Effects of Percutaneous Intradiscal Laser Nucleotomy in a Cadaveric Sheep Model

Bir Koyun Kadavrası Modelinde Perkütan İntradiskal Lazer Nükleotominin Etkileri

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Abstract: Enthusiastic reports about percutaneous intradiscal laser nucleotomy have been encouraging to neurosurgeons treating patients with intervertebral disc herniation. Since high energy is transmitted to deep tissue and the procedure is not able to be visualized unless done endoscopically, we designed this experimental study on cadaveric sheep lumbar discs to determine the physical and neuroradiological effects of laser irradiation, altering the joules of energy applied, as well as output power, and pulse interval and number. Intradiscal pressure fell during the irradiation procedures. Very high temperatures were recorded at the neural foraminae when high laser energy levels were used, these specimens showed macroscopic thermal changes in the nearby neural tissue. The vacuum phenomenon, representing vaporization of the disc, was better visualized using computerized tomography than magnetic resonance imaging.

Key Words: Laser, lumbar disc hernia, percutaneous nucleotomy

Özet: Perkütan diskiçi lazer nükleotomi ile ilgili heyecan verici yayınlar nöroşirürjiyenleri intervertebral disk herniasyonlu hastaları tedavi etmede cesaretlendirmiştir. Bu işlem sırasında yüksek enerji derinlere iletildiğinden ve endoskopik olarak yapılmadıkça da çıplak gözle izlenemediğinden, sadece uygulanılan jül'ü değil aynı zamanda atım süresini ve sayısını modifiye ederek lazer ışınlanımının uygun fiziksel ve nöroradyolojik etkilerini belirleyebilmek amacıyla koyun kadavrası lomber disklerinde bu deneysel çalışmayı planladık. Işınlanımlar sırasında diskiçi basınçlar düştü. Yüksek lazer enerji düzeyleri kullanıldığında nöral foramenlerde çok yüksek sıcaklıklar kaydedilirken komşu nöral dokularda da makroskopik olarak termal değişiklikler gözlendi. Diskin buharlaşmasını gösteren vakum fenomeni ise bilgisayarlı tomografide manyetik rezonanstan daha iyi izlenmekteydi.

Anahtar Kelimeler: Lazer, lomber disk hernisi, perkütan nükleotomi

INTRODUCTION

In the early 1980s, percutaneous chemonucleolysis with chymopapaine was developed as an alternative to conventional surgery for the treatment of herniated lumbar disc. Complications such as anaphylactic shock and paraplegia (11) steered neurosurgeons away from this technique towards automated percutaneous nucleotomy in the late 1980s (5,7,8). However, in this procedure, the automated nucleotome cannula may cause technical problems and tissue damage. Intradiscal laser nucleotomy is a recent percutaneous technique that has the following advantages: output power is controllable, extradiscal tissue damage is minimized, and complications associated with chemical substances are avoided (14). In this in vitro study using cadaveric sheep lumbar vertebrae, we determined the neuroradiological and macroscopic features, intradiscal pressure alterations, and adjacent foraminal thermal changes caused by laser nucleotomy.

MATERIALS and METHODS

In our study, we investigated four different parameters related to laser nucleotomy (LN):

1) Neuroradiological changes
2) Temperature changes at the neural foraminae
3) Intradiscal pressure changes
4) Macroscopic changes

To investigate these parameters, 24 different laser irradiation conditions were used. Each condition was performed at seven different disc spaces. One-hundred-sixty-eight cadaveric sheep vertebral sections with lumbar discs, adjacent vertebral bodies, and intact posterior elements were used during the experiments.

For each irradiation condition, magnetic resonance (MR) and computerized tomographic (CT) images of disc spaces were taken before and after the laser procedure. The vacuum phenomenon in disc spaces was represented by a hypodense area on CT scans, and as hypointensity on MR images. The extent of vacuum phenomenon varied with each laser irradiation condition.

The disc space was entered using a single-lumen 14-gauge needle. After the laser probe was introduced through the needle, first the central and then the lateral portion of the disc was vaporized, mimicking standard procedure for our human patients. We used a Neodymium-yttrium-aluminum-garnet (Nd-YAG) laser device (wavelength: 1.064 nm, Messerschmitt-Bolkow-Blohm GmbH, Germany) with its bare fiber (outer diameter 1.0 mm).

