development or marketed products to declare. This does not alter the authors’ adherence to all the PLoS ONE policies on sharing data and materials, as detailed online in the guide for authors.

* E-mail: richard.kasch@uni-greifswald.de

Introduction

Magnetic resonance imaging (MRI) has gained an important role as a noninvasive tool in biomedical research. No harmful side effects are known, and its excellent soft tissue contrast makes it the imaging procedure of choice for examinations of the spine [1,2]. While 1.5 and 3 Tesla MRI have become established in clinical routine [3], high-resolution 7 Tesla ultrahigh-field MRI is becoming increasingly available for answering more specialized questions [4]. Data on disc morphology and the effects of intradiscal therapy are still limited. MRI is well suited for providing such data, allowing measurement of intradiscal volume [5–6].

In the past a variety of different intradiscal procedures were used for treating symptomatic disc prolapse [7–10], many of which have now been abandoned [11]. Various studies have reported the clinical results of these treatments [8] [10] [12–14], and the effectiveness of some procedures has been demonstrated in high-quality studies [7] [10] [9] [15]. For many procedures, however, the mechanism of action remains to be demonstrated in an experimental setting.

More than 10 years ago, in July 2000, nucleoplasty was approved in the USA by the Food and Drug Administration (FDA) as a treatment for symptomatic disc prolapse [16]. Since then several valid studies have demonstrated its clinical effectiveness in treating the lumbar spine [16], and it is now considered safe and reliable [17]. Chen et al. experimentally demonstrated that nucleoplasty works by reducing pressure [18], and its histological effect on disc tissue has been characterized as well [19–20]. Experience with other intradiscal procedures suggests that the
clinical effectiveness of nucleoplasty is due to its volume-reducing effects [21]. To the best of our knowledge, a study experimentally investigating volume reduction after nucleoplasty has not been published in the English literature.

This study investigated the question of whether nucleoplasty has volume-reducing effects on biomechanically different spinal segments in pigs - the thoracic and thoracolumbar spine [22–23] - and whether these effects can be demonstrated by volumetry of the nucleus pulposus using in vitro data sets acquired by 7 Tesla MRI.

Materials and Methods

Specimens
Our study included 53 ex vivo discs (T8-L1) from 26 freshly slaughtered “German native breed” pigs (mean age, 12.7 months; range, 4–54 months). We differentiated between thoracic (T8 to T11) and thoracolumbar junction discs (T12 to L1). Discs were assigned randomly to either the nucleoplasty group or the placebo group, and the experiment was performed within 24 hours of slaughter. Discs showing damage (from slaughter, transport, etc.) on gross inspection or MRI were excluded from analysis (n = 1).

Imaging
Imaging was performed on a 7.1 Tesla MR imager (ClinScan, Bruker Bioscan GmbH, Ettlingen, Germany). Discs were placed on 1-channel surface coils with the ventral side down and examined. Before treatment, a mark was placed on each disc to match preoperative and postoperative disc positions relative to the coil. The entire nucleus pulposus was imaged (Fig. 1A) using axial, gapless, T2-weighted turbo spin-echo sequences (Fig. 1B-D) (repetition time (TR), 2000 ms; echo time (TE), 42 ms; slice thickness, 0.7 mm; field of view (FOV), 45x45 mm; 512x512 pixels). The acquisition time was 7:20 min.

Volumetry
MR images were viewed and processed using the OsiriX® software (version 3.6.1, 32-bit, http://www.osirix-viewer.com) [24]. Volumetry of the nucleus pulposus was performed semi-automatically. A radiologist manually outlined the junction of the nucleus pulposus and the annulus fibrosus, first cranially and then caudally, in the axial image stack (Fig. 1B-D). The software then automatically calculated the nucleus pulposus volume by multiplying the slices, and each slice was afterwards corrected manually. OsiriX® was used to calculate the nucleus pulposus volume by multiplying all outlined areas of the slices with the slice thickness. Volumes were measured and calculated in the same way before and after nucleoplasty or placebo treatment (Fig. 1A-D).

Nucleoplasty
We used the ArthroCare System 2000 (Arthrocare Deutschland, Remscheid, Germany) with control unit, foot switch, and Convenience Pack (DLR SpineWand and sterile 17-gauge Crawford needle (6°) with mandrin). Appropriate to the manufacturer’s instructions, the ex vivo coblation current, in the nucleoplasty group (Fig. 1D), was applied in 6 positions for 10 sec each to create 6 channels with an application field of 360°. In the placebo group (Fig. 1C) the identical procedure was performed but without application of current. Discs were randomized to nucleoplasty or placebo treatment. The volumes of the discs treated with and without application of coblation current were then compared to determine the effectiveness of nucleoplasty.

