



RESEARCH ARTICLE

A Cost-effective Method for the Retrieval of Nucleus Pulposus from Lumbar Spine after Cadaveric Dissection for Academic and Museum Specimen

Baneswar Baro¹, Akheruz Zaman Ahmed², Bijoy Kumar Borah³, Anubhav Das⁴, Gunamani Rabha⁵, Ritu Saloi⁶

ABSTRACT

Study Background: The clinical characteristics of lower back pain associated with intervertebral disc degeneration are increasingly well characterized, driving the development of minimally invasive intradiscal therapies. A comprehensive understanding of the nucleus pulposus is essential for advancing such approaches and requires adequate nucleus pulposus specimens. In this context, cadaveric specimens provide a valuable source for nucleus pulposus retrieval and research. **Objective:** This study aimed to develop a simple and cost-effective retrieval technique for the isolation of nucleus pulposus tissue from cadaveric specimens for anatomical, educational, and research purposes. **Methods:** At first, 42 years old male cadaver was embalmed with 10% formalin and subsequently used for routine dissection. After completion of dissection, the spinal segments containing L1, L2, L3, L4, L5 & S1 vertebrae were removed. The vertebrae were manually macerated using a scalpel & iron brush. Later on the vertebrae were separated and labelled as D1, D2, D3, D4 & D5 cutting along the body of each lumbar vertebra and subsequently decalcified dipping in 10% nitric acid for 3-4 days in two cycles. Following decalcification, individual nucleus pulposus tissues were carefully separated and retrieved. **Results:** A total of 5 nucleus pulposus were retrieved from the intervertebral disc of the lumbar spine which were labelled as 1st to 5th. The 1st in between 1st and 2nd lumbar vertebra, 2nd in between 2nd and 3rd lumbar vertebra, 3rd in between 3rd and 4th lumbar vertebra, 4th in between 4th and 5th lumbar vertebra and 5th in between 5th lumbar and 1st sacral vertebra. The size of the nucleus pulposus was found decreasing progressively from first to fifth within the annulus fibrosus of lumbar intervertebral discs. **Conclusion:** This proposed technique enables simple, precise, and cost-effective retrieval of nucleus pulposus tissue from cadaveric specimens, providing suitable material for anatomical education, research, and museum applications.

Keywords: Intervertebral Disc; Nucleus Pulposus; Annulus Fibrosus; Lower Back Pain.

Indian J. Pharm. Biol. Res. (2026): <https://doi.org/10.30750/ijpbr.14.4.52>

INTRODUCTION

Intervertebral disc degeneration is a progressive and multifactorial process that contributes to lumbar spine dysfunction and instability [1]. In healthy intervertebral disc, the extracellular matrix is rich with proteoglycans, particularly aggrecan, which plays a crucial role in maintaining hydration, load-bearing capacity, and resistance to mechanical stress while restricting the ingrowth of nerves and blood vessels [2]. Subsequently, the intervertebral disc in the young spine is predominantly aneural and avascular, features that are essential for maintaining its biomechanical integrity and facilitating efficient load distribution [3]. The physiological integrity of the adult human intervertebral disc is relatively short-lived, with degenerative changes frequently commencing as early as the third decade of life [4-5]. Progressive degeneration is characterized by a gradual loss of disc hydration, which compromises the disc's ability to withstand and efficiently distribute physiological loads [6]. This process is largely driven by the diminished capacity of the nucleus pulposus to retain water under compressive loading, accompanied by progressive disorganization of the collagenous extracellular matrix [7]. The resultant depletion of proteoglycans and

reduction in intradiscal pressure impair the disc's viscoelastic and load-bearing properties, ultimately contributing to progressive loss of disc height [8]. As the structural and biomechanical integrity of the disc deteriorates, a self-perpetuating cascade of degeneration may ensue, increasing mechanical stress on the posterior facet joints and potentially resulting in facet joint osteoarthritis, hypertrophy, and compression of adjacent neural structures [4, 9].

