On the experimental intradiscal pressure measurement techniques: a review

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Abstract: The intradiscal pressure has been essential for prevent the spinal complaints by forming a basis for clinical advice to promote the correct sitting postures. As a consequence, it is evident the need of an accurate method for measure the intradiscal pressure, to better understand the disc response to hydorstatic pressure fluctuations. Numerous reviews regarding disc mechanics are available, including intradiscal pressure benchmarks; however, an analysis on the techniques of intradiscal pressure measurement is needed. Therefore, this review will remain focused on the methodologies adopted for measure the intradiscal pressure in several conditions: for different daily activities, under external loads and for values where occurs annulus fibrosus disruption. The importance of the intradiscal pressure on disc function will be discussed as well as the some guidelines for design new measurement techniques will be defined.

Key words: Intervertebral Disc, Intradiscal Pressure.

1 Introduction

The intervertebral disc (IVD) is a fibrocartilage structure located between two vertebral bodies, which is surrounded by ligaments and muscles [23]. This intricate organization is comprised by a peripheral angle-ply laminate ring, the annulus fibrosus (AF) with a gelatinous nucleus in its center (NP), and it is limited above and beyond by the cartilaginous endplates (CEP)[14] (Fig. 1).

The IVD plays an important role at spinal level: it is responsible for the spine motion, helping the spine on the weight support and load transfer from head and upper torso to the pelvis[15,28]. The IVD is specially designed to perform these functions, since the mechanical response of disc to loading is time-dependent [25]: while the short time response is governed by viscoelastic phenomena[2,6], the long term response is guided by poroelastic and osmotic events[20,25].

Moreover, in opposition to the AF generally considered as a fibrous solid[1], the NP presents an high water content, revealing a fluid-like behavior[1]. Thus, a healthy NP is capable of sustain stress gradients due to hydrostatic pressure exhibited by NP, normally known as intradiscal pressure (IDP)[3] (Fig. 1).
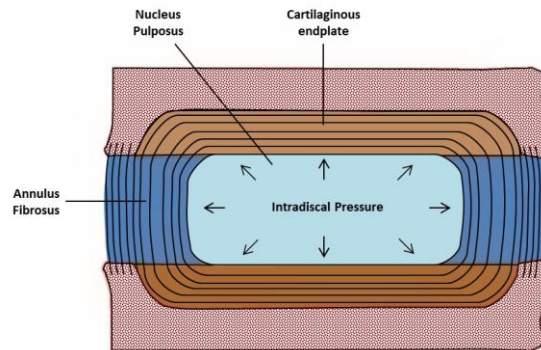

Fig. 1 – Representation of the intervertebral disc and the schematic concept of intradiscal pressure

The IDP varied with body posture and with direct compressive force applied[19]. In this review, the importance of the IDP on intervertebral disc function will be discussed and the criteria for design new IDP measurement techniques will be defined. Subsequent sections describe the previous methodologies developed to determine the IDP in physiological and in failure cases. Finally, it will conclude with some main points the development of new IDP measurement techniques.

2 The IDP importance for disc function evaluation and properties determination

The internal disc pressure or intradiscal pressure (IDP) can be defined as the hydrostatic pressure presented by the NP of an healthy IVD [3]. The IDP plays a key role on the IVD´s ability to withstand the physiological loads[24], being an important parameter to understand the spinal on the disc degeneration.

The IDP data has been essential for prevent the spinal complaints by forming a basis for clinical advice to promote the correct sitting postures[3]. The measurements of IDP helps to clarify the effect of the external loads on the IVD behavior[3] and to recognize the mechanism of IDP drop in disc degeneration. In addition, these data is the basis for physiotherapy and rehabilitation programs[29].

At a biomechanical point of view, the IDP is highly influenced by the axial spinal load[18]. According to this, an increase on the compressive load applied to healthy discs is converted into IDP [19]. Since the NP can be considered as incom-

pressible, the AF bulges outward due to the stretch of annular [26], which, together with osmotic phenomenon, promotes a loss on both disc height and volume.

The importance of IDP is reinforced due to difficult on the assessment of the disc strengthen properties. As example, a simple compressive overloading does not induce damage on the disc structure. Previous studies showed that before occurring any disc disruption, the compressive overloading promotes the vertebral endplate damage and collapse[19]. These phenomena could be explained at a cellular level by the influence of the IDP on the chondroid tissues, characteristic of the IVD [1]. On the one hand, the IDP or gradient pressures could induce the internal disruption on these tissues, causing a progressive structural failure typical on disc degeneration [1]. On the other hand, the stresses and pressures oscillation also affects the cell metabolism, where the IDP levels influences the matrix synthesis[1]. In sum, it is evident the need of an efficient method for measure the IDP, in order to better understand the mechanical behavior of IVD.

3 On the IDP measurement: a methodology review

The measurement of the IDP is a subject of intense research. Numerous authors have developed experimental methods to determine the relationship between the IDP and the disc mechanics: some authors were focused on the association between the IDP and the external load applied or posture adopted; others were more centered on the calculation of IDP value that leads to AF disruption. Next subsections will describe with more detail the studies performed under these subjects.

