Health Sciences Doctoral (PhD) School

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Image guided and controlled percutaneous laser disc decompression *ex vivo*

PhD Thesis

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1. Introduction

The 65-70% of the population over 40 years were affected by low back pain and/or herniated intervertebral disc. A study was performed in 2003 on the Hungarian population (OLEF 2003) assessed that the 49.1% of men and 63.9% of women experienced pain from the cervical, thoracal or lumbal spine. The associated costs for medical care due to the chronic pain reach the costs of ischeamic heart deseases showed by a study made in Great Britain.

Disc protrusion caused by uncontrolled mechanical loading by the patient can lead to nerve damage or loss of function at the innervated field by increasing the pressure in the nucleus pulposus.

The notability of discus hernia in lumboischialgic symptoms explored in the early of 1900. For therapy only conservative methods had been used for a long time, which followed by surgical methods. Operative intervention should be used only in cases of rupture of the annulus fibrosus (herniated disc). In the last two decades several minimally invasive surgical techniques were developed using different lasers. An alternative minimally invasive method for reducing pain is PLDD. This technique requires, a quartz fiber to be inserted into the center of the herniated disc to deliver laser energy that is converted to heat. This increases the temperature of the nucleus pulposus, thereby enhancing the evaporation of its water content. As a result, the pressure of the herniated nucleus pulposus decreases and the nerve root is decompressed.

2. Aims

Based on the previously described results in literature, we targeted the followings:

1. beyond the routinely used imaging techniques for controlling PLDD procedures, the application of surgical navigation has advantages. Based on this statement we aimed to prove that the positioning of the laser fiber can be achieved with greater precision of 3mm or less;
2. to prove that with this accuracy mentioned in the first point, the application is appropriate for avoiding the damage of the surrounding vessels and nerves;
3. to decrease the radiation exposure of the staff and the patient by using surgical navigation during PLDD;
4. to verify the physical effect of the laser radiation is detectable in small volume by MR imaging methods;
5. to investigate the MRI detected findings due to infrared laser light by pathological methods;
6. to investigate the difference of the physical effects of dissimilar laser wavelengths (980nm vs. 1470nm) by histopathology.

3. Materials and methods

Our ex vivo interventional work was done at Kaposvár University Health Center. The CT and MRI measurements made here and at Diagnosctic Center Pécs.

The experimental work had two parts:

1.a using surgical navigation—controlled by CT/MRI/surgical fluoroscopy—for precise positioning of the laser trocar

1.b detecting the physical effect of the delivered energy by cross-sectional imaging (qualitative MRI) and histology

2. comparing the effect of diode laser on different wavelength by qualitative, quantitative MRI and pathology

Specimens

Two freshly butchered ex vivo porcine lumbar spines were obtained and used (***1.a*** and ***1.b***). For the second part of the study three freshly killed bovine spine specimens were used and measured in the study.

Surgical navigation

This system uses the preoperative CT and/or MRI scans and electro-magnetic (EM) tracking technology to provide positional feedback of an instrument's location and orientation within a given location. MR imaging was performed on each cadaver before and after each laser procedure at room temperature for detecting the tissue changes caused by the laser irradiation. The accurate registration (i.e., alignment or matching) of these two data sets subsequently allowed localization of the surgical instruments within the operative space. Recently, a new autoregistration system is improving the speed and the ease of use by facilitating the employment of an intra-operative C-arm and algorithm to register the CT images. The sensors provide positional (X, Y, Z) information, which correlates the movement of the Nav Trocar to the preoperative CT images displayed on the interactive monitor.

Laser

High-intensity, small-size clinical laser equipment with fiber-optic guides was used for this study. Its wavelength is 980±10 nm, which is close to the wavelength of the Nd:YAG, and its water absorption is also similar. For achieving the aims we also used a different laser wavelength (1470±10nm) to detect the distinct physical changes.

For porcine procedures we used impulse mode of the laser on 20W power. From 200 to 700 Joules were delivered to six nucleus pulposus of the lumbar spine in one hundred joules steps. The other six discs received equally five hundred joules.

In the second part of the experiment to model decompression, a flexible laser quartz fiber inserted into the nucleus pulposus of ex vivo bovine spines using computer-assisted surgical navigation was utilized to vaporize tissue. The same energy (500J) was delivered on 5W power with all discs using both 980nm and 1470nm wavelength lasers without changing any other parameter except the wavelength. To determine the different impact of the wavelengths before and after the procedure we evaluated the discs with MRI (T_1, T_2, diffusion maps) and with histopathology.

Imaging methods

For the navigation we used CT scans to reach the accuracy. For detecting the physical effect of laser radiation we made preoperative and postoperative MR scans. The surgical navigation controlled laser procedure was supervised by C-arm fluoroscopy.