Laser irradiation was done under the following conditions:

a) Power used was 5 Watts (W), 10 W, or 15 W

b) Pulse interval at each power level was 1 or 2 seconds (s),

c) Number of laser pulses were as follows;

(30+10)= 30 pulses in the disc center, 10 pulses laterally near foramen
(60+15)= 60 " " " " " , 15 " " "
(80+20)= 80 " " " " " , 20 " " "
(75+25)= 75 " " " " " , 25 " " "

For each irradiation condition, the pause between pulses was 1 s, and we did not stop irradiating while recording temperatures. Thermal effects of the laser irradiation were measured using thermocouples (Myocardial temperature sensor, 22Gx8mm, and Mon-a-therm Model 6510, Mon-a-therm, Inc., St. Louis, Missouri, USA) placed on the posterolateral wall of the disc, adjacent to the foramen. Temperatures at the foraminae were measured before laser irradiation, after radiation was applied to the center of the disc, and after radiation was applied laterally. The temperature of the room was maintained at 24.0°C. However, because the specimens were stored in a refrigerator, the initial temperatures of given sites differed for each disc space. As a result, we accounted for temperature increases during statistical analysis.

Every block, which was composed of a disc and two adjacent vertebrae, was subjected to a constant vertical load (a 7 kg weight placed on top of each vertebral section), and intradiscal pressure was measured before and after the procedure using a 14-gauge cannula connected to a pressure transducer (Arterial transducer, Baxter, USA, and SMU 626, Hellige, Germany). Intradiscal pressure (IDP) differences obtained with laser irradiation were accounted for during statistical analysis in order to accurately evaluate the decompressive effect of LN. Since temperature was recorded in the period between two pressure measurement procedures, there was no delay between pulses. At the end of the procedures, photographs were taken of the endplates and discs in each irradiated disc space.

For statistical analysis, data were collected in 10 groups according to the joules of laser energy applied. The four variables tested were joules of laser energy applied, temperature differences recorded when the tip of the laser probe was in the central and in the lateral parts of the disc, and pressure differences. Relationships between these variables were examined using correlation analysis, and the significance of correlations were checked using a t-test. Comparisons between the groups were made using one-way ANOVA. Since the number of the samples in each group differed, differences between the groups were controlled using the least-significant-difference test. p-values less than 0.05 were accepted as significant.

RESULTS

Neuroradiologic changes:

The effects of LN were better visualized on CT scans than MR images. The shrinkage and vaporization of the disc tissues were observed as well-demarcated hypodense areas. Approximately one-fifth or one-sixth of the disc volume was seen to be vaporized on CT scans with an output power of 5 W (<1,000 joules). This proportion increased to one-third when the output power was 10 W (1,000 to 2,000 joules), and at 15 W (2,000 to 3,000 joules) more than half of the disc tissue was seen as hypodensity on CT images (Figure 1).

The number of the pulses also affected CT appearance. This was shown when the same extent of vacuum phenomenon was observed at 5 W, 1 s, 80+20 pulses and 5 W, 2 s, 30+10 pulses, and at 10 W, 2 s, 75+25 pulses and 10 W, 1 s, 15 W, 1 s, 60+15 pulses. We could not make such a determination using MR images since the demarcation between air and disc tissue is not as clear as on CT scans (Figure 2). Only after high-energy laser irradiation did the vaporized site become more prominent on MR images. At these levels, we felt that the quality of the frames on MR images could be compared with CT scans of discs irradiated with the same number of joules.

