Chapter 11

Endplate Mechanics

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KEY POINTS

- Vertebral endplates play an integral role in the mechanical and biological function and degeneration of the intervertebral disc.
- Intra-operative factors to minimize risk of interbody subsidence are implant sizing, endplate preparation and quality of the host bone.
- Results from an evaluation of the loads required to initiate device subsidence of a new Nucleus Arthroplasty™ device compared to a representative interbody fusion device look promising.
- Augmentation of vertebral bodies with low bone density may be a viable clinical technique for reducing the risk of device subsidence in patients at risk of developing osteoporosis.

INTRODUCTION

The intervertebral discs serve a largely mechanical role of absorbing and transmitting the loads of the spine. The adjacent vertebral endplates are integral to this role. Both the mechanical and biological functions of the endplates are related to their micro and macrostructure. This chapter will discuss these relationships of endplate structure, their mechanical and biological functions, and the overall impact on intervertebral disc mechanics as it relates to Nucleus Arthroplasty™ devices. Understanding endplate mechanics is important when developing interbody and Nucleus Arthroplasty (NA) devices in order to avoid subsidence and restore the load-sharing characteristics similar to those of the normal intervertebral discs.

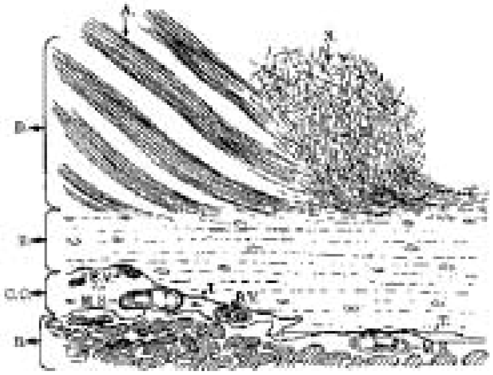

Figure 1
Schematic representation of the normal histology. A=anulus fibrosus; B=bone; BV=blood vessel; CC=calcified cartilage; D=disc; E=endplate; MS=marrow space; N=nucleus pulposus; T=tidemark. Reprinted with permission.

ANATOMICAL CONSIDERATIONS OF THE ENDPLATE

The endplates of the intervertebral disc serve as borders between the fibrocartilaginous intervertebral discs, whose fibers anchor into the endplates, and the vertebral bodies. The endplate is comprised of two layers; a layer of calcified cartilage adjacent to the vertebral bone, and a layer of hyaline cartilage adjacent to the intervertebral discs (Figure 1). Early in life, the cartilaginous endplate is thick and serves as the growth plate for the vertebral bodies. During this time, vascular and marrow contact channels extend through the cartilaginous endplate into intervertebral disc (Figure 2). With skeletal maturation, the endplates become calcified adjacent to the vertebral bone, which develops into a bony endplate layer with a thickness of approximately 0.5mm.[1] The remaining cartilaginous endplate layer adjacent to the intervertebral discs has a thickness of approximately 0.6mm.[2] The bony endplate is thickest adjacent to the nucleus pulposus, whereas the cartilaginous endplate is thinnest adjacent to the nucleus pulposus.[1, 2] The neurovascular structures and bone marrow contact channels retreat so that they terminate in the bony endplate layer (Figure 3). Nerve fibers are most concentrated in regions adjacent to the nucleus pulposus, with innervation density similar to the outer disc anulus fibrosus.

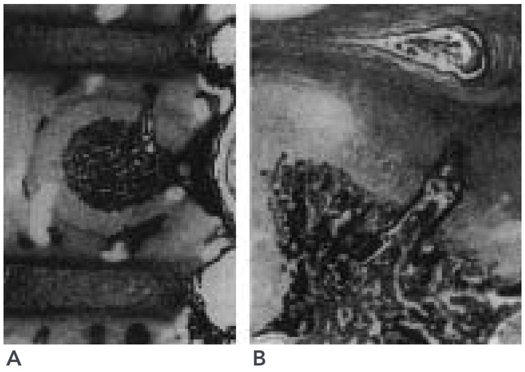

Figure 2
(a) Human vertebral centrum development (1 year). Note the vascular cartilage canals throughout the nonossified centrum. A large vessel crosses the transphyseal region of the primary centrum ossification center, traveling toward the superior disc region. (b) Specimen from a 6-year old boy who died of traumatic injury. A transphyseal vascular process extends toward the superior disc and its vessels. Reprinted with permission.