Intervertebral disc degeneration is a major contributor to low back pain, a prevalent condition that imposes a substantial global burden on individuals and healthcare systems. According to the Global Burden of Disease studies, lower back pain represents one of the leading causes of disability worldwide and contributes considerably to disability-adjusted life years. Degenerative disc disorders associated with lower back pain are estimated to affect approximately 632 million individuals world-wide, accounting for nearly 40% of all lower back pain cases [1, 8]. The global burden of lower back pain is expected to increase further with population ageing and demographic growth, underscoring the need for effective strategies for the prevention and management of intervertebral disc degeneration [6].

¹Professor, Department of Anatomy, Bongaigaon Medical College & Hospital, Bongaigaon, Assam, India

²Assistant Professor, Department of Anatomy, Bongaigaon Medical College & Hospital, Bongaigaon, Assam, India

³Associate professor, Department of Anatomy, Tinsukia Medical College & Hospital, Tinsukia Assam, India

⁴Senior Resident, Department of Anatomy, Diphu Medical College & Hospital, Diphu, Assam, India

⁵Associate Professor, Department of Anatomy, Diphu Medical College & Hospital, Diphu, Assam, India

⁶Professor, Department of Anatomy, Diphu Medical College & Hospital, Diphu, Assam, India

Corresponding Author: Baneswar Baro, Professor & HOD, Department of Anatomy Bongaigaon Medical College and Hospital, Bongaigaon, Assam, India. Email: anatomybmch12@gmail.com

How to cite this article: Baro B, Ahmed AZ, Borah BK, Das A, Rabha G, Saloi R. A Cost-effective Method for the Retrieval of Nucleus Pulposus from Lumbar Spine after Cadaveric Dissection for Academic and Museum Specimen. Indian J. Pharm. Biol. Res. 2026;14(4):358-364

Conflict of Interest: None declared.

Source of Funding: This research was financially supported by the Department of Health Research through Multi-Disciplinary Research Unit DMCH, Diphu, Assam, India.

Received: 01.10.2026 Revised: 10.10.2026 Accepted: 18.10.2026

The clinical and diagnostic characteristics of lower back pain associated with degenerative disc disease linked with nucleus pulposus have also become increasingly well characterized [9-10]. Given the substantial clinical burden associated with lower back pain, an expanding range of minimally invasive intradiscal therapeutic strategies is currently being developed and investigated, with the overarching goals of restoring disc structure and function, alleviating pain, and delaying or preventing the progression of degenerative changes [9, 11]. To achieve this goal, a comprehensive understanding of the nucleus pulposus is important. Such understanding requires adequate availability of nucleus pulposus specimens for anatomical and research purposes. In this context, cadaveric specimens serve as an important source for the retrieval and study of nucleus pulposus tissue.

Our study aimed to develop a simple and cost-effective retrieval technique for isolation of the nucleus pulposus from the lumbar intervertebral discs from a post-dissection cadaveric specimens. Nucleus pulposus is a soft, gelatinous structure present at the centre of each intervertebral disc and enclosed by the annulus fibrosus, where it plays a crucial role in cushioning the spine and

dissipating mechanical loads and compressive forces [12]. Due to its soft consistency, central location, and complex structural relationship with the surrounding annulus fibrosus and vertebral disc, the retrieval of nucleus pulposus became challenging during routine dissection class. Henceforth, it is often discarded along with the remaining vertebral tissues following dissection.

Our study demonstrates a simple and cost-effective retrieval technique for the isolation of nucleus pulposus from the lumbar intervertebral discs from cadaveric specimens. This retrieval technique may provide a better understanding of the size, shape, and anatomical position of the nucleus pulposus within the lower lumbar spine to orthopaedic and spine surgeons. These may thereby facilitate improved appreciation of its clinical relevance. Furthermore, the retrieved specimens can serve as valuable three-dimensional anatomical teaching models for undergraduate and postgraduate students, enhancing their understanding of nucleus pulposus morphology and spatial relationships. Furthermore, the technique may facilitate the preservation of nucleus pulposus specimens for future anatomical, educational, and research applications, including their use in anatomical museums.