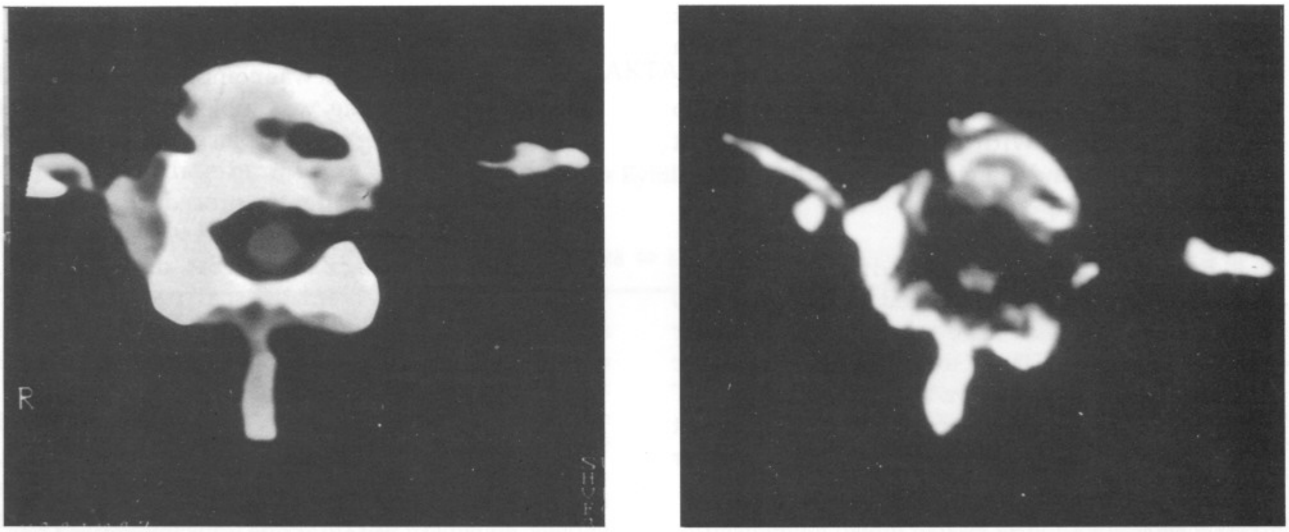

Figure 1: After 15 W, 1 s, 75+25 pulses(1,500 joules) of LN: A) 1/3 of the disc was seen to be vaporized on CT scans, B) but the best MR frame was not sufficient to make this determination.

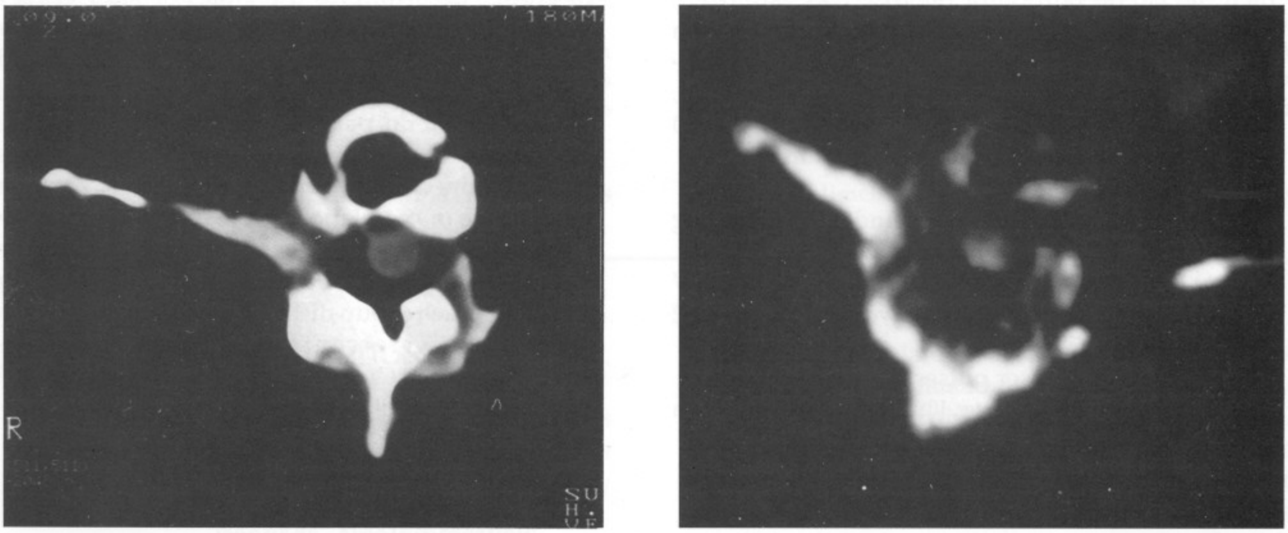

Figure 2: After 15 W, 2 s, 75+25 pulses(3,000 joules) of LN: A) half of the disc was vaporized on CT scan, B) a similar volume of vacuum phenomenon was observed with MR images.

Temperature changes at the neural foraminae:

Temperatures consistently increased with increasing power, number of pulses, and length of interval(Table 1). At 5 W, the recorded increases in the temperatures varied from 3.2 to 20.8°C, depending on repetition time and interval. These variations ranged from 4.8 to 33.0°C, and from 7.6 to 40.3°C for output powers of 10 W and 15 W, respectively.

At 5 W and 15 W, the pulse interval did not seem to affect temperature, but with output power of 10 W, when the interval was increased to 2 s we recorded temperature increases of 9.4 to 14.8°C above other discs that were irradiated with an interval of 1 s.