Data Selection
A total of 52 discs were included. Unpaired samples – randomly selected, independent value pairs – were assigned to one of two groups: thoracic discs and thoracolumbar junction discs, which have different biomechanical characteristics. Independent value pairs were selected randomly to minimize the potential for systematic bias (global disc disease in an individual pig, for example). Thus, only one functional lumbar spinal unit (vertebral-disc-vertebra) (T8/T9 and T9/T10) was considered per spine. The two groups (therapy versus placebo group) were formed using the SAS randomization program. For the thoracic spine, 18 discs were assigned to the therapy group and 18 to the placebo group. For the thoracolumbar spine, each group was assigned 8 discs.

Statistics
The data were assessed with the Wilcoxon test for independent (nonparametric) samples using SAS 9.1 TS (XP_PRO Windows NT Server, Cary, North Carolina, USA). Data are given as absolute values and standard deviations. Calculated differences were considered statistically significant at p < 0.05.

Results
There were no complications during the interventions. All porcine discs were found to be normal, showing no abnormalities or degenerative changes. In both postoperative groups we were able to track the placebo/nucleoplasty channel created in the center of the disc (Fig. 1C-D). The average nucleus volume for all 52 examined discs was 0.799 (SD: 0.212) ml.

The results for thoracic discs were as follows. The average baseline volume was 0.754 (SD: 0.203) ml in the nucleoplasty group (n = 18) and 0.786 (SD: 0.219) ml in the placebo group (n = 18), showing no statistically significant difference (p = 0.130) (Fig. 2). Thoracic discs treated with nucleoplasty showed a significant nucleus pulposus volume reduction (pre- versus postprocedure) of 0.052 (SD: 0.035) ml or 6.50% (p < 0.0001). Placebo-treated thoracic discs showed a significant volume increase (due to instrument manipulation) of 0.062 (SD: 0.053) ml or 8.42% (p = 0.0002) (Table 1, Fig. 3).

In the thoracic group, nucleoplasty decreased nucleus volume by 0.114 (SD: 0.054) ml or 14.72% compared with the placebo group (Table 2, Fig. 4).

The average baseline volume of the larger thoracolumbar junction nuclei was 0.850 (SD: 0.200) ml for the nucleoplasty group (n = 8) and 0.881 (SD: 0.214) ml for the placebo group (n = 8), showing no significant difference (p = 0.461) (Fig. 2). For the thoracolumbar junction group as well, a significant post-nucleoplasty volume reduction (pre- versus postprocedure) of 0.082 (SD: 0.042) ml or 7.25% (p = 0.0078) was demonstrated. In the placebo group, a nonsignificant volume increase (due to instrument manipulation) of 0.011 (SD: 0.082) ml or 4.36% (p = 0.547) was measured (Table 1, Fig. 3).

In the thoracolumbar junction group, nucleoplasty decreased nucleus volume by 0.093 (SD: 0.081) ml or 11.61% compared with the placebo group (Table 3, Fig. 4).

Discussion
Different studies have demonstrated the effectiveness of minimally invasive intradiscal procedures in treating symptomatic disc prolapse [7–8] [10] [12] [16,25] [26]. In order to gain long-term acceptance, however, clinical treatment methods require more than simply evidence-based data evaluation. Their effectiveness must also be measurable in experimentally verifiable
models [27]. For chemonucleolysis or percutaneous laser disc decompression (PLDD), with a level of evidence II-2 for short- and long-term pain relief, [8] the mechanism of action has now been clarified in an experimental setting [14] [28–31]. For nucleoplasty, however, before this study, this was not the case.

Coblation employs an electrolyte-rich medium to generate a plasma field of highly ionized particles with enough energy to break the molecular bonds in soft tissue, so that tissue is vaporized and escapes through the introducer needle [32]. It is a technology that has been successfully established in a number of therapeutic fields, not only those involving the musculoskeletal system [33–34]. The risk of indirect injury to nerve structures close to the discs has been discussed repeatedly. Temperatures of 60 to 65°C or even higher can be reached at a distance of 3–4 mm from the probe [35]. Considering that neurodegeneration begins at 45°C [36], this is not to be taken lightly. Several experiments, however,
performed both in vivo and in vitro using discs from pigs and sheep, have demonstrated that any tissue damage produced by coblation will be confined to the plasma field surrounding the electrode [19–20] [36].