The endplates are thought to be the primary mode for fluid flow into and out of the disc. The semi-permeable nature of the endplates is integral to the creep response, and the diurnal variation in pressure, of the intervertebral disc. The resistance of the endplates to fluid flow is direction-dependent, with resistance to fluid flow out of the disc much greater than resistance to fluid returning into the disc.[3] Thus, the endplates provide a physical barrier

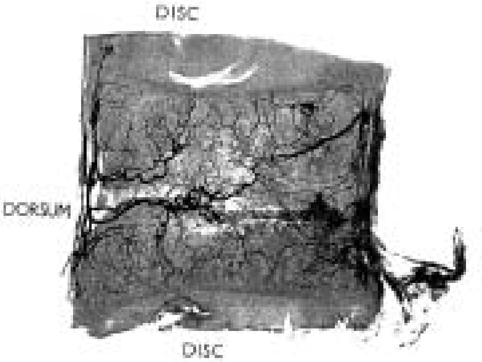

Figure 3
Sagittal section through a mature L2 vertebral body, showing the distribution of the nutrient arterioloes throughout the body, without vascular communication with the disc space or cartilaginous endplate. Reprinted with permission.

enabling hydrostatic pressurization of the intervertebral disc as compressive load is applied, and, in conjunction with osmotic pressure, enable re-hydration of the disc as load is removed. Fluid flow occurs across the bony endplate through marrow contact channels and in the cartilaginous endplate by diffusion.

In addition to fluid flow, the endplates (especially the central regions adjacent to the nucleus pulposus) are the primary route for metabolite and waste product transport. Nutrients reach the cartilage endplates via the marrow contact channels and capillary buds of the bony endplates. Diffusion through the adult cartilage endplates occurs and depends both on the properties of the metabolite solute including molecular size and charge, and the cartilage matrix. Larger sized molecules, such as growth factor-binding protein complexes, are excluded from diffusion into the intervertebral disc by the large, negatively charged aggregating proteoglycans.[2]

ALTHOUGH THE ETIOLOGY OF INTERVERTEBRAL DISC (IVD) DEGENERATION IS LIKELY MULTIFACTORIAL, THERE IS INCREASING EVIDENCE THAT POINTS TO THE ENDPLATE AS HAVING A PRIMARY ROLE IN THE DEGENERATIVE CASCADE.

CHANGES WITH DEGENERATION

Although the etiology of intervertebral disc (IVD) degeneration is likely multifactorial, there is increasing evidence that points to the endplate as having a primary role in the degenerative cascade.[4] Several important and notable changes to the endplate take place in disc degeneration, including matrix disorganization, decrease in cell density in the endplate, cracks in the endplate cartilage, and further reduction in endplate vascularity. IVD degeneration is also associated with calcification of the endplate cartilage and a reduction in the number of marrow contact channels, which results in decreased endplate permeability. These changes have been shown to correlate with biochemical degeneration of the disc.[5] Structural endplate changes that appear related to the presence of disc degeneration are also associated with a reduction in the diffusion across the endplate. It has recently been shown that endplate cartilage has the most limiting effect on diffusion, and thereby controls the sole mechanism for nutritional transport to the nucleus pulposus. Therefore, endplate damage, whether in the form of cracks, fissures, fractures, or Schmorl's nodes, which disrupt the nutritional delivery to the disc, may contribute to the progression of the degenerative cascade of the IVD.[4]

Degeneration causes somewhat paradoxical changes to the cartilage and bony endplates. With degeneration, the proteoglycans of the cartilage endplate break down, enabling larger molecules, both beneficial and detrimental, to diffuse in and out of the disc. Ultimately, age and other degeneration-related changes to endplate vascularity and permeability are thought to be detrimental to the nutritional status of the intervertebral disc, and directly contribute to the IVD degenerative cascade. These endplate changes precede age-related changes to the nucleus pulposus, and may be the harbinger of intervertebral disc degeneration.[4]