The number of pulses seemed to be more strongly associated with temperature elevations than interval time. The highest temperatures were recorded after 80+20 or 75+25 pulses. Also, marked temperature increases were recorded when higher numbers of pulses were delivered to the lateral portion of the disc. Repetition times of 75+25 pulses resulted in higher temperatures than other combinations. Although initial disc temperatures were about 20°C, the final temperatures were often above 45.0°C (and up to 56.2°C) when the output power was 15 W. Similar high temperatures were also recorded when the intervals were 2 s for 5 W and 10 W output powers.

In other words, the number of joules of laser energy applied were closely related to observed increases in temperature. The mean temperature increases at 1,000, 2,000, and 3,000 joules were 14.20°C, 28.56°C, and 32.96°C, respectively.

Intradiscal pressure changes:

Our study showed that LN had decompressive effects. The mean initial IDPs under a constant vertical load of 7 kg were 199.91±54.99 mmHg before laser irradiation. Pressure differences rose in proportion to increases in output power, pulse interval, and repetition frequency (Table 2). Output power was most strongly correlated with pressure difference, but the effect of interval on pressure changes was not clear. Also, repetition times of both 80+20 and 75+25 pulses resulted in much more significant decreases in intradiscal pressure than other pulse frequencies, but the latter (75+25 pulses) seemed more effective. Pressure differences were usually over 20 mmHg after 5 W, 2 s of laser irradiation; over 30 mmHg after 10 W, 2 s; and over 40 mmHg after 15 W, 2 s of laser application. In short, IDP fell proportionately as joules of applied laser energy increased. The mean pressure decreases at 1,000, 2,000, and 3,000 joules were 44.60 (22.3% of the mean initial IDP), 84.33 (42.1%), 95.0 (47.5%) mmHg, respectively.

Table I: Mean temperature increases (°C) and standard deviations (SD) for each laser irradiation condition are listed.

	30+10 pulses		60+15 pulses		80+20 pulses		75-25 pulses	
	central	lateral	central	lateral	central	lateral	central	lateral
5 W, 1 s	1.20±0.12	3.20±0.12	6.40 ±0.17	15.20±0.17	4.30 ±0.12	9.90±0.11	5.00 ±0.15	16.10±0.14
5 W, 2 s	5.60±0.14	7.50±0.11	7.20 ±0.23	12.20±1.23	2.60 ±0.82	23.40±1.98	15.50±1.42	18.90±1.69
10 W, 1 s	1.60+0.29	4.80+0.60	2.70 +0.35	9.80+1.06	5.60 +0.49	12.10+0.81	10.80+1.01	27.70+2.02
10 W, 2 s	5.20+0.64	14.20+1.25	10.00+1.08	16.00+1.11	12.00+0.92	26.90+1.28	19.20+0.92	33.00+1.30
15 W, 1 s	3.10+0.69	24.20+1.74	4.80 +0.80	7.60+1.02	17.10+1.42	26.90+1.28	16.47+1.35	28.50+1.90
15 W, 2 s	4.10+0.75	10.30+1.73	17.50+1.72	25.80+1.90	22.20+1.90	31.30+2.38	22.60+2.35	34.40+2.14

Table II: Mean pressure decreases (mmHg) and SDs for each laser irradiation condition are listed (n=7).

	30+10 pulses	60+15 pulses	80+20 pulses	75+25 pulses
5 W, 1 s	10.00 +1.73	15.00 +1.41	16.00 +1.41	20.00 +1.29
5 W, 2 s	20.00 ±1.29	28.00 ±1.73	35.00 ±1.73	45.00 ±1.73
10 W, 1 s	20.00 +1.74	30.00 +2.16	45.00 +2.16	45.00 +1.29
10 W, 2 s	27.00 ±1.41	70.00 ±2.82	80.00 ±4.35	88.00 ±3.55
15 W, 1 s	25.00 +1.73	60.00 +4.08	60.00 +4.69	77.00 +3.16
15 W, 2 s	45.00 ±3.87	85.00 ±3.74	90.00 ±1.87	100.00±4.65

Macroscopic changes;

