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Abstract. The purpose of the present study was to measure the intradiscal pressure signal of an anesthetized sheep under spontaneous breathing. An ultra-miniature fiber optic high-pressure sensor was implanted into the nucleus pulposus of the fifth lumbar intervertebral using a dorsolateral transforaminal approach. Results suggested the periodicity of the intradiscal pressure signal was similar to the mean respiratory rate of the animal. The average resting intradiscal pressure was also calculated and compared to available data. © *2014 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JBO.19.3.037006]

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1 Introduction

The intradiscal pressure is the pressure measured in the nucleus pulposus (NP) of an intervertebral disc (IVD). This fibrocartilaginous structure found between adjacent vertebrae of the spine has two main components: the NP and the annulus fibrosus (AF). The NP is a semifluid, amorphous, highly hydrated, and proteoglycan-rich region located near the center of the IVD.[1] The AF encloses the NP and acts like a solid elastic ring preventing its gel-like fluid to escape.[2] In the mechanical view, the NP is considered to be incompressible, exhibiting a hydrostatic behavior.[3] Thus, it is well designed to act as a cushion protecting the spine elements from loads, which is usually followed by an increase in the intradiscal pressure.[4]

Intradiscal pressure data from Nachemson's studies formed the basis of the current knowledge about the *in vivo* loading conditions of the spine.[5] In 1959, he was the first to measure *ex vivo* intradiscal pressure in human discs.[6] During the 1960s and 1970s, Nachemson et al.[7–9] also carried out *in vivo* measurements of intradiscal pressures for several body postures and tasks, which became a reference in the field. Since that time, few *in vivo* studies have been published.[10–13] Apart from more demanding ethical aspects conducting animal and human research, it has been suggested that the large dimensions of these conventional sensors (usually >1 mm diameter) could interfere with the natural disc behavior and lead to disc degeneration.[14] So minimally invasive sensors could represent a significant advance in this field and fiber optic sensors (FOS) seem to represent an interesting alternative to the large conventional sensors.[15–18] In fact, some successful efforts have been made to demonstrate it. Dennison et al.[19] have used a needle housing a fiber Bragg grating sensor of 0.4 mm outer diameter (OD) to measure the intradiscal pressure in cadaveric spines. A more smaller sensor with an outer diameter of 366 μm and based

on a Fabry-Pérot configuration was proposed by Hsieh et al.[20] and Nesson et al.[21,22] It has been used for *in vitro* measurements of intradiscal pressures in rodent tail discs.[20–23] Some commercial solutions are also available, such as those from Radi Medical Systems (Uppsala, Sweden) and Samba Sensors (Västra Frölunda, Sweden). The sensor from Radi Medical Systems is an intensity-modulated sensor with a diameter of 550 μm and was used to monitor intradiscal pressure in sedated pigs[24] and patients suffering from lumbar back pain.[25] Samba sensors have been used to measure intradiscal pressures in pigs,[26,27] rabbits,[28] and human cadaveric spines.[29] Even so, the number of *in vivo* studies reporting the use of FOS to measure intradiscal pressures seems to be scarce. However, as pointed by Wilke et al.,[11] such kind of data seems to be critical for the validation of models that predict spinal loads.

In the present study, an effort has been made to demonstrate FOS potentialities measuring the intradiscal pressure pattern during spontaneous breathing. The breathing effect in the intradiscal pressure is observable only *in vivo* and corresponds to a small periodic variation that is superimposed on the intradiscal pressure signal.[30] It is measured in a resting position under general anesthesia and the effect seems to exist slightly or disappear in the standing or the sitting position.[10] It has been suggested that it could play an important role in the nutrition of the IVD, helping to pace the rate of diffusion and osmosis of nutrients from blood vessels of the vertebral body through the cartilage endplate into the disc matrix.[30,31]

2 Material and Methods

2.1 *Fiber Optic Sensor*

An ultra-miniature fiber optic high-pressure sensor (Samba Preclin 360 HP, Västra Frölunda, Sweden) has been used