Some intradiscal procedures have proven to be more effective when they are restricted to discs that have not lost too much height or volume due to degeneration [37]. Intradiscal electrothermal therapy (IDET) offers, significant relief in one-half of chronic discogenic low back pain patients [10] and, has been demonstrated to be more effective than placebo only when height loss of the discs in the segment treated is less than 20% [38]. With height loss of 50% or more, no therapeutic effect can be demonstrated at all [14]. The efficacy of most intradiscal procedures is tied to a particular disc volume, limiting their usefulness in cases of height loss or disc degeneration. For this reason our study only included discs that were free of all signs of degenerative damage in the preinterventional MRI.

Chen et al. demonstrated experimentally that nucleoplasty involves a reduction in pressure within the disc [18]. Using three human cadavers they also showed that the intradiscal pressure reduction achieved by nucleoplasty on lower thoracic and lumbar discs was dependent on the degree of disc degeneration. Applying monopolar radiofrequency in an in vivo sheep model Podhaysky et al. also demonstrated an intradiscal pressure reduction that was still measurable 4 weeks later [37]. The demonstrated pressure effects are attributable to the reduction in nucleus pulposus volume we show in our study. To our knowledge, such quantitative volume effects have not been published before.

The mechanism of action of PLDD can be described as volume reduction – which also results in intradiscal pressure reduction [39–41]. Volumetry of organs and organ systems is widely used and well established in medical research and has found a prominent place in routine clinical examinations as well. MR data sets are used to outline the target volume manually, semiautomatically, or fully automatically. This, along with the remaining image parameters (slice thickness, gap), is used to calculate the volume. Volumetry is thus used in the diagnosis of neurodegenerative diseases, cardiac diseases, and stroke as well as in the planning and follow-up of operative and nonoperative cancer treatment [42–45].

![Figure 2. Initial nucleus pulposus volumes in the independent thoracic (placebo group n = 18, nucleoplasty group n = 18) and thoracolumbar (placebo group n = 8, nucleoplasty group n = 8) groups in a box-whisker plot, presenting the 25% (lower box end), 50% (marking in the box) and 75% quartiles (lower and upper box end). The whiskers represent the smallest and largest values in the 1.5 × interquartile range. The group differences were not significant - p = 0.130 and p = 0.461. doi:10.1371/journal.pone.0041497.g002](#)
Tissue vaporization with reduction of the nucleus pulposus volume appears to be the mechanism of action by which nucleoplasty reduces pressure in intact discs as used in our study. Chen et al. demonstrated this volume-reducing effect qualitatively by performing postoperative histological examinations [19] without providing any observations on the quantitative extent of ablation or its effects. Case et al. also showed a correlation between pressure and volume changes in the disc [21].

Our experimental data show that, in a placebo-controlled setting, nucleoplasty can be used to reduce the initial volume of nucleus pulposus by a statistically highly significant degree. We attribute the volume increase in the placebo group to the fact that

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Postoperative volumes in the independent placebo and nucleoplasty groups for the two spinal segments investigated. doi:10.1371/journal.pone.0041497.g003

| Cohort                  | n    | Absolute volume change | Placebo group | p    | Nucleoplasty group | Placebo group |
|-------------------------|------|------------------------|---------------|------|--------------------|---------------|
| Thoracic discs          | 36   | −0.052 ml (SD: 0.035)  | <0.0001       | 0.062 ml (SD: 0.053) | 0.0002 | −6.30%            | 8.42%         |
| Thoraco-lumbar discs    | 16   | −0.082 ml (SD:0.042)   | 0.0078        | 0.011 ml (SD:0.082)  | 0.547  | −7.25%            | 4.36%         |

**Table 1.** Summary of intradiscal volume changes in the thoracic (n = 36) and thoracolumbar (n = 16) spine: nucleoplasty versus placebo.

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the nucleus was pushed aside and compressed by insertion of the Spine Wand. Conversely, in the nucleoplasty group, the compressed volume was reduced with the coblation current.