Macroscopic changes of irradiated disc tissues and endplates occurred in proportion to the laser energy used, and were more striking than the neuroradiological findings. The disc margins neighboring the vaporized part were carbonated near the site where the tip of the probe had been inserted. This empty space was larger macroscopically than seen on CT scans (Figure 3). When output power was high, not only the nucleus pulposus, but also the endplate and annulus adjacent to the foramen were destroyed (Figure 4). Output power greater than 5 W, 2 s, 60+15 pulses (750 joules) led to striking disc tissue destruction. At 10 W, 1 s, 80+20 and 75+25 pulses (1,000 joules), macroscopically one-third of the disc was vaporized; at 15 W, 1 s, 80+20 and 75+25 pulses (1,500 joules) one-half, and at 15 W, 2 s, over half of the disc was vaporized. Endplate burn was first observed after a laser irradiation of 5 W, 2 s, 30+10 pulses (400 joules). Concavity of the endplate occurred at output power of 10 W, 2 s (>800 joules). The annulus fibrosus started to show damage when 15 W, 2 s, 60+15, 80+20, and 75+25 pulses of laser irradiation was applied. The most noticeable changes near the foramenae were observed at 15 W, 2 s, 80+20 and 75+25 pulses of irradiation. At this level of irradiation, almost all disc tissue was carbonized and the dura was discolored.

Figure 3: After 15 W, 1 s, 75+25 pulses(1,500 joules) of LN, over half of the disc is vaporized, leaving a carbonized surface, macroscopic changes in the posterior longitudinal ligament, endplate and annulus fibrosus.

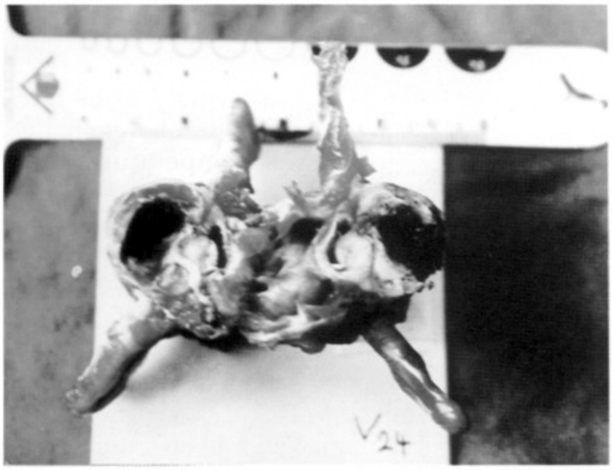

Figure 4: After 15 W, 2 s, 75+25 pulses (3,000 joules) of LN: Almost complete disc vaporization with carbonization of the disc and endplate together. Macroscopic thermal changes are also seen in the dura.

Table III: Mean temperature increases (°C), pressure decreases (mmHg), and SDs for 10 groups of samples are listed. Correlation analysis showed that all four variables were positively correlated ($p<0.05$).

GROUPS	n=	JOULES CENTER + LATERAL	TEMPERATURE CENTER mean SD	DIFFERENCES LATERAL mean SD	PRESSURE DECREASES mean SD
I	7	150 + 50	1.20 ±0.13	3.20 ±0.13	10.00 ±1.73
II	21	300 + 75	4.53 +2.16 *	9.16 +4.50	17.00 +2.56
III	14	400 + 100	4.65 ±0.38 *	13.06 ±3.21 *	20.00 ±1.46
IV	21	450 + 150	4.33 +2.13 *	15.40 +6.58 *	26.66 +2.00 *
V	7	600 + 200	5.20 ±0.64 *	14.20 ±0.31 *	30.00 ±2.16
VI	35	800 + 200	7.05 +3.19	13.15 +3.27	44.60 +5.78
VII	14	1000 + 200	11.86 ±6.77	17.94 ±7.56	60.00 ±4.22
VIII	14	1200 + 300	16.78 ±1.37 *	27.70 ±1.51 *	73.50 ±4.71
IX	21	1600 + 400	16.23 +3.36	28.56 +3.54	84.33 +5.01
X	14	2400 + 600	22.40 ±2.06	32.96 ±2.67	95.00 ±6.95

(*) The least-significant-difference test revealed no significant differences between the consecutive groups II, III, IV,V, and VI, or VIII and IX for central irradiations, III, IV,V, and VI, or VIII and IX for lateral irradiations, and IV and V for pressure decreases ($p>0.05$).

Statistical analysis (Table 3):

Correlation analysis showed that all four variables were positively correlated. All the correlation coefficients (r) were greater than 0.5524, indicating strong relationships. During all double correlations, t-values were greater than 2.31 ($p<0.05$). Comparison between the groups using one-way ANOVA showed that no significant difference in temperature increases occurred when 600 to 1,000, and 1,500 to 2,000 joules of laser irradiation were applied. When we compared the groups according to pressure decreases, we also found significant differences between them, apart from consecutive groups IV and V (650 to 800 joules of laser energy).