VERTEBRAL ENDPLATE BIOMECHANICS

Compared with the more widely studied nucleus pulposus and anulus fibrosus, relatively little is known about the mechanical properties of the vertebral endplate. The endplates distribute spinal loads across the intervertebral disc. The individual mechanical properties of the bony and cartilaginous endplates act in conjunction with vertebral body and intervertebral disc mechanical properties to govern overall motion segment mechanics.

The calcified cartilage of the bony endplate provides stiffness and strength to the endplate construct. The trabecular bone adjacent to the endplates is more dense and rodlike compared to the trabecular architecture further removed from the endplate. Bony endplate mechanical properties vary with spatial location; the greatest strength and stiffness in the postero-lateral regions, and lowest values in the central and antero-central regions (where interbody devices are commonly placed).[1] One study showed that the points closest to the pedicles were about 2.5 times stronger than more centrally-located points.[1] It has also been shown that the inferior endplate is stiffer and 40% stronger than the superior endplate. Sacral endplates are stronger than superior lumbar endplates, and among sacral endplates, posterior test sites were 3 times stronger than anterior sites.[1] Decrease in bone mineral density of the vertebral bodies causes these variations to become more pronounced.[1, 6]

In the healthy intervertebral disc, the cartilaginous endplate is pivotal in maintaining a uniform stress distribution between the intervertebral disc and the vertebral body. The fibers of the intervertebral disc are anchored into the cartilaginous endplate, directly transmitting intervertebral disc loads to the endplate and ultimately the vertebral body. Furthermore, hydrostatic pressurization of the nucleus pulposus results in axial bulging of the endplates. The collagen fibers of the cartilaginous endplate are oriented parallel to the axial surface of the tissue; thus,

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bulging results in tension in the endplate tangential to the bulge. The biphasic mechanical properties (permeability and aggregate modulus) of the cartilaginous endplates have been shown to be similar to those of articular cartilage, and likely vary with strain.

Structural disruptions of endplate integrity such as macroscopic and microscopic anomalies, bony intrusions, and thinning of the endplate can occur early in life, and may precede clinically apparent endplate failure that occurs years later. Failure may occur through acute or chronic mechanisms. Perey (1957) described three major forms of endplate failure: 1) central (non-degenerate discs), 2) peripheral, and 3) complete endplate. In central failures, compressive loads increased the nuclear hydrostatic pressures, causing excessive loading and failure in the endplate. In contrast, degenerate discs, characterized by a loss of proteoglycan and hydrostatic pressures, displayed peripheral failure patterns since most of the load under compression is then transmitted through the anulus. As a result, the endplate is loaded in the periphery and fails accordingly.[8]

The mechanical properties of both the endplate and the vertebral body have been shown to be rate dependent, with failure load increasing with increasing load application rate (i.e. quasi-static vs. impact loading). Removal of the bony endplate—often required prior to placement of an interbody fusion device to facilitate bone-implant osseointegration—has been shown to detrimentally affect stiffness and endplate failure load.[9] Thus, intact endplates appear to be an important factor in increasing the failure loads of devices in contact with the endplate surfaces. Furthermore, while failure stress increases with increasing load rate for the vertebral body, the endplates are not similarly affected. At high loading rates, the vertebral bodies may fail via a bursting mechanism initiated by the intrusion of intervertebral disc material through an endplate fracture.[10] Fatigue testing of motion segments has shown that the endplates typically fail first, accompanied by micro-fracture of the trabecular architecture of the vertebral body.[11]