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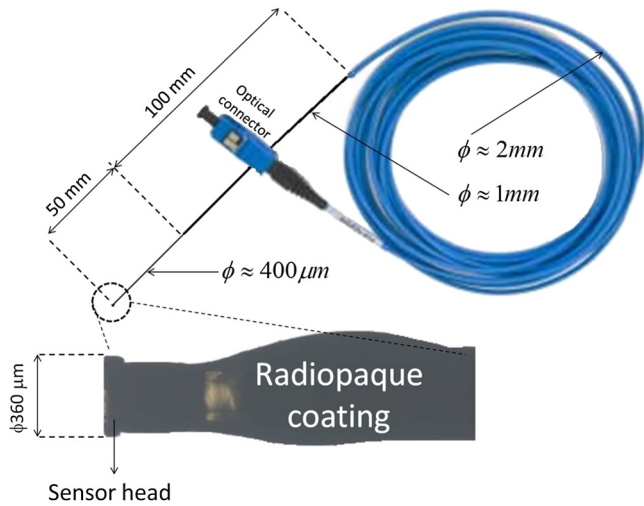
Fig. 1 Illustration of the Fabry-Perot sensor at the end of the lead fiber/cable (the sensing head and the nearby lead fiber were coated with a radiopaque material, which allowed knowing the position of the sensor inside the body).

(Fig. 1). It consisted of a silicon sensing head with 360 μm OD mounted on an optical multimode fiber with ~400 μm OD.

Prior to *ex vivo* and *in vivo* experiments, the sensor was left at room temperature for ~10 min in a solution of 4% Cidezyme (CIDEZYME® Enzymatic Detergent Solution, Johnson & Johnson, Medical Inc., Irvine, California) in water and rinsed afterward in distilled and deionized water.
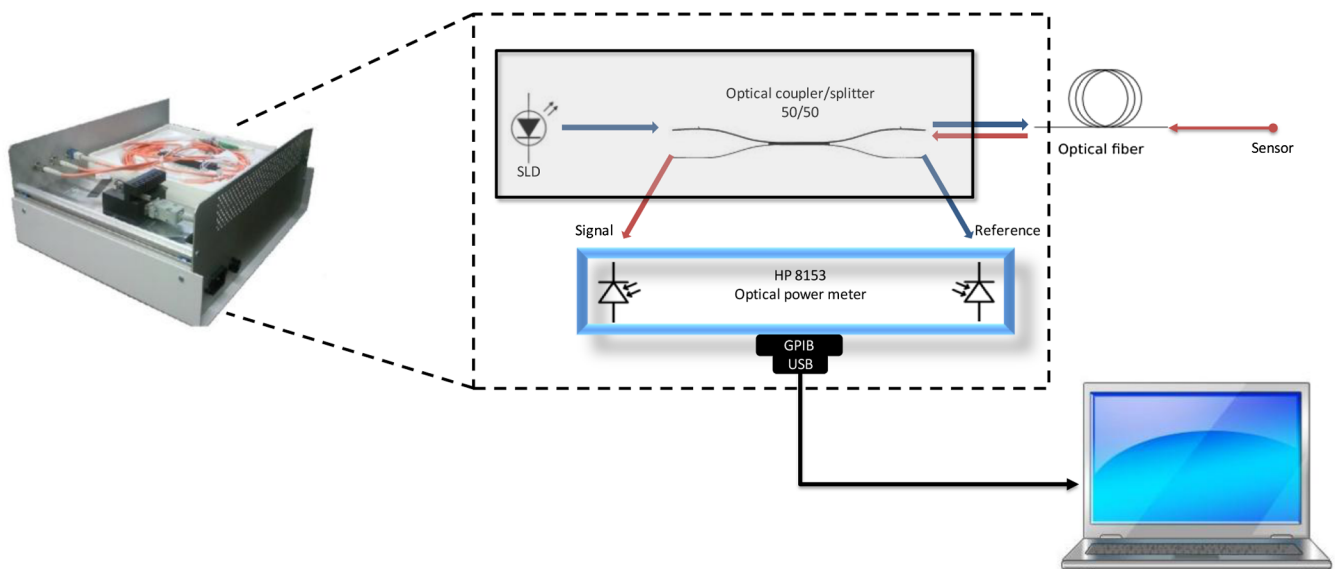
2.2 Interrogation Unit

A purpose-built interrogation unit connected to a portable computer was used to interrogate the sensor. The basic functioning of the system is depicted in Fig. 2.