DISCUSSION:

Some reports have labeled laser nucleotomy ineffective based on results from histological and radiological experimental studies (12,13). However, laser nucleotomy causes some physical changes in the irradiated discs, and we believe that these may play an important role in terms of the therapeutic effect of this method at least in a limited population of patients. Laser irradiation produces water vapor, carbon, CO_2, and carbonated disc tissue fragments. During the procedure, heat is distributed through the disc and annulus toward adjacent structures (10,15). Also, vaporization and shrinkage of disc tissue causes a decrease in the bulk of material in the disc space (2). These two physical changes are perhaps the ones most strongly correlated with relief of symptoms in nonsequestrated disc herniations after LN (2,3,15).

High temperatures result from tissue vaporization, needle warming, and the vapor produced by laser irradiation (10). Exhausting the vapor and use of Teflon-coated hardware can decrease the amount of heat that is distributed (15). In our study, the vapor was drawn out through the needle lumen and occasionally through the hole in the annulus that had been created by a cannula placed for pressure measurement. We did not use teflon-coated needles, but those commonly used by our neurosurgeons in daily clinical practice.

The aim of surgical techniques in treating nonsequestrated disc herniation is to reduce IDP by removing disc tissue. When the bulk of the disc is removed, IDP decreases at rest and after vertical loading. Although the IDP increases in proportion to the load, as in normal discs, the IDP of adjacent nonirradiated discs increases more steeply (15). Nerubay et al. reported that IDP decreased in all instances after disc irradiation of lumbar intervertebral discs in dogs, with the drop ranging from 10% to 69% (6). We also observed IDP reduction of approximately 1/3-1/2 of the initial pressures. Relief of patients' symptoms after LN may, in large part, be due to this decrease in IDP.

However, the role of thermal changes is less clear. Schoenenberger et al. showed a strong correlation between macroscopic size of necrosed area and real-time monitored temperature spread measured by the superconducting, open-configuration MR system (10). Some authors have recorded high temperatures of close to 40°C at the annulus (1,15). Our investigation showed that foraminal temperatures reached 40.0-56.0°C, even though the initial temperatures were below normal human body temperature. This may be related to the size of the sheep specimens. The temperature increases were consistent after vaporization of the lateral part of discs as well, and such high temperatures may damage nerve roots. There have been few clinical reports published concerning nerve root damage after LN. The complex regional pain syndrome type II, with sympathetically maintained pain, which may be seen after a number of spinal procedures, may also occur after laser nucleotomy and can result in serious disability (9). However, our findings indicate that nerve root damage may easily occur, especially when attempts are made to satisfactorily decompress the lateral portions of discs.

Conversely, it is possible that the heat energy actually contributes to the therapeutic effect of LN. If the heat damages or permanently depolarizes bare C-fibers or thin myelin-covered A-delta fibers, or decreases the threshold for depolarization of the large, myelin-covered A-beta fibers which already have low thresholds, analgesia may result (4); however, this has yet to be investigated.

Based on our previous experience with other percutaneous techniques, we did not expect to find any radiographic decrease in disc bulging after LN. Discography performed immediately after LN is the most valuable technique for demonstrating the proportion of disc that has been vaporized. CT delineates the vacuum phenomenon, which is the most significant finding after LN. A large volume of vacuum phenomenon detected with CT is a sign of satisfactory decrease in disc volume and IDP. If LN is not performed endoscopically, early CT scanning of the irradiated disc space may be help in assessing the completeness of disc vaporization.

In planning this study , our aim was to produce some reliable results that might be useful for modifying laser therapy in patients who suffer burning sensation in their legs during procedures. We did gain some insights applicable to daily clinical practice. In such patients, it would be prudent to initially allow pauses between pulses and let the vapor exhaust to cool the tissue, and to vaporize only the center portion of the disc, not the lateral areas. When these adjustments are not sufficient, it is advisable to reduce output power and delay heating, thus to reach the appropriate joule level with more pulses, and decrease IDP via this route. If all these maneuvers fail, there is no point in continuing the procedure.

CONCLUSION:

LN causes a predictable decrease in intradiscal pressure and achieves disc destruction. The increases in temperature near the neural foraminae are disturbing, however, and further in vivo research should be done to determine the benefit or harm caused by the high temperatures associated with LN.

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