MATERIALS AND METHODS

The study was carried out from an unclaimed 42 years old male cadaver received in the Department of Anatomy, Diphu Medical College and Hospital (DMCH), Diphu, Karbi Anglong, Assam, India. This study was approved by the institutional ethics committee of DMCH, Diphu with reference no DMCH/EC/2022/105/772 dated 09.07.2024 and has, therefore, been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and all subsequent revisions. All the materials used in this study were shown in figure 1. The body was embalmed first by using 10% formalin (Sigma-Aldrich Corporation, USA), and was kept in formalin tank. Thereafter the body was given to MBBS students for dissection. After completion of the academic whole body dissection the lumbosacral spine consisting of five lumbar (L1-L5) vertebrae and first sacral vertebra were separated from the dissected cadaver. This was done by making the first cut in the body of L1 vertebra and the second cut in the body of 1st sacral vertebra. After that five lumbar vertebrae along with 1st sacral vertebra were collected (Figure 2: b). Then maceration of the separated vertebrae were done manually with the help of scalpel & iron brush. After completion of maceration, the undivided lumbar and sacral vertebrae were dipped in 10% nitric acid solution for 3-4 days for decalcification [13] and then the intervertebral discs were separated by cutting

through the body of each lumbar vertebra, later on each intervertebral disc was labelled as D1(in between the body of L1 and L2 vertebra), D2 (in between the body of L2 and L3 vertebra), D3 (in between the body of L3 and L4 vertebra), D4 (in between the body of L4 and L5 vertebra) & D5 (in between the body of L5 and S1 vertebra).

After completion of this step these labelled vertebral sections were dipping in 10% nitric acid solution and examined every day to check the extent of decalcification, so as to avoid over doing it. After 3-4 days, after obtaining an optimum level of decalcification, the sections of vertebrae were removed from the 10% nitric acid solution. After demineralization individual disc was separated from the body with the help of required instruments. Following separation, the individual disc was again treated with 10 % nitric acid for 48 hours. After that, 5 nucleus pulposus were collected from the five lumbar intervertebral disc. After removing the surrounding annulus fibrosus (fibrocartilage) by using small scissors with careful

dissection, the nucleus pulposus were labelled and preserved in 10% formalin.

RESULTS

A total of 5 nuclei pulposi were retrieved from the five lumbar intervertebral discs as described in the materials & methods sections. Immediately after retrieval, images were taken using a digital camera and preserved in 10% formalin. The following figure 3 depicts the nucleus pulposus which are now ready to be used in various academic teaching programs. The nucleus pulposus were labelled as 1st to 5th. It was observed that the size of the nucleus pulposus was found decreasing progressively from first to fifth within the annulus fibrosus of lumbar intervertebral discs. However, in this study we are focussing on retrieval of nucleus pulposus for academic purposes. Henceforth, we don't focus more on size of nucleus pulposus. In qualitative assessment studies the key morphological features can be used for sex and age determination remained clear and unimpaired by the preservation process.