As can be observed, the power of the incoming light of a superluminescent diode was split 50/50 at the optical coupler/splitter. In such a way, part of this light was used as the signal

of reference (at ~1300 nm) in order to account for source power fluctuations (measured in μW) and the remaining light was used to interrogate the sensor. At the sensor head, the light is back-reflected to the coupler/splitter and the corresponding power measured at the optical power meter (Fig. 2). The output signal (sensorsignal/referencesignal) was measured at a sampling rate of 17 Hz. A GPIB-USB controller (Prologix, LLC, Washington) was used to allow communication between the PC and the optical power meter (Fig. 2).

2.3 Sensor Calibration and Data Acquisition

A purpose-built pressure device was used for calibration of the sensor (Fig. 3). The functioning of the pressure device consists of rotating the screw that is connected to the syringe plunger pushing the water inside the syringe into the acrylic chamber (previously filled with distilled water). This action increases the pressure and the rotation in the opposite direction decreases it. On both sides of the acrylic chamber a bolt and nut with passing holes allowed insertion of the sensor into the acrylic chamber (Fig. 3). The sensor was guided through the hole by means of a hypodermic needle that was retracted after sensor insertion. To seal the passing holes, a septum of silicone located in between the bolt and nut was used. Using the previous setup, three increasing and decreasing pressure cycles from 0.0 to 14.0 bar (step of 0.5 bar) were performed for sensor calibration. A manometer intended for medical applications (WIKA 111 series; EN 837-1) with a pressure range from −1 to 15 bar and accuracy class of 1.6 was used for pressure readings. Once the pressure is adjusted, the manometer indicator stays static, allowing signal readings without any type of screw/pressure adjustment being necessary for the measured range. A LabVIEW routine was implemented to control data acquisition and store an array of values ($n = 10$) of the output signal at each calibration step. The averaged calibration data points were plotted and the calibration coefficients were calculated using fitting functions. These coefficients were used in another LabVIEW routine that was implemented for pressure readings during *ex vivo* and *in vivo* experiments.

Fig. 2 Schematic representation of the interrogation unit and of the basic functioning of the system used to interrogate the sensor.
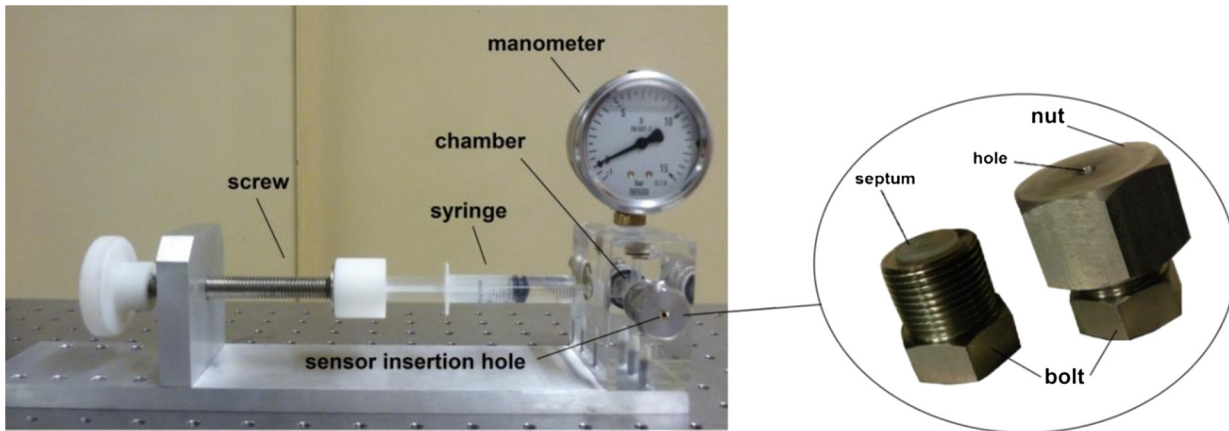
Fig. 3 The pressure device used to calibrate the sensor.

The maximum error introduced by hysteresis of the sensor was calculated as a percentage of the maximum pressure used during calibration (14.0 bar). Maximum sensor drift during a measurement period of 30 min was also calculated for pressures of 0.0, 7.0, and 14.0 bar.