Dosimetry

After reviewing the literature we could not find data according to dose load on the staff and/or the patient during PLDD helped by C-arm fluoroscopy. In place of previously standard C-arm fluoroscopy, in these days there are some other techniques for image guided and controlled surgical procedures. Cross-sectional imaging (CT/MRI) provided more spatial, anatomical information with use of surgical navigation can lead to leave the necessary of use C-arm flouruscopy. This can result the reduction of direct and scatter dose for staff and the patient. In our study for modeling disc decompression we measured the scattered dose from the specimen to the staff.

Histological work of the specimen

After the laser irradiation and CT and MR documentation, the lumbar intervertebral discs from each specimen were harvested and dissected. Since the porcine disc is narrow, the discs were cut in half and photo-documented. Using a plastic template, same-size specimens from each intervertebral disc were excised for histologic examination. For evaluating the physical effect of PLDD the samples were examined under 100x magnification by pathologist.

4. Results

The role of imaging for controlling the accuracy of PLDD

Monitoring of a needle trocar is essential during percutaneous laser discectomy and the use of CT /MRI in this experimental study provided superior spatial and soft tissue resolution to that of the single-plane C-arm fluoroscopy views. The additional spatial configuration data provided by CT navigation facilitated the puncture position of the navigated trocar tip on axial and sagittal images, enabling for precision laser ablation of the intervertebral disc.

Using a high-intensity diode laser, we aimed to improve the safe insertion of the laser trocar with the aid of a stereotactic computer-assisted surgical navigation system.

We determined that the Nav Trocar was inserted into the intervertebral disc accurately with the aid of the computer-assisted surgical navigation system with 1.0-1.5mm total system tip-tracking accuracy (1.4±0.2 and 1.1±0.2mm) confirmed by spot X-ray fluoroscopy and further measured by the "distance from trocar" feature available on the navigation system.

Dosimetry results

To determine the dose load from scattered dose to the staff and the patient, we set measurements from 50 and 100 centimeters from the specimen. The phantom what was used for this measurements stayed also 40 centimeters from the X-ray tube and from the image intensifier (isocentric set). The dose rate of the C-arm fluoroscope was 80µrtg/s during cine mode. The background scattered dose was 80nSv/h and the dosimeter measured dose equivalency in 10mm depths. For regulation of the dose load, the Hungarian law has reference dose values for the staff based on International Atomic Energy Agency's (IAEA) guidelines. According to this the dose load can not exceed the 100mSv limit in 5 consecutive years, and can not exceed the 50mSv limit in one year. Based on our dose measurements 50 centimeters from the X-ray source the value was 0.0096% of the one year limit and 0.0048% of the five year limit. 100 centimeters from the source these values were 0.0024% and 0.0012%.

In the literature we found some data about the procedure time of pedicle screw insertion. For this intervention the requivisite time period of using C-arm fluoroscopy was 38s. Our results show that by using computer assisted surgical navigation the procedure time can be decreased to $1/4^{th}$ of the conventional fluoroscopy time. According to this, we decreased the dose load of the staff and the patient.

Detecting physical effects of PLDD by magnetic resonance imaging

a) The postoperative MR study showed changes in the disc compared with images obtained before laser irradiation. Postdissection macroscopic examination demonstrated that the insertion of the Nav Trocar was in the intended target area of the disc as planned by the computer software and correlated with low-dose pulse X-ray shots. Under magnification, visual examination of the lumbar vertebrae showed no evidence of disruption to the adjacent nerve root and visceral or vascular structures. Furthermore, the microscopic examination revealed tissue coagulation changes in the uniformly and in the gradually irradiated discs.

b) The aim of this study was to investigate the impact of diode laser disc decompression at different wavelengths (980nm vs. 1470nm, i.e., different water absorption characteristics). To determine the different impact of the wavelengths before and after the procedure we evaluated the discs with MRI (T_1, T_2, diffusion maps). There was no statistical difference between the temperature values of the specimens before and after the measurements.

The application of the 980nm laser caused significant decrease in T_1 values and significant increase in T_2 values at the site of laser treatment; however, no significant T_1 and T_2 changes could be detected by averaging the whole nucleus pulposus. It appears that the 980nm laser has an effect on water diffusion limited only to the site of the application. No diffusion changes were detected in the nucleus pulposus and the site of the laser application was not visible on the diffusion-weighted images.

