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Intradiscal pressure measurements: A challenge or a routine?

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ABSTRACT

Intradiscal pressure (IDP) is an essential biomechanical parameter and has been the subject of numerous *in vivo* and *in vitro* investigations. Although currently available sensors differ in size and measurement principles, no data exist regarding inter-sensor reliability in measuring IDP. Moreover, although discs of various species vary significantly in size and mechanics, the possible effects of sensor insertion on the IDP have never been investigated. The present *in vitro* study aimed to address these issues.

The synchronized signals of two differently sized pressure transducers (Ø1.33 and Ø0.36 mm) obtained during the measurements in two species (bovine and caprine) and their influence on the measured pressure were compared. First, the discs were subjected to three loading periods, and the pressure was measured simultaneously to assess the inter-sensor reliability. In the second test, the effect of the sensor size was evaluated by alternatingly inserting one transducer into the disc while recording the resulting pressure change with the second transducer.

Although both sensors yielded similar pressure values (ICC: consistency: 0.964–0.999; absolute agreement: 0.845-0.996) when used simultaneously, the sensor size was determined to influence the measured pressure during the insertion tests. The magnitude of the effect differed between species; it was insignificant in the bovine specimens but significant in the caprine specimens, with a pressure increase of 0.31–0.64 MPa (median: 0.43 MPa) obtained when the larger sensor was inserted.

The results suggest that sensor selection for IDP measurements requires special attention and can be crucial for species with smaller disc sizes.

1. Introduction

As the most direct method of estimating spinal loads, intradiscal pressure (IDP) has been extensively studied in intervertebral discs *in vivo* (Nachemson and Morris, 1964; Sato et al., 1999; Takahashi et al., 2006; Wilke et al., 1999) and *in vitro* (McNally and Adams, 1992; Nachemson, 1960; Naylor and Smare, 1953; Panjabi et al., 1988) over the past six decades. This procedure was initially challenging due to the large artifacts associated with the early sensors (McNally et al., 1992; Nachemson, 1981); however, it has progressed into a routine procedure due to the development of high precision pressure sensors (Dennison et al., 2008; McNally et al., 1992; Nesson et al., 2008).

Due to the limited number of human specimens and a rising interest in the use of animal models for pre-clinical studies, pressure measurements have often been performed in different species *in vivo* (Ekström et al., 2004; Reitmaier et al., 2013) and *in vitro* (Guehring et al., 2006; Vergroesen et al., 2014). However, as with any other invasive procedure, the implantation of the pressure sensor may influence the disc behavior. Elliott et al. (2008) determined that a ratio of needle diameter to disc height ≥40% leads to acute changes in disc mechanics (*e.g.*, compressive stiffness or neutral zone length) after a needle puncture injury. Based on these findings and considering the large differences in the disc shape, size, and material composition between various species (Beckstein et al., 2008; O'Connell et al., 2007; Showalter et al., 2012), the objective of the present study was to identify the possible impact of sensor insertion on the IDP in different species. Because the currently available sensors differ in dimensions and underlying physical principles, the study also attempted to assess inter-sensor reliability.

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2. Materials and methods

2.1. Specimen preparation

Sixteen motion segments (eight caprine, eight bovine) were harvested from skeletally mature caprine lumbar spines and bovine tails and visually inspected to exclude any with spinal diseases and damage. After all the surrounding muscles, soft tissues, facets, and transverse processes were removed, each vertebra was cut parallel to the disc mid-plane at approximately 3–5 mm from the endplate, which yielded segments consisting of an intervertebral disc with parts of the adjacent vertebral bodies. The specimens were then wrapped in saline-soaked gauze, placed in plastic bags, and stored frozen at −20 °C. Prior to testing, the specimens were thawed for 8 h at room temperature in phosphate-buffered saline (PBS) for rehydration.

2.2. Pressure sensors

Two common pressure sensors were used. The first, a 1.33-mm-diameter pressure sensor needle (CTN/4F-HP; Gaeltec devices Ltd., Dunvegan, Isle of Skye, Scotland), hereafter referred to as the 'large sensor', is based on resistive strain gauge technology and was designed for the measurement of pressures between 0 and 3 MPa. The sensor is mounted in a 3.5-mm-long window, 5 mm from the tip of the needle (Fig. 1a). The sensor was calibrated using a custom pressure chamber before testing.

The second sensor (360 HP; Samba Sensors, Gothenburg, Sweden) was a 0.36-mm-diameter miniature fiber optic pressure sensor, hereafter referred to as the 'small sensor'. The sensing element (Fabry–Pérot cavity) is located at the tip of the optical fiber (Fig. 1a). The sensor is factory-calibrated to measure pressures between 0 and 1.7 MPa and does not require further calibration due to the constant wavelength of the light source. More technical details about the sensor can be found elsewhere (Hoejer et al., 1999; Nesson et al., 2008).

2.3. Sensor positioning

To prevent the sensors from being damaged during insertion, the disc was punctured on the right anterolateral side using a 19-gauge needle (outer diameter – 1.07 mm, inner diameter – 0.7 mm) prior to inserting the large sensor. For the small sensor, a 0.4-mm cannula, inserted at the right posterolateral side, remained in the disc during testing due to the fragility of the optical fiber. Attention was paid to ensure a perfect alignment of the sensor face with the end of the cannula. Both sensors were positioned in the nucleus center at a small distance from each other to avoid contact. The sensing elements (perpendicular to the needle in the large sensor and longitudinal in the small sensor) of both sensors were aligned to measure the pressure in approximately the same radial direction. To maintain the position of pressure sensors within the discs, sensor cables were sutured to the annulus superficial layers. Sensor positioning was controlled by C-arm X-ray unit examinations after testing.

