In vivo measurement of the pressure signal in the intervertebral disc of an anesthetized sheep

Paulo Roriz
João M. C. Ferreira
José C. Potes
Maria T. Oliveira
Orlando Frazão
José Luís Santos
José António de Oliveira Simões
In vivo measurement of the pressure signal in the intervertebral disc of an anesthetized sheep

Paulo Roriz, a,b,* João M. C. Ferreira, b José C. Potes, c Maria T. Oliveira, c Orlando Frazão, b José Luís Santos, b and José António de Oliveira Simões a

aUniversity of Aveiro, Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, 3810-193 Aveiro, Portugal
bINESC-Porto and Faculty of Sciences of the University of Porto, Rua do Campo Alegre, 687, 4150-179, Porto, Portugal
cUniversidade de Évora, Instituto de Ciências Agrárias e Ambientais Mediterrânicas, Veterinary Department, Núcleo de Mitra, Apartado 94, 7002-554 Évora

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)

Keywords: fiber optic sensors; pressure; breathing; in vivo.

Paper 130765RR received Oct. 22, 2013; revised manuscript received Feb. 10, 2014; accepted for publication Mar. 3, 2014; published online Mar. 31, 2014.

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. The AF encloses the NP and acts like a solid elastic ring preventing its gel-like fluid to escape. In the mechanical view, the NP is considered to be incompressible, exhibiting a hydrostatic behavior. 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.

Intradiscal pressure data from Nachemson’s studies formed the basis of the current knowledge about the in vivo loading conditions of the spine. In 1959, he was the first to measure ex vivo intradiscal pressure in human discs. During the 1960s and 1970s, Nachemson et al. 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. 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.

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. In fact, some successful efforts have been made to demonstrate it. Dennison et al. 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. and Nesson et al. It has been used for in vitro measurements of intradiscal pressures in rodent tail discs. 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 and patients suffering from lumbar back pain. Samba sensors have been used to measure intradiscal pressures in pigs, rabbits, and human cadaveric spines. 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., 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. 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. 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.

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...
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).

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 \( \left( n = 10 \right) \) 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.
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 transfemoral approach into the center of the NP, similar to that used in discography and percutaneous nucleotomy, was followed for sensor implantation.

A dorsolateral transfemoral approach into the center of the NP, similar to that used in discography and percutaneous nucleotomy, was followed for sensor implantation. 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 \( \pm 0.002 \) 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...
Breathing had a significant effect on the intradiscal pressure, which seems to decrease with breathing rate and increase with breathing volume.  

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 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. In the previous studies, the mean resting pressure ranged from 0.7 (Ref. 26) to 2.0 bar. 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). In the study of Nachemson and Morris, 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. 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. 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

This work was supported by the Portuguese Foundation for Science and Technology (FCT) fellowship SFRH/BD/45130/2008. It was also funded by FEDER Funds through the Operational Programme for Competitiveness Factors—COMPETE (FCOMP-01-0124-FEDER-010257) and National Funds through FCT under the Strategic Project PEst-C/AGR/UI0115/2011.

References


Paulo Roriz received a PhD in mechanical engineering from the Faculty of Engineering of the University of Aveiro (2013). Graduated (1993) and MSc (1996) in sports by the Faculty of Sports of the University of Porto. He is an assistant professor at the Instituto Universitário da Maia-ISMAI and a researcher at INESC Porto Optoelectronics and Electronic Systems Unit. His research interests include optical fiber sensors for biomechanical and biomedical applications, spin biomechanics and locomotion. He is a member of SPIE and former vice president of the UP-SPIE Chapter.

João M. C. Ferreira graduated in physics by the University of Porto in 1986. He works for INESC Porto in R&D and technology transfer. He worked for FiberSensing in hardware development and testing. His research interests include optical fiber communications and sensors, wireless infrared, PCB high-speed electronics, signal conditioning and PLLs. He organized and taught courses on optical communications and instrumentation electronics and supervised graduate and post-graduate students.

José C. Potes has performed scientific activity in the area of reproductive control, namely in embrio transfer, artificial insemination with application of laparoscopic surgery, surgery in ruminants, namely of the digestive system, orthopaedic surgery in small animals and equine, neurosurgery and thoracic surgery in small animals. He has done research involving the use of endoscopic techniques for diagnosis and treatment and the area of biomaterials for orthopaedic application, namely for total hip arthroplasty.

Journal of Biomedical Optics

037006-5

March 2014 • Vol. 19(3)

Downloaded From: https://www.spiedigitallibrary.org/journals/Journal-of-Biomedical-Optics on 15 Jan 2020
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use
Maria T. Oliveira graduated in veterinary medicine at ICBAS-UP in 2002 and postgraduated in small animal soft tissue surgery at FMV-ULHT in 2010. She has experience both in large and small animal medicine. Her main interests are in radiology, internal medicine and surgery. She has been a PhD student in veterinary sciences at Évora University since 2012, with a research area of biomaterials in vivo applications.

Orlando Frazão graduated in physical engineering from the University of Aveiro, Portugal. He received his PhD from the University of Porto, Portugal. From 1997 to 1998, he was with the Institute of Telecommunications, Aveiro. Presently, he is an invited assistant professor in the department of physics of Faculty of Science at University of Porto. He is also a senior researcher at Optoelectronics and Electronic Systems Unit, INESC Porto. His present research interests included optical fiber sensors and optical communications. He has more than 300 papers in international journals and conferences. He has three scientific awards. He is a senior member of SPIE and OSA.

José Luís Santos graduated in applied physics (optics and electronics) from University of Porto (1983). He received a PhD (1993) and Habilitation (2008) from the same university. His main research interests are related to optical fiber sensing and optical fiber technology. He holds the position of full professor of physics and astronomy at the University of Porto and is a researcher of INESC Porto Optoelectronics and Electronic Systems Unit. He is a member of OSA, SPIE, and Planetary Society.

José António de Oliveira Simões has a PhD in mechanical engineering from the Faculty of Engineering of the University of Porto. He is an associate professor of the University of Aveiro and director of the College of Arts and Design of Matosinhos. Research interests are within the development of novel biomedical implant concepts and investigation of product development methodologies. He is author/co-author of more than 500 scientific publications and 11 patents/models (5 international). He has received scientific prizes from the Portuguese Orthopaedics and Traumatology Society and within industrial design contests.