The application of the 1470nm laser caused a T_1 signal decrease similar to the 980nm laser treatment at the site of the laser application. This change, however, did not reach a significant level. The T_1 signal of the whole nucleus pulposus increased significantly. The 1470nm laser application site in the nucleus pulposus was not visible on the T_2 or the ADC images. The T_2 signal did not change in the whole nucleus pulposus either, but the ADC increased significantly if the whole nucleus pulposus is considered. Overall, the 980nm laser caused T_1 and T_2 changes only at the site of the laser application, while the 1470nm laser caused T_1 and ADC changes in the whole nucleus pulposus and no significant changes at the laser application site.

Pathological results

Microscopical work unfolded the tissue changes in the laser-ablated nucleus pulposus.

After histological evaluation here we demonstrate the result:

a) In PLDD, a quartz fiber is inserted into the center of the herniated disc to deliver laser energy that is converted to heat. This increases the temperature of the nucleus pulposus, thereby enhancing the evaporation of its water content. Routine pathological methods showed carbonisation zone at the site of the application by sudden heat elevation during the procedure. We proved steam bubble formation zone in the surroundings of the carbonisation zone. The size of bubbles depends on the wavelengths of the laser light.

b) The histopathological evaluation of the control and laser-ablated discs revealed differences between the two laser wavelengths. At the site of the application, the carbonization zone was wider (a range of 300-400μm) in the case of the 980nm laser, and the bubbles caused by the heat were greater in size and showed confluent features.

Following the 1470nm laser irradiation, a narrower belt (a range of 200-300μm) of the canal was carbonized. The bubble formation zone was 600-700μm with the 980nm laser in contrast to the 300 to 400μm zone seen with the 1470nm laser. The bubble formation caused by the 1470nm laser was nonconfluent.

5. Conclusions and discussion

In the 1940s, individual cranial landmarks could be referenced to stereotactic guidance systems that resulted in the development of arc-based stereotactic frames based on the Cartesian idea. According to this in the 3 dimensional coordinate system every point's position depends on the distance and the angle of the plane of another point. When CT and MR imaging became available, these patient-attached frames allowed for significant precision in localizing intracranial structures through what is called today frame-based stereotaxy. When computing power increased in the 1990s, stereotaxy evolved to ''frameless stereotaxy''. These modern stereotactic surgical navigation systems now provide an operator with a three-dimensional visual ''road map'' of a patient's anatomy utilizing the display of a particular imaging modality with the precise position and orientation of a surgical instrument relative to the surrounding anatomy. Today computer-assisted frameless navigation is a newly evolving technology that has been further adapted from intracranial surgery for use in minimally invasive spinal procedures

In this study, we demonstrated the use of computer navigation to track solid-state diode laser beam delivered through fiber optics for transcutaneous laser discectomy. Because this procedure is complicated by a critical triangular zone of blood vessels and nerves in the close proximity of the intervertebral space, it is important to very precisely navigate the surgical instrument safely through this zone. We showed that it was possible to achieve precise placement for debulking of disc material with an accuracy error of preferably 2mm or less. As it was expected the most accurate navigation could be reached at the L_4 level. At this level was the most precise of the connection between the dynamic reference tool and the spinal processus. As far the target volume was away from the transmitter as the accuracy of the navigation was declenided based on potential changes of the magnetic field.

With the growth of minimally invasive surgical procedures in the spine limiting direct anatomic views by percutaneous approaches, the dependence on the intraoperative use of mobile C-arm fluoroscopy is expanding. During such procedures the surgeon and assisting operating staff may be positioned directly adjacent to the image intensifier beam, leading to higher exposure to radiation. Studies have shown that fluoroscopy-assisted pedicle screw placements expose the spine surgeon to significantly greater levels of X-ray dose than those experienced by nonspinal surgeons. To our knowledge there is no publication in the literature to compare the dose exposure in computer assisted surgical navigation and the C-arm fluoroscopy aided PLDD.

Avoiding the health damage of the staff who work in direct radiation, the International Atomic Energy Agency give some direction for making the rules. Based on this the Hungarian Law control the dose load of the staff. According to this the dose load can not exceed the 100mSv limit in 5 consecutive years, and can not exceed the 50mSv limit in one year. Our results show that the radiation exposure can be decreased down to 0.00289% of the international limit depending on the distance and position of the staff from the radiation source by using computer assisted surgical navigation.

Benzel et al. needed 38s for pedicle screw insertion, while in other publication this time was 63s. A team leaded by Choi compared the navigation technique to fluoroscopy method and they showed 4.6s in pedicle screw insertion with navigation. This mean significant dose load reduction to the staff and the patients. There are several factors which disturb the exposition time of radiation during percutaneous procedures. This can be inaccurate spatial point description, or different operative techniques, but we can mention the application of different experience with radiological and surgical techniques.

Comparing to the standard C-arm fluoroscopy, the frameless stereotactic navigation is developed which is showed in the accuracy.