2.4 Ex Vivo and In Vivo Experiments

Ex vivo and *in vivo* experiments were conducted by skilled veterinarians at the facilities of the Veterinary Hospital of the University of Évora. Experiments were authorized by competent national authorities and conducted according to the guidelines for animal care of the Federation of Laboratory Animal Science Association. *Ex vivo* experiments were useful to decide about the most appropriate *in vivo* surgical approach and to test the whole system and sensor performance prior to *in vivo* measurements.

For *in vivo* measurements, the Samba sensor was implanted in the fifth lumbar intervertebral disc (IVD) of a four-year-old female merino ewe with 45 kgf body-weight, under general anesthesia [Fig. 4(a)]. The animal was maintained on a radiolucent table in a lateral right recumbence position. Endotracheal intubation was performed and the anesthesia was maintained through isoflurane (2 to 3%) in oxygen with spontaneous ventilation. The heart and respiratory rates were controlled [Fig. 4(a)].

A dorsolateral transforaminal approach into the center of the NP, similar to that used in discography and percutaneous nucleotomy, was followed for sensor implantation.[32] The lumbar region was prepared for needle puncture with a povidone-iodine solution. A guiding needle was inserted percutaneously in the dorsolateral intervertebral disc space under fluoroscopic control [Fig. 4(b)]. Once positioned in the NP, the stylet point of the needle was taken out and the pressure sensor was passed fully through the cannula and introduced into the NP. The cannula was retracted from the IVD and data collection started.

## 3 Results and Discussion

3.1 Sensor Calibration

The average results of the three calibration cycles are presented in Fig. 5. The differences on the output signal between consecutive steps of calibration of 0.5 bar were calculated. On average, these differences were of $(5.754 \pm 0.472) \times 10^{-4}$. The mean

standard deviation of each step of calibration was $(2.022 \pm 0.262) \times 10^{-4}$, which represents $\sim$35% of the average difference between consecutive steps of calibration. The previous data were used to calculate the calibration coefficients using a linear regression model (Fig. 5).

Maximum hysteresis of the sensor was 0.46%. Maximum sensor drift during a measurement period of 30 min for pressures of 0.0, 7.0, and 14.0 bar was ± 0.002 bar.

3.2 In Vivo Experiments

The percutaneous approach under fluoroscopic control seems to be the adequate technique for animal experiments and to ensure a transition to human *in vivo* applications. Moreover, compared to an open approach, where inner organs and tissues are

(a)

(b)
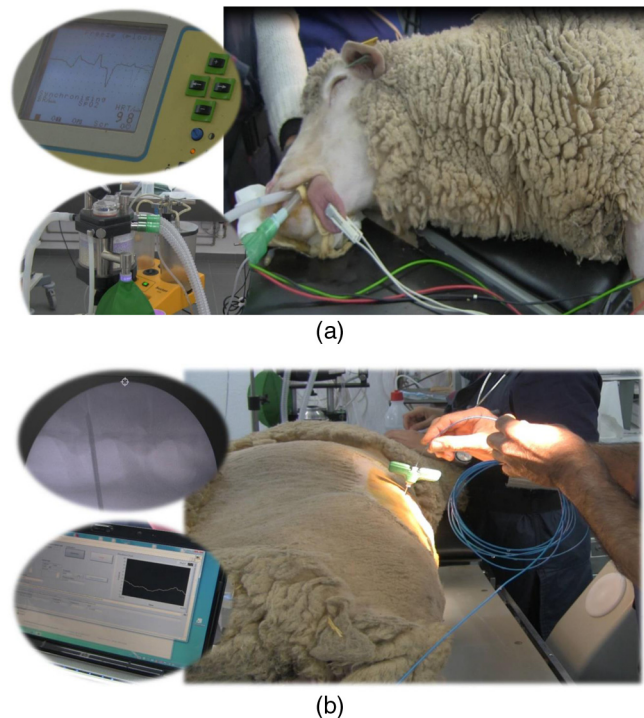
Fig. 4 (a) The anesthetized sheep was maintained on a radiolucent table in a lateral right recumbence position under control of heart rate and respiratory rate. (b) Implantation of the Samba sensor into the nucleus pulposus of the intervertebral disc under fluoroscopic control.
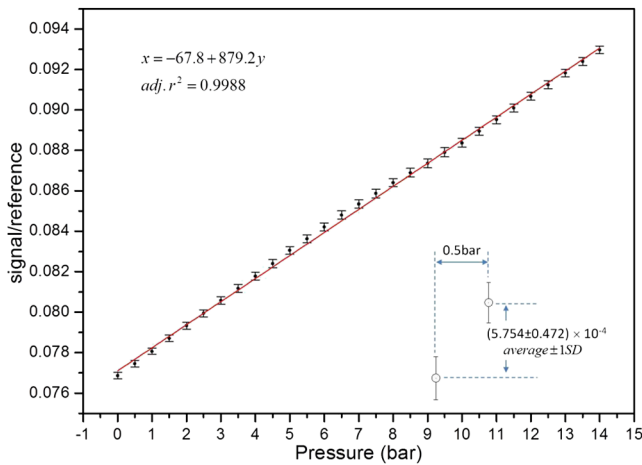
Fig. 5 Calibration points of three pressure calibration cycles. A detail on the average of the differences between consecutive steps of calibration was shown. Y-error bars represent one standard deviation (SD). A linear regression model was applied to calculate the calibration coefficients.