Our study examined regions of the porcine spine that bear the closest anatomical resemblance to the human spine [46–48]. First we quantified the volume-reducing effects of nucleoplasty on the lower thoracic spine and on the thoracolumbar junction to the upper lumbar spine, corroborating this effect by comparison with the placebo group. We demonstrated that nucleoplasty reduced initial nucleus pulposus volumes and also that these volume reductions – (T8-T11 = 14.72%) and (T12 to L1 = 11.61%) – were significant compared to the placebo procedure. Although the porcine disc model we used is very similar to the human spine, our experimental results do not allow us to draw any conclusions regarding the volume reduction in humans. This is precluded because porcine and human discs are not fully identical and because we did not measure the amount of material removed.

While the thoracic discs of the thoracic spine were smaller than the discs of the thoracolumbar junction, the volume reduction achieved by nucleoplasty was similar in the two groups. It can be assumed that decompression involves the entire anulus fibrosus and not the herniated disc portion alone [28]. Intradiscal pressure

**Table 2.** Analysis of intradiscal volume changes in the thoracic spine for independent pairs (n = 18).

| Thoracic discs | Average (mean) | Median | SD | Range | Interquartile range | p    |
|----------------|----------------|--------|----|-------|---------------------|------|
| Δ V absolute in ml | 0.114 | 0.093 | 0.054 | 0.207 | 0.076 | <0.0001 |
| Δ relative in % | −14.725 | −15.090 | 6.747 | 25.980 | 6.670 | <0.0001 |

Figure 4. Differences between initial and postoperative volumes for placebo and nucleoplasty groups. Comparison of the values of the thoracic group and thoracolumbar group shows a volume increase in the placebo group and a volume reduction in the nucleoplasty group (−markers denote “mild” outliers within the 1.5× and 3× interquartile ranges). doi:10.1371/journal.pone.0041497.g004
Table 3. Analysis of intradiscal volume changes in the thoracolumbar spine for independent pairs (n = 8).

| Thoraco-lumbar discs | Average (mean) | Median | SD   | Range | Interquartile range | p     |
|----------------------|----------------|--------|------|-------|---------------------|-------|
| A V absolute in ml   | 0.093          | 0.115  | 0.081| 0.264 | 0.073               | <0.05 |
| A relative in %      | −11.610         | −11.880| 8.280| 27.240| 8.480               | <0.05 |

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decreases in proportion to volume reduction [21]. The proteins within the nucleus pulposus exert an osmotic force that produces a continual flow of water into the disc [30]. Nucleoplasty, like PLDD, denatures some of the proteins, thus reducing the reperfusion effect in a way that contributes to the long-term effectiveness of the procedure [19] [41].

Conclusion

Our study demonstrates that nucleoplasty has a volume-reducing effect on the nucleus pulposus of the thoracic and thoracolumbar spine. While this effect was demonstrated in an experimental setting and remains to be verified in patients, our results suggest that the potential benefit likely to be achieved in the clinical setting is of interest and deserves to be pursued further.

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Author Contributions

Conceived and designed the experiments: R. Kasch R. Kayser HM BM. Performed the experiments: R. Kasch FS BM R. Kayser RP. Analyzed the data: R. Kasch FS BM R. Kayser WD SR. Contributed reagents/materials/analysis tools: RP. Wrote the paper: R. Kasch R. Kayser FS SR WD HM.