One of the aims was—over proving the accuracy helped by surgical navigation—to measure the physical effect of PLDD by qualitative and quantitative MR methods and show it by histopathological methods. We used 980 and 1470nm wavelength diode laser light for the study. The 1470nm laser light has different absorption nature in water (40 times greater). Knowing the water content of the nucleus pulposus, we expected different effect. The 980nm wavelength produced a wider carbonization zone and had a greater destructive effect on tissue at the site of the laser application than 1470nm light. In the carbonized area, the decreased T_1 values may reflect the water content decrease due to vaporization. The T_2 increase in the carbonized zone can be explained by the change in tissue anisotropy (i.e., orientation of proteins) and change in proteoglycan content. No diffusion changes could be detected in the carbonized area, possibly because of low spatial resolution (i.e., large partial voxel effect). No change in any MR parameters was observed if the whole nucleus pulposus is taken into account. These findings suggest that the 980nm laser has a well-localized effect in the tissue, and the laser energy was absorbed in a small restricted volume.

The 1470nm wavelength caused a narrower carbonization zone with nonconfluent bubbles at the site of the application. The carbonization zone was seen only on T_1-weighted images, since the T_1 measurement had the highest spatial resolution. The T_2 and diffusion weighted images could not resolve the small tissue changes (i.e., narrower carbonization zone) in contrast to those caused by the 980nm wavelength. The T_1 signal was slightly decreased at the site of application (in the carbonization zone), suggesting a tissue water content decrease; however, this alteration did not reach the level of statistical significance ($P=0.069$). The same energy of 500J was delivered to each disc at both wavelengths, thus the narrower carbonization zone in the case of the 1470nm wavelength may suggest that there is absorption excess in the disc further away from the application's site. Both T_1 and ADC values are increased significantly if the whole nucleus pulposus was taken into account, while T_2 signal remained constant. The increased T_1 values in the entire nucleus pulposus indicate that an opposite tendency is observed compared with the carbonization zone. We hypothesize that the free water fraction may be increased (i.e., the same MR parameter fingerprint as seen in extracellular brain edema, free water fraction) by application of the 1470nm laser, of which there is a larger water absorption property in contrast to 980nm wavelength.

In summary, the different MR imaging parameter changes (i.e., ADC and T_1 signal increase in the whole nucleus pulposus) may suggest additional tissue interactions than those seen with the 980nm wavelength. Since all quantitative MRI parameters are temperature dependent, the temperature of the disc was rigorously measured before and after the laser application and the MR imaging measurement was started only when the disc cooled down to its initial room temperature. Temperature sensitive T_2-weighted measurements were performed, which did not show significant difference between the results before and after the procedure. Furthermore, the spatial resolution of T_2 and ADC measurements was not enough to point out subtle MR parameter changes in the carbonization zone at the site of the application of 1470nm laser.

Main limitation of our study was the room temperature in vivo. It was very important to hold the temperature of the specimens at the same level before and after the procedure. Since all the quantitative MR parameters are temperature dependent. If there were any difference between the temperature of the discs, the T_2 measurements should show difference also. Furthermore the T_2 and ADC measurements spatial resolution did not provide enough information for detecting any MR parameter changes surrounding the carbonization zone when we used 1470 nm wavelength laser light.

In conclusion, T_1 and T_2 signal changes were observed at the site of application in the intervertebral disc after a diode laser application at a 980nm wavelength. In addition T_1 and ADC value changes were observed after diode laser application at the 1470nm wavelength in the nucleus pulposus as a whole. The quantitative MR imaging measurement of the laser effect may help to assess the PLDD therapy objectively. The 1470nm laser with larger water absorption properties appears to have an effect on the entire nucleus pulposus and not only in the surrounding tissue of laser fiber (carbonization zone).

6. New scientific results

1. By using computer assisted surgical navigation for percutaneous laser discectomy we could reach 2mm accuracy in positioning the laser quartz fiber.
2. Compared to two dimensional fluoroscopy, we proved in this study that the more detailed computer tomography for PLDD is more useful and safe, although the CT was not real-time imaging method in this study. We did not remark any artificial damage of the vessels and nerves in the operation area after the PLDD.
3. By using computer assisted surgical navigation the procedure time was shorter, shortening the use of C-arm fluoroscopy time and decreasing the

radiation exposure of the staff and of the patient, what we showed foremost.

4. We proved—despite of the small volume—that qualitative and quantitative magnetic resonance imaging is suitable for detecting the physical effect of percutaneous laser discectomy.
5. First in Hungary we justified with pathological methods the MRI proved physical effects caused by PLDD.
6. Foremost we described in the literature the correlation between wavelengths and the caused pathological differences of distinct laser lights, confirmed by histopathology.

7. Publications, abstracts and presentations

Publications in foreign language

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Abstracts

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