exposed, the technique is less invasive. In fact, in the present study, the animal was able to recover and released to its natural environment in <4 h. The complete operation from the beginning to the end of anesthesia lasted for ~2 h.

The intradiscal pressure variation pattern observed during spontaneous breathing under general anesthesia was observed once the sensor was *in situ*. A section of this pattern was plotted in Fig. 6.

On average, the signal periodicity was 2.81 ± 0.12 s (time peak to peak), which corresponds to ~21.30 ± 0.12 pressure cycles per minute (Fig. 6). The previous rate was similar to the mean respiratory rate under spontaneous ventilation, which was 20.5 breaths per minute. Sato et al.[10] found that the pressure wave pattern was synchronized with the number of respirations but did not present the corresponding rates. The effects of breathing rate and volume on disc pressure were studied by Keller et al.[30] in lumbar discs of anesthetized pigs. In that case, instead of promoting spontaneous ventilation, a ventilator was used to control the previous parameters.
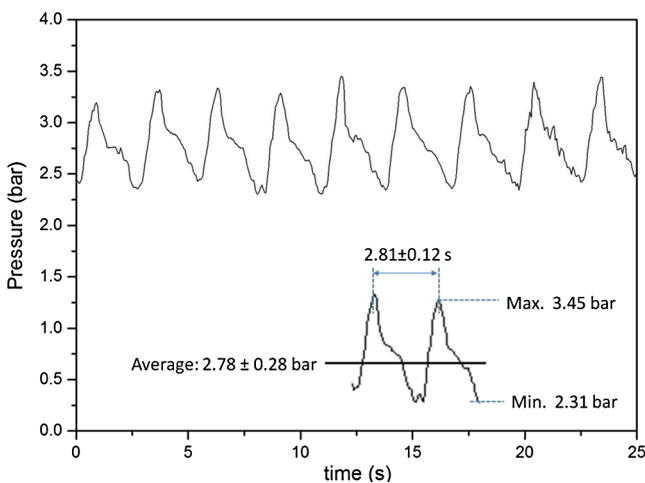
Fig. 6 Intradiscal pressure pattern in the fifth lumbar disc during spontaneous breathing. Average pressure and time were detailed as well as maximum and minimum pressures.

Breathing had a significant effect on the intradiscal pressure, which seems to decrease with breathing rate and increase with breathing volume.[30]

In the present study, pressure fluctuations ranged between 2.31 and 3.45 bar with a maximum amplitude of 1.14 bar (Fig. 6). On average, the resting intradiscal pressure corresponding to lateral right recumbence position was 2.78 ± 0.28 bar (Fig. 6). Few studies have registered the possible effect of breathing on intradiscal pressure. Moreover, in most of them, the phenomenon was only presented graphically along with the calculation of the mean resting (physiologic, intrinsic, or baseline) pressure.[10,24,26,27] In the previous studies, the mean resting pressure ranged from 0.7 (Ref. 26) to 2.0 bar.[27] These pressures were measured in anesthetized pigs and are lower than the mean resting pressure registered in the present study (2.78 bar). On the other hand, higher mean resting pressures were also reported. For example, the resting pressures found in rabbit lumbar discs ranged between 2.2 and 4.2 bar (mean was 3.6 bar).[28] In the study of Nachemson and Morris,[7] the mean pressure obtained for human subjects in the reclining position was 5.4 bar (ranging between 1.4 and 8.3 bar). Finally, in thoracic discs of human subjects, which have the same kyphotic curvature as the lumbar spine of a sheep, the mean resting pressures found were closer to those of the present study, ranging from 2.0 to 3.4 bar.[13] In the previous study, it was also found that the pressure depends on the resting position and disc level. For example, for the same disc levels (T9 to T10, T10 to T11), the resting pressure was higher for the lying on side position (3.0 bar) than in the lying prone position (2.0 bar). Ekström et al.[24] also suggested the resting pressure can be influenced by the pre-tension in the ligaments and the AF, being also highly dependent on the angulation of the vertebrae. The above factors may explain the differences found between studies. While some of them seem difficult to control, such as the pre-tension in the ligaments and the AF, further research seems necessary to better understand these phenomena. Using FOS also seems an excellent contribute to study them because they are minimally invasive and should not affect the natural behavior of the IVD.