ENDPLATE MECHANICS IN DEGENERATIVE DISC DISEASE

No study to date has quantified the degree of endplate mechanical compromise that accompanies disc degeneration, which is the subject of current research efforts at our institute. As intervertebral disc degeneration causes a reduction in water content in the nucleus pulposus, the mechanism for compressive load-bearing then changes from hydrostatic pressurization in the nucleus pulposus and tensile hoop stress in the anulus fibrosus to direct compressive force transmission to both the nucleus pulposus and the anulus fibrosus.[12, 13] Endplate failure may also contribute to the alteration in load-sharing in the degenerated IVD because it decompresses the pressurized state of the nucleus pulposus, which may result in a transfer of compressive load-bearing from the nucleus pulposus to the anulus fibrosus. Ultimately, alterations to the normal loading behavior of intervertebral disc tissues is thought to initiate structural damage to those tissues.[14] With these changes, the spatial variations in vertebral architecture and mechanical properties become more evenly distributed across the disc. In many cases of endplate failure, depressurized disc material is allowed to penetrate the vertebral body (i.e. Schmorl's nodes), and it has been hypothesized that this may initiate vertebral body fracture.[10]

CLINICAL CONSIDERATIONS

Endplate Subsidence and Failure with Interbody Devices

Adequate anterior column support is critical for most spinal reconstructive procedures as it facilitates the achievement of appropriate sagittal alignment, coronal balance, and load-sharing between anterior and posterior columns, thus enabling the optimal biomechanical environment for spinal fusion or, alternatively, motion preservation. Subsidence of an interbody device is a common and potentially devastating problem as it may lead to segmental kyphosis, coronal plane deformities, compression of neural elements, pseudarthrosis, and failure of instrumentation. The most common factors associated with endplate subsidence

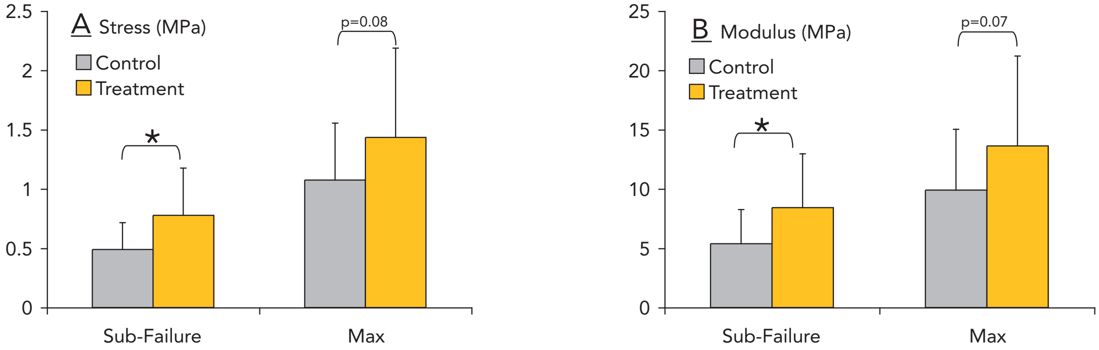


Figure 4

Average (std dev) sub-failure and max A) stress and B) apparent modulus in Treatment (vertebral bodies augmented with Cortoss in lumbar TDR) and controls, *$p \leq 0.05$.

and failure in the setting of an interbody device are 1) implant geometry and size, 2) degree of endplate removal/preparation, and 3) regional endplate strength. Each of these factors is addressed below.[15]

Intra-operative Methods to Prevent Subsidence

There is an increasing body of literature that has focused on methods to optimize the integrity of the bone-implant interface at the time of initial surgery. Such attention may maximize the longevity of the first procedure, and therefore minimize the risk of requiring a potentially more involved revision surgery.

The first and easiest technique to maximize the strength of the bone-implant interface is appropriate implant sizing. Whether the interbody device to be implanted is a fusion cage, total disc replacement (TDR), or nucleus replacement, it is critical to avoid relying solely on the central, weakest portion of the vertebral body.[16] When it is technically feasible, the largest size device that can be safely implanted should usually be used in order to achieve maximum fit. Devices that require removal of a substantial portion of the anulus fibrosus for placement of an interbody device (e.g. total disc arthroplasty devices) will engage more of the apophyseal rim, which in turn should minimize the risk of device subsidence. As has been shown in the sizing of total disc replacement devices, larger devices rest on more peripheral regions of bone with a higher stiffness, and therefore produce less stress at the endplate surfaces, which results in less device displacement under compressive loads. As shown in Chapter 10 of this publication, implant sizing is critical for nucleus replacement devices and can have a significant impact on the load support by the device. With proper sizing, a nucleus implant (HydraFlex™ device by Raymedica, LLC) demonstrated nearly equal load sharing with the anulus, thus reducing the risk for central implant subsidence.