References

1. McGirt MJ, Eastwick S, Varga P, Vilecdec M, Trummer M, et al. (2009) A prospective cohort study of close interval computed tomography and magnetic resonance imaging after primary lumbar discectomy: factors associated with recurrent disc herniation and disc height loss. Spine (Phila Pa 1976) 34: 2044–2051.
2. Arun R, Freeman BJ, Scammell BE, McNally DS, Cox E, et al. (2009) ISLIS Prize Winner: What influence does sustained mechanical load have on diffusion in the human intervertebral disc?: an in vivo study using serial postcontrast magnetic resonance imaging. Spine (Phila Pa 1976) 34: 2324–2337.
3. Weintraub MI, Kleeur A, Cole SP (2007) Biologic effects of 3 Tesla (T) MR imaging comparing traditional 1.5 T and 0.6 T in 1023 consecutive outpatients. J Neuroimaging 17: 241–245.
4. Krug R, Stehling C, Kelley DA, Majumdar S, Link TM (2009) Imaging of the musculoskeletal system in vivo using ultra-high field magnetic resonance at 7 T. Invest Radiol 44: 613–618.
5. Pfirrmann CW, Metzolf A, Effering A, Hodler J, Roos N (2006) Effect of aging and degeneration on disc volume and shape: A quantitative study in asymptomatic volunteers. J Orthop Res 24: 1086–1094.
6. Violas P, Estivalezes E, Briot J, Sales de Gauzy J, Swider P (2007) Quantification of intervertebral disc volume properties below spine fusion, using magnetic resonance imaging, in adolescent idiopathic scoliosis surgery. Spine (Phila Pa 1976) 32: E405–412.
7. Kalliwada JW, Terheggen MA, Groen GJ, Sluijter ME, Derby R, et al. (2010) Discogenic low back pain. Pain Pract 10: 560–579.
8. Singh V, Manchikanti L, Benyamin RM, Helm S, Hirsch JA (2009) Percutaneous lumbar laser disc decompression: a systematic review of current evidence. Pain Physician 12: 573–588.
9. Manchikanti L, Derby R, Benyamin RM, Helm S, Hirsch JA (2009) A systematic review of mechanical lumbar disc decompression with nucleoplasty. Pain Physician 12: 361–372.
10. Helm S, Hayek SM, Benyamin RM, Manchikanti L (2009) Systematic review of the effectiveness of thermal annular procedures in treating discogenic low back pain. Pain Physician 12: 207–232.
11. Nordby EF, Wright PH, Schoefield SR (1995) Safety of chemomucoidalysis. Adverse effects reported in the United States, 1982–1991. Clin Orthop Relat Res 122: 132–144.
12. Steppan J, Meaders T, Muto M, Murphy KJ (2010) A metaanalysis of the effectiveness and safety of ozone treatments for herniated lumbar discs. J Vasc Laser Surg Med 22: 275–280.
13. Case RB, Choy DS, Altman P (1995) Change of intradiscal pressure versus volume change. J Clin Laser Med Surg 13: 143–147.
14. Kim YJ, Brischweil KH, Leyne LG, Rham S, Kim YW (2007) Is the T9, T11, or L1 the more reliable proximal level after adult lumbar or lumbosacral instrumented fusion to L5 or S1? Spine (Phila Pa 1976) 32: 2563–2561.
15. Vernon-Roberts B, Fazzalari NL, Manthey BA (1997) Pathogenesis of tears of the annulus investigated by multiple-level transaxial analysis of the T12-L1 disc. Spine (Phila Pa 1976) 22: 2641–2646.
16. OsrinX (2010) Version 3.6.1, 32-bit, Available: http://www.osrin-viewer.com.
17. Zhu H, Zhou XZ, Cheng MH, Shen YX, Dong QR (2011) The efficacy of coblation nucleoplasty for protrusion of lumbar intervertebral discs at a two-year follow-up. Int Orthop.
18. Bokov A, Skorodumov A, Irelow A, Supak Y, Kukarin A (2010) Differential treatment of nerve root compression pain caused by lumbar disc herniation applying nucleoplasty. Pain Physician 13: 469–490.
19. Mayer HM (2008) Reviewer's comment concerning “Percutaneous cervical nucleoplasty treatment in the cervical disc herniation” [Jian Li, et al. MS-no: ESJO-D-08-00079R2]. Eur Spine J 17: 1670.
20. Ding L, Liu Z (2010) A review of current treatment for lumbar disc herniation in children and adolescents. Eur Spine J 19: 205–214.
21. Choy DS, Altman P (1995) Fall of intradiscal pressure with laser ablotion. J Clin Laser Med Surg 13: 149–151.
22. Schenk B, Brouwer PA, van Buchem MA (2006) Experimental basis of percutaneous laser disc decompression (PLDD): a review of literature. Lasers Med Sci 21: 245–249.
23. Kutschera HP, Lack W, Buchelt M, Beer R (1998) Comparative study of surface displacement in disks following chemomucoidalysis and lasermucomydosis. Lasers Surg Med 22: 273–280.