Figure 1: Images of all the instruments used in this study

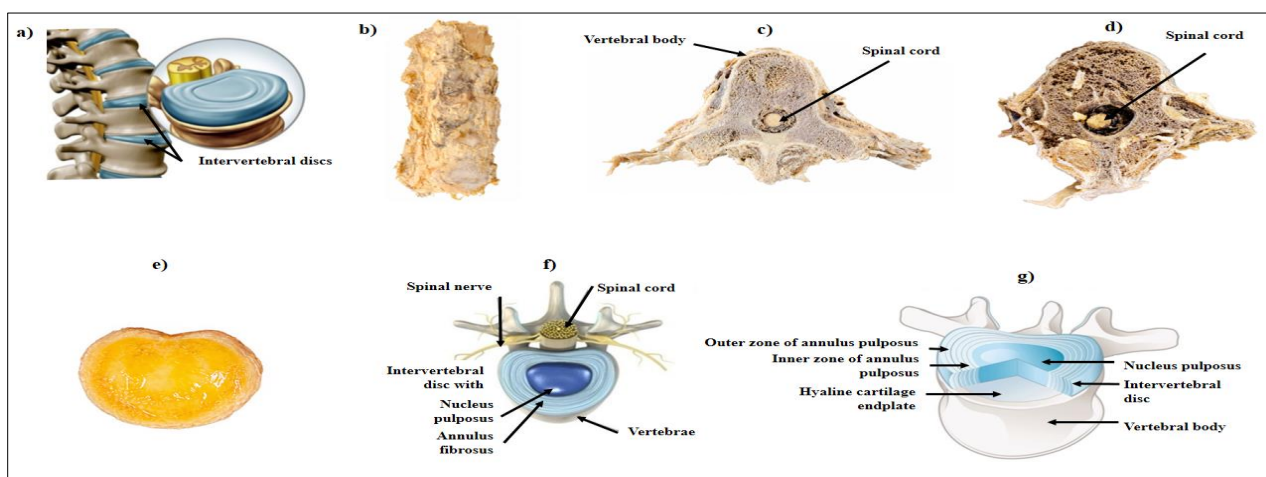


Figure 2: a) Representative image of lumbar vertebrae showing intervertebral discs (source from internet); b) Lumbar vertebrae after extraction from the cadaver before decalcification; c) Vertebrae after 1st step of decalcification; d) Vertebrae after 2nd step of decalcification after removal of nucleus pulposus; e) Collected nuclei pulposi after 2nd step of decalcification; f) Representative image showing spinal cord with spinal nerve(source from internet); g) Representative image showing location of nuclei pulposi with layers of annulus fibrosus (source from internet)

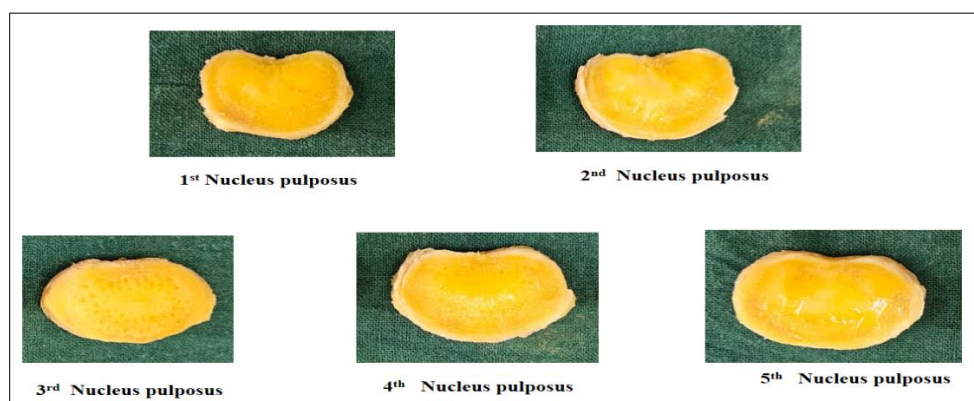


Figure 3: The images showing the nuclei pulposi from five lumbar intervertebral discs (1st nucleus pulposus between 1st and 2nd lumbar vertebra, 2nd between 2nd and 3rd lumbar vertebra, 3rd between 3rd and 4th lumbar vertebra, 4th between 4th and 5th lumbar vertebra and 5th between 5th lumbar and 1st sacral vertebra)

DISCUSSION

Body donation for medical education is an important step for the society where individuals voluntarily consent to donate their bodies for medical education and research through a formal informed-consent process represents an essential source of human cadaveric specimens for anatomical and biomedical studies. Many unclaimed bodies that received at the anatomy department from the forensic department after completion of institutional policies and ethical clearance, also serve an important source of cadaver for medical education for undergraduate students. The principle that “the dead teach the living” reflects the fundamental contribution of human cadavers to anatomical education and research, including investigations of spinal anatomy and intervertebral disc structure [14]. The dissection and retrieval of morphologically intact, healthy lumbar intervertebral disc and nucleus pulposus that lies in between the vertebrae from donated human cadavers remain limited, despite of its importance in spine research, spine surgery and medical education. Henceforth, this present study demonstrated a simple cost effective retrieval technique of nucleus pulposus from human cadaveric specimens. This proposed technique was designed to facilitate efficient procurement while preserving the anatomical integrity and morphology of nucleus pulposus. Such specimens may provide valuable material for anatomical, biomechanical, and translational spine research while ensuring adherence to established ethical standards governing the use of donated human cadaveric tissues [15].