4 Final Remarks

In this study, FOS were explored to perform minimally invasive *in vivo* studies and measuring a possible effect of breathing on intradiscal pressure. A surgical protocol similar to the one used in humans was applied, suggesting these sensors can be integrated in human surgical procedures without major difficulty. In <4 h, the animal was able to recover and released to its natural environment. Even so, present sensor is for nonclinical use only. In fact, to our best knowledge, there is no similar commercially available FOS (in the range of 0 to 15 bar or higher) approved by the Food and Drug Administration for clinical use. The whole system worked well. However, the interrogation unit requires further improvements, such as synchronizing the breathing and heart rate with pressure rate in order to correlate them. Portability and wireless data transmission along with higher acquisition rate should also be considered to perform dynamic studies.

Removing the sensor from the measurement site and reimplanting it in the same or another disc would substantially increase the surgery time. Each new measurement would include sensor cleaning, a new puncture and successive reorientation of the fluoroscopic system to guide and position the

sensor into the NP. Thus, once the periodic pattern was observed, it was decided to perform a continuous measurement for a period of ∼5 min. Doing it we were aware that the repeatability of measurements could not be assessed, which represents a limitation of the present work.

Meanwhile, SAMBA sensors ceased to exist, which limits the ability to repeat the experiment with new SAMBA sensors. Alternatively, it seems possible to use other sensors, such as those of FISO Technologies Inc. (Québec, Canada).

Finally, further research seems mandatory to produce clinically relevant information and for data comparison between different studies.