24. Chen SS, Humphrey JD (1998) Heat-induced changes in the mechanics of a collagenous tissue: pseudoelastic behavior at 37 degrees C. J Biomech 31: 211–216.
25. Timms MS, Temple RH (2002) Coblation tonsillectomy: a double blind randomized controlled study. J Laryngol Otol 116: 450–452.
26. Choy DS, Altman P (1995) Lippitz SR, Nedelevkovic SS (2010) A systematic review on the effectiveness of the Nucleoplasty procedure for discogenic pain. Pain Physician 13: 117–132.
27. Berbaum K (2009) Percutaneous cervical disc decompression. Surg Radiol Anat 31: 379–387.
28. Chen YC, Lee SH, Chen D (2005) Intradiscal pressure study of percutaneous disc decompression with nucleoplasty in human cadavers. Spine (Phila Pa 1976) 28: 661–665.
29. Chen YC, Lee SH, Saenz Y, Lehman NL (2003) Histologic findings of disc, end plate and neural elements after coblation of nucleus pulposus: an experimental nucleoplasty study. Spine J 3: 466–470.
30. Lee MS, Cooper G, Lutz GE, Doty SB (2003) Histologic characterization of coblation nucleoplasty performed on sheep intervertebral discs. Pain Physician 6: 439–442.
31. Case RB, Choy DS, Altman P (1995) Change of intradiscal pressure versus volume change. J Clin Laser Med Surg 13: 143–147.
32. Chen YC, Lee SH, Saenz Y, Lehman NL (2003) Percutaneous laser disc decompression: a systematic review of current evidence. Plast Reconstr Surg 112: 83–96.
33. Chen SS, Humphrey JD (1998) Heat-induced changes in the mechanics of a collagenous tissue: pseudoelastic behavior at 37 degrees C. J Biomech 31: 211–216.
35. Nau WH, Diederich CJ (2004) Evaluation of temperature distributions in cadaveric lumbar spine during nucleoplasty. Phys Med Biol 49: 1583–1594.
36. Kapural L, Melshail N, Hicks D, Kapural M, Sloan S, et al. (2008) Histological changes and temperature distribution studies of a novel bipolar radiofrequency heating system in degenerated and nondegenerated human cadaver lumbar discs. Pain Med 9: 68–75.
37. Podhajsky RJ, Belous A, Johnson K, Maul DH, Finch PM (2007) Effects of monopolar radiofrequency heating on intradiscal pressure in sheep. Spine J 7: 229–234.
38. Pauza KJ, Howell S, Dreyfuss P, Pelozzi JH, Dawson K, et al. (2004) A randomized, placebo-controlled trial of intradiscal electrothermal therapy for the treatment of discogenic low back pain. Spine J 4: 27–35.
39. Choy DS, Diwan S (1992) In vitro and in vivo fall of intradiscal pressure with laser disc decompression. J Clin Laser Med Surg 10: 433–437.
40. Choy DS, Thorsten J, Moser F (1992) The relationship of lumbar disc volume to body size. J Clin Laser Med Surg 10: 433–434.
41. Choi JY, Tanenbaum BS, Mäner TE, Dao XV, Nelson JS, et al. (2001) Thermal, mechanical, optical, and morphologic changes in bovine nucleus pulposus induced by Nd:YAG (λ = 1.32 micron) laser irradiation. Lasers Surg Med 28: 248–254.
42. Baghi M, Mack MG, Hambek M, Bislas S, Muerthel R, et al. (2007) Usefulness of MRI volumetric evaluation in patients with squamous cell cancer of the head and neck treated with neoadjuvant chemotherapy. Head Neck 29: 104–108.
43. Groschel K, Hauf TK, Laff A, Patrinos N, Dichtlwein J, et al. (2004) Magnetic resonance imaging-based volumetry differentiates progressive supranuclear palsy from corticobasal degeneration. Neuroimage 21: 714–724.
44. Karlo C, Reiner CS, Stolzmann P, Breitenstein S, Marincek B, et al. (2010) CT- and MRI-based volumetry of resected liver specimen: comparison to intraoperative volume and weight measurements and calculation of conversion factors. Eur J Radiol 75: e107–111.
45. Loitojen JM, Jarvinen VM, Cheong B, Wu E, Kivisto S, et al. (2008) Evaluation of cardiac biventricular segmentation from multiaxis MRI data: a multicenter study. J Magn Reson Imaging 20: 626–636.
46. Lundin O, Ekstrom L, Hellstrom M, Holm S, Sward L (1998) Injuries in the adolescent porcine spine exposed to mechanical compression. Spine (Phila Pa 1976) 23: 2574–2579.
47. Alini M, Eisenstein SM, Ito K, Little C, Kettler AA, et al. (2008) Are animal models useful for studying human disc disorders/degeneration? Eur Spine J 17: 2–19.
48. Cotterill PC, Kostuik JP, D’Angelo G, Fernie GR, Maki BE (1986) An anatomical comparison of the human and bovine thoracolumbar spine. J Orthop Res 4: 298–303.