3.1 Relationship between IDP and posture or external loading

Previous studies have investigated the relationship between an external loads applied or posture and IDP, on lumbar[5,9,11,12,18,21,29] or on cervical[4,8,17]discs.

The methodologies developed for measure the IDP were diverse (Table 1).

Table 1. Previous studies reporting the IDP according to the type of load/posture adopted

Author	Year	Transducer Type	IDP evaluation	Mean IDP(MPa)
Lumbar spine				
Nachemson	1964/1965	Liquid-filled	Relaxed standing	0.70
			Relaxed sitting	1.13
Nachemson & Elfstrom	1970	Piezoresistive	Relaxed standing	0.72
			Relaxed sitting	1.00
Schultz	1982	Piezoresistive	2400 N axial load	1.60

Sato	1999	Piezoresistive	Relaxed standing	0.53
			Relaxed sitting	0.63
Wilke	1999	Piezoresistive	Relaxed standing	0.50
			Relaxed sitting	0.46
			Lifting a 20-kg weight with round flexed back	2.30
Heuer	2007	Laser scanning	500N axial load	0.49
Dennison	2008	Fibre Gratings	800N axial load[1]	2.40 to 3.50
Cervical spine				
Hattori	1981	Piezoresistive	53 N axial load	0.31
			75 N axial load	0.45
			100 N axial load	0.59
			155 N axial load	0.91
Pospiech	1999	Piezoresistive	**Muscular inactivation**	
			- Flexion/Extension	0.23-0.32
			Muscular activation	
			- Flexion/Extension	0.36-0.64
Cripton	2001	Piezoresistive	~1000 N axial load	3.5

The first approaches were performed on the 1960s and 1970s[12,13,16] on *in vivo* situation, alerting for the importance of IDP on the spinal biomechanics[3]. A pressure transducer using elastic polyethylene tubing threaded over the side near of a tip from hollow liquid-filled needle, connected with an electromanometer, was used in healthy discs for IDP determination. The data showed that a healthy NP could behave hydrostatically and the IDP is dependent on the posture. Even though the interesting findings, this pioneer approach presents a couple of limitations. First, the polyethylene membrane does not present enough sensitivity for dynamic pressure measurements. Second, the fluid-filled needle is not prepared to bend more than 20º[12].

The evolution of the transducer technology and its increased accuracy leads to a decrease on the IDP measurement (a reduction of 25 and 33%)[3], due to the replacement of liquid-filled sensors by the piezoresistive ones, as well as the set of calibration to body temperature rather than room temperature[3].

The initial approach using was developed by Nachemson & Elfstrom[11], using a piezoresistive semiconductor strain gauge embebed in a rigid resin into a tip of a 0.8 mm diameter transducer needle[3]. This sensor allows bending until 40º without affecting the IDP measurement[3], increasing the IDP measurement accuracy.

In early 80´s, Schultz et al.[22] tried to validate a biomechanical model lumbar spine by monitoring IDP and myoelectric signals, using a piezoresistive transducer for IDP measurement. This study pointed to 1.6 MPa of mean IDP, for a compres-

sive load as much as 2.4 kN. The main finding of this study was that overloading could be a promoter of low back disorders.

In end of the 90s, two important studies were published: Sato et al. [18] developed a new approach using a piezoresistive sensor to determine the IDP in vivo young patients (25±2 y.o.). The innovative principle of this method is the sensor positioning: the sensing diaphragm was mounted laterally on the transducer needle (1.2-mm diameter); Wilke et al. [29], studied the IDP *in vivo*, in one volunteer performing various daily life activities. To measure the IDP, a piezoelectric pressure transducer, with 1.5 mm diameter and 7 mm length, was implanted in the NP of a healthy L4–L5 disc. However, in this case, the IDP was record with a telemetrically, avoiding the problem of having a needle *in situ*. These studies reported similar IDP for standing position and reinforced the idea that in vivo IDP varied according to the adopted position of the body and the compressive force applied.

Although the accuracy of piezoelectric sensors, they are not able to characterize pressure profiles within disc[5]. With the advances on the sensor technology, new sensors were adapted for IDP measurement. Dennison et al.[5] used small diameter (125 µm) fiber-bragg grating, which consist on an optical fiber with a Bragg grating inscribed into a fiber core. These sensors present a biocompatibility, mechanical compliance and insusceptibility to electromagnetic interference. The results reported a linear response of disc pressure to compressive loads.

The IVD bulging was also adopted as an indirect parameter of the internal stress measurement of the disc. Heuer et al.[9] quantified the IDP *ex vivo* using a non-contact laser scanning method, which measure a 3D contour. The test consists on the application of 15 min of a 500 N static compression. This work showed that these loads results on an IDP of 0.49 MPa (range: 0.36–0.53 MPa), decreasing linearly to 0.48 MPa (0.36–0.52 MPa) when discs were constantly compressed.