Acknowledgments

References

1. L. J. Smith and N. L. Fazzalari, "Regional variations in the density and arrangement of elastic fibres in the anulus fibrosus of the human lumbar disc," *J. Anat.* **209**(3), 359–367 (2006).
2. C. Hirsch, "Studies on the mechanism of low back pain," *Acta Orthop. Scand.* **20**(4), 261–274 (1951).
3. H. Schmidt et al., "Intradiscal pressure, shear strain, and fiber strain in the intervertebral disc under combined loading," *Spine* **32**(7), 748–755 (2007).
4. P. A. Cripton, G. A. Dumas, and L. P. Nolte, "A minimally disruptive technique for measuring intervertebral disc pressure in vitro: application to the cervical spine," *J. Biomech.* **34**(4), 545–549 (2001).
5. A. Nachemson, "The influence of spinal movements on the lumbar intradiscal pressure and on the tensile stresses in the annulus fibrosus," *Acta Orthop. Scand.* **33**(1),183–207 (1963).
6. A. Nachemson, "Measurement of intradiscal pressure," *Acta Orthop.* **28**(4), 269–289 (1959).
7. A. Nachemson and J. M. Morris, "In vivo measurements of intradiscal pressure: discometry, a method for the determination of pressure in the lower lumbar discs," *J. Bone Joint Surg. Am.* **46**(5), 1077–1092 (1964).
8. A. Nachemson, "The effect of forward leaning on lumbar intradiscal pressure," *Acta Orthop.* **35**(1), 314–328 (1965).
9. A. Nachemson and G. Elfstrom, "Intravital dynamic pressure measurements in lumbar discs. A study of common movements, maneuvers and exercises," *Scand. J. Rehabil. Med.* **1**(Suppl. 1), 1–40 (1970).
10. K. Sato, S. Kikuchi, and T. Yonezawa, "In vivo intradiscal pressure measurement in healthy individuals and in patients with ongoing back problems," *Spine* **24**(33), 2468–2474 (1999).
11. H. J. Wilke et al., "Intradiscal pressure together with anthropometric data: a data set for the validation of models," *Clin. Biomech.* **16**(Suppl. 1), S111–S126 (2001).
12. K. Sato, K. Nagata, and T. Hirohashi, "Intradiscal pressure after repeat intradiscal injection of hypertonic saline: an experimental study," *Eur. Spine J.* **11**(1), 52–56 (2002).
13. D. J. Polga et al., "Measurement of in vivo intradiscal pressure in healthy thoracic intervertebral discs," *Spine* **29**(12), 1320–1324 (2004).
14. C. L. Korecki, J. J. Costi, and J. C. Iatridis, "Needle puncture injury affects intervertebral disc mechanics and biology in an organ culture model," *Spine* **33**(3), 235–241 (2008).
15. P. Roriz et al., "Fiber optic intensity-modulated sensors: a review in biomechanics," *Photonic Sens.* **2**(4), 315–330 (2012).
16. P. Roriz et al., "Review of fiber optic pressure sensors for biomedical and biomechanical applications," *J. Biomed. Opt.* **18**(5), 050903 (2013).
17. E. Cibula et al., "Miniature all-glass robust pressure sensor," *Opt. Express* **17**(7), 5098–5106 (2009).
18. D. Donlagic and E. Cibula, "All-fiber high-sensitivity pressure sensor with SiO2 diaphragm," *Opt. Lett.* **30**(16), 2071–2073 (2005).
19. C. R. Dennison et al., "Validation of a novel minimally invasive intervertebral disc pressure sensor utilizing in-fiber Bragg gratings in a porcine model: an ex vivo study," *Spine* **33**(17), E589–E594 (2008).
20. A. H. Hsieh et al., "Intradiscal pressures in rat tail discs measured using a miniaturized fiber-optic sensor," *J. Biomech.* **39**(Suppl. 1), S28 (2006).
21. S. Nesson, M. Yu, and A. H. Hsieh, "A miniature fiber optic pressure sensor for intradiscal pressure measurements of rodents," *Proc. SPIE* **6528**, 65280P (2007).
22. S. Nesson et al., "Miniature fiber optic pressure sensor with composite polymer-metal diaphragm for intradiscal pressure measurements," *J. Biomed. Opt.* **13**(4), 044040 (2008).
23. D. Hwang et al., "Role of load history in intervertebral disc mechanics and intradiscal pressure generation," *Biomech. Model. Mechanobiol.* **11**(1–2), 95–106 (2012).
24. L. Ekström et al., "In vivo porcine intradiscal pressure as a function of external loading," *J. Spinal Disord. Tech.* **17**(4), 312–316 (2004).
25. B. Hök et al., "Pressure microsensor system using a closed-loop configuration," *Sens. Actuat A Phys.* **41**(1–3), 78–81 (1994).
26. S. Höejer et al., "A microstructure-based fiber optic pressure sensor for measurements in lumbar intervertebral discs," *Proc. SPIE* **3570**, 115–122 (1999).
27. H. Hebelka et al., "The transfer of disc pressure to adjacent discs in discography: a specificity problem?," *Spine* **35**(20), E1025–E1029 (2010).
28. T. Guehring et al., "Intradiscal pressure measurements in normal discs, compressed discs and compressed discs treated with axial posterior disc distraction: an experimental study on the rabbit lumbar spine model," *Eur. Spine J.* **15**(5), 597–604 (2006).
29. L. Ferrara et al., "A biomechanical assessment of disc pressures in the lumbosacral spine in response to external unloading forces," *Spine J.* **5**(5), 548–553 (2005).
30. T. S. Keller et al., "1990 Volvo Award in experimental studies: the dependence of intervertebral disc mechanical properties on physiologic conditions," *Spine* **15**(8), 751–761 (1990).
31. J. P. G. Urban, S. Smith, and J. C. T. Fairbank, "Nutrition of the intervertebral disc," *Spine* **29**(23), 2700–2709 (2004).
32. J. N. A. Gibson, J. G. Cowie, and M. Iprenburg, "Transforaminal endoscopic spinal surgery: the future 'gold standard' for discectomy?—a review," *Surgeon* **10** (5), 290–296 (2012).

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