Jha *et al.*, stated that intervertebral disc degeneration is a major contributor to chronic axial lower back pain and represents a substantial global health burden [16]. Degenerative disc disease is a significant contributor to lower back pain, which affects

approximately 7.5% of the global population [17-18]. The nucleus pulposus, the gelatinous central component of the intervertebral disc, is particularly affected during intervertebral disc degeneration [12]. Therefore, understanding its morphology, composition, size, and anatomical position is important for advancing clinical and anatomical knowledge. Due to the deep anatomical location of the nucleus pulposus makes cadaveric retrieval challenging, limiting its availability for anatomical education and research. An effective retrieval technique could enhance practical anatomical teaching and improve understanding of nucleus pulposus morphology and spatial relationships. Accordingly, this study aimed to develop a simple technique for retrieving nucleus pulposus specimens from the lumbar spine and successfully obtained five nuclei pulposi specimens. The 1st from first lumbar intervertebral disc which lies between the bodies of 1st and 2nd lumbar vertebra, the 2nd from second lumbar intervertebral disc which lies between the bodies of 2nd and 3rd lumbar vertebra, the 3rd from third lumbar intervertebral disc which lies between the bodies of 3rd and 4th lumbar vertebra, the 4th from fourth lumbar intervertebral disc which lies between the bodies of 4th and 5th lumbar vertebra, the 5th from fifth lumbar intervertebral disc which lies between the bodies of 5th and 1st sacral vertebra. Liu *et al.* observed that nucleus pulposus is thickest from superior to inferior in the lumbar region, followed in thickness by the cervical region; it is the thinnest in the thoracic region [19]. In our study it has been observed that the size of the nucleus pulposus keeps on increasing from superior to inferior. The lightest nucleus pulposus was the first that was present between 1st and 2nd lumbar vertebra and the heaviest was the 5th between 5th lumbar and 1st sacral vertebra. Ogaili *et al.*, stated that the intervertebral disc is a fibro cartilaginous structure that forms a symphysis between adjacent vertebral bodies, facilitating spinal mobility while enabling efficient load transmission and

distribution. Its biomechanical properties allow physiological loads to be distributed across the vertebral column, even during spinal flexion and extension [1]. Structurally, the intervertebral disc comprises three principal components: the central nucleus pulposus, the surrounding annulus fibrosus, and the cartilaginous endplates [20] (Figure 2: g).

Nucleus pulposus forms the gelatinous central core of the intervertebral disc and is composed predominantly of water, proteoglycans, type II collagen, elastin, and other non-collagenous matrix proteins. It contains approximately 70-90% water, while its dry weight consists primarily of proteoglycans (35-65%) and fine type II collagen fibrils (5-20%) [1]. The high water and proteoglycan content of the nucleus pulposus enables it to resist compressive forces, facilitate spinal mobility, and dissipate mechanical energy. Its ability to withstand compression is largely dependent on the water-binding capacity of its proteoglycan-rich extracellular matrix. With ageing and degeneration, progressive depletion and alteration of proteoglycans reduce water retention and compromise the biomechanical function of the nucleus pulposus [1, 21]. The abundant sulfated glycosaminoglycans within proteoglycans confer a high fixed-charge density, promoting water retention and osmotic swelling that enable the nucleus pulposus to exhibit both fluid- and semi-solid-like mechanical behaviour [22]. The water-retaining capacity of proteoglycans provides a sponge-like cushioning effect, allowing the intervertebral disc to withstand, absorb, and distribute compressive loads effectively [21]. The nucleus pulposus specimens retrieved in the present study demonstrated considerable flexibility and elasticity, due to type II collagen, elastin, and other non-collagenous matrix proteins. Due to its high contents of sulfated glycosaminoglycans, the retrieved nuclei pulposi were soft, gelatinous and semi-solid shaped structure. The fibrous structure surrounding the nucleus pulposus is known as the annulus fibrosus. It consists of approximately 15-25 concentric layers of highly organized collagen fibers, referred to as lamellae (Figure 2: g). Within each lamella, collagen fibers are arranged obliquely, with adjacent lamellae exhibiting alternating fibers orientations. This unique architecture enables the intervertebral disc to withstand circumferential tensile stresses while contributing to the restriction of excessive rotation and bending between adjacent vertebrae. The dry weight of the annulus fibrosus is composed primarily of collagen (approximately 20%), elastin (2%), and proteoglycans (20%). The thickness of individual lamellae ranges from approximately 100 to 500 μm , with the outer lamellae generally being thicker than the inner lamellae. Adjacent lamellae are separated by interlamellar tissue containing cells, elastic fibers, and a