> WITH PROPER SIZING, A NUCLEUS IMPLANT (HYDRAFLEX™ DEVICE BY RAYMEDICA, LLC) DEMONSTRATED NEARLY EQUAL LOAD SHARING WITH THE ANULUS, THUS REDUCING THE RISK FOR CENTRAL IMPLANT SUBSIDENCE.

The second intra-operative consideration is endplate preparation. While this intra-operative step may receive more attention with fusion or total disc replacement devices, which aim to achieve an osseointegration between the device and host bone, this is less of an issue in nucleus arthroplasty implantation. Nucleus replacement devices allow preservation of the cartilaginous endplate which in turn provides additional mechanical support, and minimizes the risk of device subsidence and endplate fracture. For these reasons, there is no formal endplate preparation and no tissue removal with Nucleus Arthroplasty devices. Instead, the diseased nucleus pulposus is completely removed to remove the pain generator and to create space for proper functioning of the Nucleus Arthroplasty device. Although nucleus pulposus swelling pressures and flow states influence the mechanics of the underlying vertebral endplate, no study to date has quantified the biomechanical effect of nuclear tissue removal and implantation of a Nucleus Arthroplasty device on vertebral endplate mechanics. It stands to reason, that Nucleus Arthroplasty devices made from materials that allow continued fluid movement through the endplate may have physiologic benefits. However, this needs to be further investigated in a clinical setting.

The final contributing factor to bone-implant interface strength is the quality of the host bone. Recently, "vertebroplasty" has gained popularity as a relatively safe, minimally invasive, effective treatment for osteoporotic vertebral fractures. Filling of fractured vertebrae with injected bone cement has been shown to reduce stresses in the anulus and neural arch, resulting in a more even distribution of compressive forces on the disc and adjacent vertebral bodies. Other biomechanical studies have shown that vertebral augmentation results in an improvement in adjacent motion segment stiffness, and compressive load-bearing, the effects of which are more pronounced in vertebral bodies with low bone density. Recently, the clinical use of vertebroplasty in conjunction with total lumbar disc replacement (TDR) has been described. Furthermore, the authors have shown in a biomechanical cadaveric spine study that vertebral augmentation with Cortoss (Orthovita, Malvern, PA) in lumbar TDR significantly improves the sub-failure mechanical properties of the implant-endplate interface, with more dramatic differences in low bone density specimens (Figure 4).[17] These findings demonstrate that vertebral augmentation potentially reduces the risk for implant subsidence and endplate failure in patients who have or are at risk for the development of osteoporosis. Future studies will evaluate further the potential role for vertebral augmentation with Nucleus Arthroplasty devices.

Endplate Subsidence Characteristics of Interbody Devices

Interbody nuclear replacement is emerging as an alternative to interbody fusion in the treatment of degenerative disc disease (DDD). Device subsidence is an inherent clinical risk of any interbody device. However, despite promising clinical results with nucleus replacement devices, concerns related to endplate remodeling or endplate subsidence exist.

Beaubien, et al[18] evaluated the cadaveric subsidence characteristics of two nucleus replacement devices (PDN-SOLO® and HydraFlex™, Raymedica, LLC, Minneapolis, Minnesota) to a PEEK interbody fusion device. The PDN-SOLO nucleus replacement device has the largest and longest worldwide human clinical experience. PEEK interbody devices have demonstrated good long clinical outcomes for interbody fusion. The HydraFlex device is the latest product offering by Raymedica, LLC and has several improved design features, including a more anatomically-shaped implant design, a larger contact footprint, and a faster hydrating and softer hydrogel core which reduces device stiffness.