2.4. Measurement protocol

To assess the inter-sensor reliability, the nucleus pressure was measured by both sensors simultaneously under cyclic loading. For that, two bovine and two caprine specimens were subjected to a 3.5-h loading protocol. The loading sequence consisted of 30 min of dynamic preload consisting of 50 N compression superimposed with a sinusoidal signal of ±10 N for the caprine specimens and 80±20 N for the bovine specimens, followed by three loading periods (Fig. 1b), each consisting of a 30-min high load phase under 130±20 N dynamic compression for the caprine specimens and 200±40 N for the bovine specimens, as well as a low load phase of 30 min at 50±10 N for the caprine specimens and 80±20 N for the bovine specimens. All dynamic loads had a sinusoidal profile with a frequency of 1 Hz. The axial compression tests were performed using a servo-hydraulic fatigue testing machine (Instron 8872; Instron and IST, Norwood, Canada).

The effect of the sensor size was evaluated by alternatingly inserting one transducer into the disc while recording the resulting pressure change with the second transducer. This test was performed without any external load. The test started by inserting the small sensor. After two minutes, the large sensor was also inserted while the effect of the insertion was recorded by the small sensor. After another two minutes, the small sensor was removed and reinserted again after two minutes. During the latter procedure, the nucleus pressure was measured by the large sensor. Finally, the large sensor was removed, and the IDP was measured by the small sensor during the last two minutes. This test was performed on 6 bovine and 6 caprine discs.

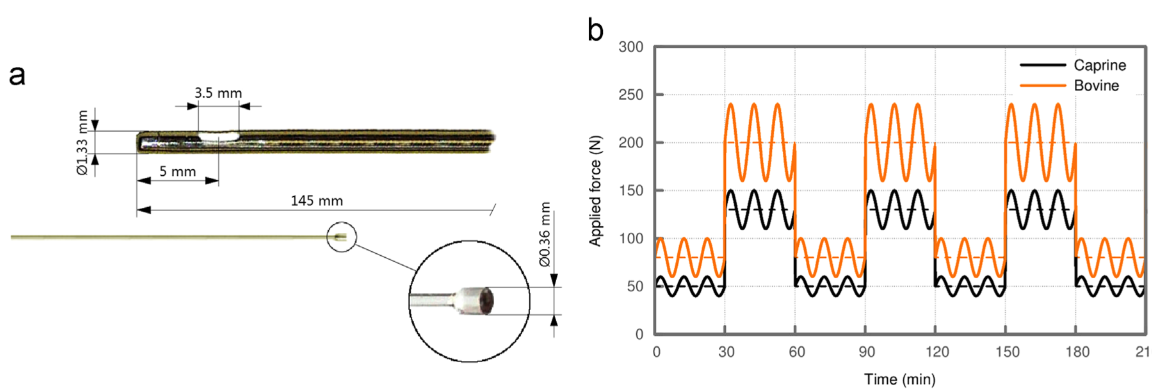

Fig. 1. (a) Pressure sensors used for the measurements; and (b) loading protocol for the mechanical tests.

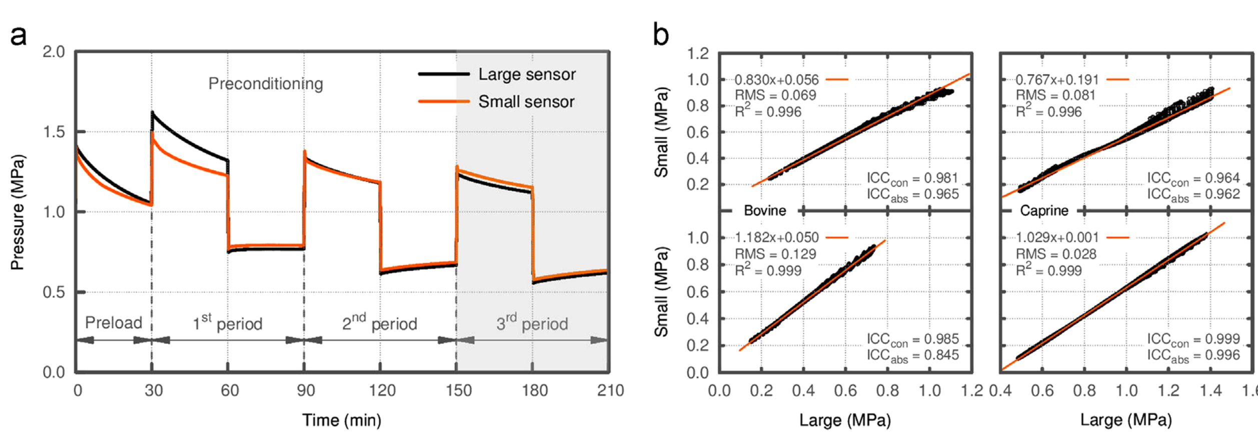

Fig. 2. (a) A representative example of a pressure measurement during mechanical testing. The preload consisted of 30 min dynamic sinusoidal load at 50±10 N for the caprine specimens and 80±20 N for the bovine specimens. The sinusoidal components are filtered out for clarity. (b) Comparison between the pressure sensors illustrated by a linear regression model (equations and coefficients of determination are provided) for each test (the lower-right plot represents the test illustrated in (a)). Additionally, the RMS (in MPa) and the ICC values for consistency (ICC_{con}) and absolute agreement (ICC_{abs}) are provided.