proteoglycan-rich extracellular matrix [1]. Structurally, the annulus fibrosus can be divided into inner and outer regions. The inner annulus fibrosus predominantly contains type II collagen fibers and is characterized by rounded, chondrocyte-like cells, whereas the outer annulus fibrosus primarily consists of type I collagen fibers produced by elongated, spindle-shaped fibroblast-like cells of mesenchymal origin [1]. The cartilaginous endplate forms another important structural component of the intervertebral disc. However, the primary objective of the present study was the retrieval of the nucleus pulposus rather than the preservation of the annulus fibrosus. Therefore, preservation of the annulus fibrosus was not required for the proposed study. During the retrieval procedure, the annulus fibrosus was deliberately removed to facilitate clear exposure and subsequent harvesting of the nucleus pulposus. Thus, the annulus fibrosus was carefully dissected and removed before nucleus pulposus retrieval. Nerurkar *et al.*, stated that nucleus pulposus replacement has emerged as a potential therapeutic strategy for the treatment of intervertebral disc degeneration [22]. Depletion of proteoglycans, a characteristic feature of disc degeneration, results in reduced hydration, increased stiffness, decreased disc height, and diminished biomechanical compliance [23]. It had been stated that the nucleus pulposus is naturally rich in proteoglycans, native disc tissue may represent a suitable source for proteoglycan replacement. Beall *et al.* said that cadaveric donor-derived nucleus pulposus tissue could potentially be harvested and processed with minimal manipulation for use as an allograft [11]. The nucleus pulposus specimens which were retrieved using the present methodology may therefore have potential for application as allografts in patients with chronic intervertebral disc degeneration. However, further preclinical and clinical studies are warranted to establish their safety, feasibility, biological properties, and clinical applicability.

CONCLUSION

This proposed technique enables simple, precise, and cost-effective retrieval of nucleus pulposus tissue from dissected cadaver, providing suitable material for anatomical education, research, and museum applications. The retrieved tissue may also have potential for future allograft applications in intervertebral disc degeneration; however, further preclinical and clinical studies are required to establish its safety, feasibility, biological properties, and therapeutic potential.

Authors Contributions: All the authors had contributed equally in this present study.

ACKNOWLEDGMENT

The authors thank the Department of Anatomy of Diphu Medical College & Hospital (DMCH), Assam, India for providing cadaver to perform this study, the Multi-Disciplinary Research Unit, DMCH for the human

resource and infrastructure, and the Department of Health Research, Ministry of Health & Family Welfare, Govt. of India for the financial support. This study would not have been possible without their invaluable contributions.