Subsidence tests were conducted in cadaveric motion segments (L2-3 or L4-5). The specimens were potted in resin after the bone mineral density (BMD) had been measured using DEXA. Devices were implanted into the cadaveric segments according to manufacturer's recommendations. Next, the anulus and posterior elements were removed to isolate the device-endplate interface. For each specimen, compression tests were performed starting at 800 N and increasing in 200 N increments until failure. Fluoroscopic imaging was utilized to identify initiation of device subsidence, defined as radiographic endplate deformation compared to the baseline image. Testing was stopped after occurrence of gross device subsidence (>2mm subsidence). The BMD versus failure load relationship was investigated using linear regression. The test methods utilized are considered worst case since all load passes through the device and does not account for the soft tissue load sharing reported in Chapter 10.

Normalized to the HydraFlex device, the authors reported the PDN-SOLO device was 1.7 times stiffer, and the PEEK cage was 20 times stiffer. The BMD was similar for all test groups with the device subsidence load correlating with BMD. Loads to initiate subsidence utilizing fluoroscopic imaging demonstrated not only higher loads for the HydraFlex device compared to the PDN-SOLO and PEEK devices (3200 ± 1224 N versus 2050 ± 191 N, and 2700 ± 837 N, respectively), but also differing failure mechanisms (Figure 5). It is hypothesized that the lower stiffness of the

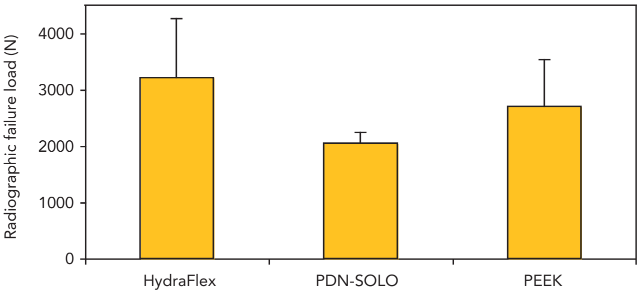
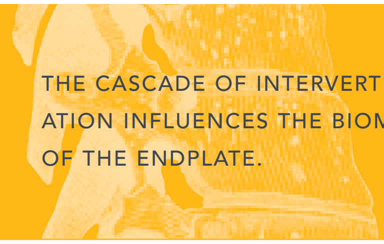


Figure 5
Load at initiation of subsidence of 3 interbody devices.

HydraFlex device allowed for more device deformation with increasing loads, improving endplate conformity and effectively distributing endplate stress, resulting in a less pronounced initial endplate failure and slow progression of subsidence with initial endplate failure noted approximately 600-800 N prior to gross (>2mm) device subsidence. Conversely, subsidence of the high stiffness PEEK spacer occurred simultaneously with fracture of the endplates.

The results from this study demonstrated that the HydraFlex device has greatly improved the *in vitro* subsidence performance. While the intended function of the Nucleus Arthroplasty devices and a PEEK spacer are decidedly different, comparisons between their subsidence characteristics offers insight into the expected clinical performance.



THE CASCADE OF INTERVERTEBRAL DISC DEGENERATION INFLUENCES THE BIOMECHANICAL INTEGRITY OF THE ENDPLATE.

CONCLUSION

The cascade of intervertebral disc degeneration influences the biomechanical integrity of the endplate. One clinical concern with interbody devices is endplate failure. Intra-operative factors to minimize risk of interbody subsidence are implant sizing, endplate preparation and quality of the host bone. For fusion and total disc arthroplasty devices, using the largest size device that can be safely implanted engages more of the apophyseal rim and reduces the segment displacement under compressive loads. In side-by-side testing of a PEEK fusion device versus the HydraFlex Nucleus Arthroplasty device, the HydraFlex device demonstrated higher loads required to initiate endplate subsidence. For patients at risk of developing osteoporosis, initial biomechanical and clinical results from vertebral body augmentation used to ameliorate interbody device subsidence and catastrophic failure are promising. However, additional clinical studies of these technologies and techniques are needed to determine if they are viable.

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