In contrast to the extensive experimental work on lumbar IDP, the data related to cervical pressure is extremely scarce. The measurements on the cervical are challenging due to small size and anatomy of cervical IVDs.

Hattori et al.[8] was the first study recording the cervical IDP in vivo. A needle-based pressure transducer was used to measure IDP, during common neck movements. The results found no differences between cervical IVDs, detecting the values of 0.31MPa and 0.91MPa for 53N and 155N of axial load, respectively.

Later, Pospiech et al.[17] studied the IDP of cervical spine *in vivo* under simulated muscular forces in intact spines as well as in fused specimens. The IDP was measured using a pressure transducer mounted on a 1.3 mm-diameter needle. The results showed significant increase in IDP when the musculature was activated and a marked increase in IDP in both segments adjacent to fusion IVDs.

Alhough the importance of these findings, the cervical IDP measurement presents more difficult, since they cervical annular fibers could disrupt with the needle-tip insertion, due to its rigidity and its large diameter (over 1mm) [4]. To minimizing the AF disruption and reduce the distortion of the IDP signals or specimen kinematic behavior, Cripton et al.[4] tested *ex vivo* the cervical IDP response to external loads, using with a 0.26 mm diameter flexible electric wires passing through

AF. They found a maximum of 3.5MPa for cervical IDP, with 1000N load, while in lumbar for the same load, it is common an IDP of 1MPa.

3.2 The annular failure strength due to inflation method pressurization

Despite the panoply of mechanical testing found on literature intending to elucidate the contribution of loads to annular tear or disruption, the effect of the IDP fluctuation on the AF injury remains largely unknown. The measurement of the IDP value that leads to AF disruption is a subject of extreme interest, not only to understand the mechanisms of IVD failure but also for IVD replacement designing, since it should withstand the daily routine activities without collapsing.

Some studies determined the maximum value of IDP that annular fibers support before failure[10,19,27]. The table 2 reports the failure IDP in previous studies.

Table 2. Previous studies reporting failure pressure data several IVD models.

Author	Year	Models	Mean failure pressure (MPa)
Schetchman	2006	Lumbar bovine	18 ± 3
Veres	2010	Lumbar ovine	14.1 ± 3.9
Menkowitz	2005	Cervical human spine	0.28 (min-máx:0.1-1.18)

Schechtman et al. (2005) investigated the intrinsic failure strength of the intact bovine caudal disc under a simple mode of inflation, using a hydraulic actuator. They injected a colored hydrogel, under monitored pressure, into the NP. It was found a mean hydrostatic failure pressure of 18±3MPa. This method allowed understanding the alterations of the intrinsic disc strength associated with prior loading history or degeneration. However, it does not give information about the microstructural behavior of inner annular fibers after the inflation.

Later, Veres et al.[27] used the same technique performed by Schechtman et al. (2005) to investigate the role of high IDP on annular fibers disruption in ovine lumbar IVDs. This team included the analysis of the AF damage after pressure insertion by a microstructural investigation. The main findings showed that posterior annular region is more susceptible to disruption than the other disc regions, due to its inability to distribute hydrostatic pressures circumferentially.

In terms of cervical spine, Menkowitz et al. [10] documented a mean intradiscal rupture pressure of 0.28 MPa (range 0.1-1.18 MPa), using a 25G needle for the insertion of an contrast dye with IDP monitoring during time. This study showed that in cervical spine the injury could be induced at lower pressures.

4 The criteria for a new method for intradiscal measurement

All these methodologies helps to generate valuable data, useful for a pre-clinically evaluation of disc injuries. However, some difficulties are noticed on the experimental determination of IDP: the direct measurements of IDP through in vivo studies are normally avoided since the insertion of a transducer into the IVD could damage it[29]. Therefore, the technique for in vivo IDP measurement should be non-invasive, since the IDP must be determined without disc disruption. This is essential for *in vivo* human tests, since the discs should keep its complete functions after the IDP monitoring. New techniques must be also accurate, as the IDP magnitude is low and highly sensitive to movements or load application.

In terms of annular failure strength, more studies should be performed to fully understand the rupture mechanism. Previous studies did not follow-up how the failure occurs: they only assessed the IVD structure after the rupture. Therefore, it is desirable an approach that assesses the disc behavior during the inflation.

A promising method for both in vivo IDP monitoring and the disc inflation follow-up is the use of imaging resources. With the advance of imaging techniques, the assessment of inner IVD pressure is possible, representing a non-invasive approach that could be better explored. In addition, coupling a inflation method with a microstructural assessment real time could bring a new light on poorly understood mechanism of IVD failure related to higher IDP values.

New techniques must also allowing the measurement of IDP on different types of materials inside the IVD, with potential to replace NP, in order to find a material which could has the similar hydrostatic response as NP.

To conclude, notwithstanding the great efforts performed in past for experimental IDP measurement, new approaches and techniques are needed in order to better understand the IDP influence on disc behavior.

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