REFERENCES

- Ogaili RH, Alassal A, Za'aba NF, Zulkiflee I, Mohd Isa IL. Regenerative strategies for intervertebral disc degeneration. *J Orthop Transl* [Internet]. 2025;53:286–308.
- Empere M, Wang X, Prein C, Aspberg A, Moser M, Oohashi T, et al. Aggrecan governs intervertebral discs development by providing critical mechanical cues of the extracellular matrix. *Front Bioeng Biotechnol*. 2023;11(March):1–19.
- Kepler CK, Ponnappan RK, Tannoury CA, Risbud M V., Anderson DG. The molecular basis of intervertebral disc degeneration. *Spine J* [Internet]. 2013 Mar 1 [cited 2026 Sep 14];13(3):318–30.
- Kushchayev S V, Glushko T, Jarraya M, Schuleri KH, Preul MC, Brooks ML, et al. Abcs of Degenerative Spine Back Pain. 2018;253–74.
- Urban JP, Roberts S. Ar629. *Arthritis Res Ther*. 2003;5(3):120–30.
- Ferreira ML, De Luca K, Haile LM, Steinmetz JD, Culbreth GT, Cross M, et al. Global, regional, and national burden of low back pain, 1990–2020, its attributable risk factors, and projections to 2050: a systematic analysis of the Global Burden of Disease Study 2021. *Lancet Rheumatol*. 2023;5(6):e316–29.
- Vergoesen PPA, Kingma I, Emanuel KS, Hoogendoorn RJW, Welting TJ, van Royen BJ, et al. Mechanics and biology in intervertebral disc degeneration: a vicious circle. *Osteoarthritis Cartil* [Internet]. 2015;23(7):1057–70.
- Mohd Isa IL, Mokhtar SA, Abbah SA, Fauzi MB, Devitt A, Pandit A. Intervertebral Disc Degeneration: Biomaterials and Tissue Engineering Strategies toward Precision Medicine. *Adv Healthc Mater*. 2022;11(13):1-12
- Lorio MP, Beall DP, Calodney AK, Lewandrowski KU, Block JE, Mekhail N. Defining the Patient with Lumbar Discogenic Pain: Real-World Implications for Diagnosis and Effective Clinical Management. *J Pers Med*. 2023;13(5).
- Han CS, Hancock MJ, Sharma S, Sharma S, Harris IA, Cohen SP, et al. Low back pain of disc, sacroiliac joint, or facet joint origin: a diagnostic accuracy systematic review. *eClinicalMedicine* [Internet]. 2023;59:101960.
- Beall DP, Davis TT, Amirdelfan K, Naidu RK, DePalma MJ, Costandi S, et al. Supplemental nucleus pulposus allograft in patients with lumbar discogenic pain: results of a prospective feasibility study. *BMC Musculoskelet Disord* [Internet]. 2025;26(1):1
- Raftery K, Rahman T, Smith N, Schaer T, Newell N. The role of the nucleus pulposus in intervertebral disc recovery: Towards improved specifications for nucleus replacement devices. *J Biomech* [Internet]. 2024;166(February):111990.
- Prasad P, Donoghue M. A comparative study of various decalcification techniques. *Indian J Dent Res*. 2013;24(3):302–8.
- Brenner E, Bleys RLAW, de Caro R, Catereniuc I, Chirculescu ARM, Destrieux C, et al. The legal and ethical framework governing body donation in Europe – 2nd update on current practice. *Ann Anat - Anat Anzeiger* [Internet]. 2024 Feb 1 [cited 2026 Sep 14];252:152195.
- Za'aba NF, Razak R, Zulkiflee I, Kamarrudin AH, Mustafa MN, Joyce K, et al. Human cadaveric spine dissection: A protocol for harvesting lumbar intervertebral discs from body donors. *Ann Anat* [Internet]. 2025;260:152680.
- Jha R, Bernstock JD, Chalif JI, Hoffman SE, Gupta S, Guo H, et al. Updates on Pathophysiology of Discogenic Back Pain. *J Clin Med*. 2023;12(21).
- Wu A, March L, Zheng X, Huang J, Wang X, Zhao J, et al. Global low back pain prevalence and years lived with disability from 1990 to 2017: estimates from the Global Burden of Disease Study 2017. *Ann Transl Med*. 2020;8(6):299–299.
- Zheng CJ, Chen J. Disc degeneration implies low back pain. *Theor Biol Med Model* [Internet]. 2015;12(1):1–10.
- Liu JKC. Intervertebral Disc: Anatomy, Physiology, and Aging. *Benzel's Spine Surg Tech Complicat Avoid Manag Vol 1-2, Fourth Ed* [Internet]. 2017 ;1–2:119-123.e1.
- Mohd Razak R, Harizal NAA, Azman MAZ, Mohd Redzuan NS, Ogaili RH, Kamarrudin AH, et al. Deciphering the Effect of Hyaluronic Acid/Collagen Hydrogel for Pain Relief and Tissue Hydration in a Rat Model of Intervertebral Disc Degeneration. *Polymers (Basel)*. 2024;16(18):1-11
- Chen S, Fu P, Wu H, Pei M. Meniscus, articular cartilage and nucleus pulposus: a comparative review of cartilage-like tissues in anatomy, development and function. *Cell Tissue Res*. 2017;370(1):53–70.
- Nerurkar NL, Elliott DM, Mauck RL. Mechanical design criteria for intervertebral disc tissue engineering. *J Biomech* [Internet]. 2010 Apr 19 [cited 2026 Sep 14];43(6):1017–30
- Samanta A, Lufkin T, Kraus P. Intervertebral disc degeneration—Current therapeutic options and challenges. *Front Public Heal*. 2023;11.