Biomechanics of cervical intervertebral disc replacement

for partial fulfillment of master degree in Orthopedic surgery

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Aim of the work

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ACDF…… anterior cervical disectomy and fusion.
CDA…….. cervical disc arthroplasty.
IDP……….intra discal pressure.
LZ ........ angular lax zone .
ROM ..........range of motion.
SZ............ stiff zone .
TDA......... total disc arthroplasty.
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Introduction

The intervertebral disc is a major load bearing component of the spine. The mechanical loading of the disc is one of the main causes of its degeneration. For chronic patients, the treatment regimen may range from conservative approach to surgical procedures, including fusion with and without instrumentation. The fusion has proven successful in reducing the segmental motion. However, a majority of patients after a fusion procedure may still experience pain. The procedure may also lead to adjacent level degeneration, pseudarthrosis and donor site pain. These shortcomings have led the researchers to develop alternative approaches such as the total disc arthroplasty which is expected to preserve motion and relieve pain. Thus, it is essential to evaluate the clinical outcomes in terms of an artificial disc’s ability to provide normal kinematics following total disc replacements.

The wide clinical experience in the area of lower extremity joint replacements suggests that the long-term success of any total arthroplasty system is a function of three primary factors: implant design parameters (geometry, material, kinetics, ROM in all 6 degrees of freedom), patient related parameters (weight, kinematics, age) and surgeon related factors such as surgical procedures. One expects that similar parameters would influence the long-term success of the cervical disc replacement. (1)
For more than 50 years, anterior cervical discectomy and fusion (ACDF) has been the workhorse procedure for cervical degenerative pathology. The procedure has yielded successful results clinically in multiple large series. Advances in allograft and cage techniques as well as the use of anterior plating systems have diminished complications in ACDF. However, concerns about adjacent segment degeneration (ASD) have lowered some enthusiasm for the procedure. (1)

Cervical disc arthroplasty has the potential to maintain anatomical disc space height, normal segmental lordosis, and physiological motion patterns after surgery. These characteristics may reduce or delay the onset of degenerative disc disease at adjacent cervical spinal motion segments after anterior cervical decompression surgery. (2)

Cervical disc replacement has been developed as a motion-preserving alternative to fusion, with the hope that retained motion at the operative level may reduce adjacent segment disease. Cervical disc replacement has become an acceptable alternative to anterior cervical fusion for the surgical treatment of cervical spine spondylosis resulting in radiculopathy or myelopathy following anterior discectomy and decompression.
Anatomy of the cervical spine

Overview:

The cervical spine is made up of 7 vertebrae. The first two vertebrae, C1 and C2, are highly specialized and are given unique names: atlas and axis, respectively. C3-
C7 vertebrae are more classic vertebrae, having a body, pedicles, laminae, spinous processes, and facet joints. The seventh cervical vertebra is slightly different in it has a transitional form, it has a larger spinous process that is not bifid. (3)

The lateral edges of the superior surface of each body are sharply turned upward to form the uncinate processes that are characteristic of the cervical region.

C1 and C2 form a unique set of articulations that provide a great degree of mobility for the skull. C1 serves as a ring or washer that the skull rests upon and articulates in a pivot joint with the dens or odontoid process of C2. Approximately 50% of flexion extension of the neck happens between the occiput and C1; 50% of the rotation of the neck happens between C1 and C2. (4)

The cervical spine is much more mobile than the thoracic or lumbar regions of the spine. Unlike the other parts of the spine, the cervical spine has transverse foramina in each vertebra for the vertebral arteries that supply blood to the brain. (6)

**Gross Anatomy:**

The cervical spine functions to provide mobility and stability to the head while connecting it to the relatively immobile thoracic spine. The cervical spine may be divided into 2 parts: upper and lower.
Figure(1.1) showing cervical spine anatomy.
Figure (1.2): showing a typical cervical vertebra. (4)

Upper cervical spine:

The upper cervical spine consists of the atlas (C1) and the axis (C2). These first 2 vertebrae are quite different from the rest of the cervical spine. The atlas articulates superiorly with the occiput (the atlanto-occipital joint) and inferiorly with the axis (the atlantoaxial joint). (4)
Figure (1.3): showing superior view of Atlas vertebra.(4)

Atlas (C1):

The atlas is ring-shaped and does not have a body, unlike the rest of the vertebrae. Fused remnants of the atlas body have become part of C2, where they are called the odontoid process, or dens. The odontoid process is held in tight proximity to the posterior aspect of the anterior arch of the atlas by the transverse ligament, which stabilizes the atlantoaxial joint. The apical, alar, and transverse ligaments provide stability and prevent posterior displacement of the dens in relation to the atlas.(5)

The Atlas is made up of a thick anterior arch, a thin posterior arch, 2 prominent lateral masses, and 2 transverse processes. The transverse foramen, through which the vertebral artery passes, is enclosed by the transverse process.(Figure 1.3)
On each lateral mass is a superior and inferior facet (zygapophyseal) joint. The superior articular facets are kidney-shaped, concave, and face upward and inward. These superior facets articulate with the occipital condyles, which face downward and outward. The relatively flat inferior articular facets face downward and inward to articulate with the superior facets of the axis.

According to Steele's rule of thirds, at the level of the atlas, the odontoid process, the subarachnoid space, and spinal cord each occupy one third of the area of the spinal canal. (6)

**Axis (C2)**

The axis has a large vertebral body, which contains the odontoid process (dens). The odontoid process articulates with the anterior arch of the atlas via its anterior articular facet and is held in place by the transverse ligament. The axis articulates with the atlas through its superior articular facets, which are convex and face upward and outward. (Figure 1.4). (7)

**Embryology OF C2:**

It is derived from 4 ossification centers: 1 for the body, 1 for the odontoid process, and 2 for the neural arches.

At birth, a cartilaginous disc space called the neurocentral synchondrosis separates the odontoid process from the body of C2. The synchondrosis is fused with the body at the age of 6 years. The apical portion of the dens ossifies by age 3-5 years and fuses with the rest of the dens around age 12 years. This synchondrosis should not be confused with a fracture. (7)
Ligaments of the upper cervical spine:

The atlanto-occipital and the atlantoaxial joints are secured by the external and internal ligaments.

The external ligaments consist of the atlanto-occipital, anterior atlanto-occipital, and anterior longitudinal ligaments.

The internal ligaments have 5 components, as follows:

1. The transverse ligament holds the odontoid process in place against the posterior atlas, which prevents anterior subluxation of C1 on C2.
2. The apical ligament lies anterior to the lip of the foramen magnum and inserts into the apex of the odontoid process.
3. The paired alar ligaments secure the apex of the odontoid to the anterior foramen magnum.
4. The tectorial membrane is a continuation of the posterior longitudinal ligament to the anterior margin of the foramen magnum.
5. The accessory atlantoaxial ligament connects the atlas to the axis then it continues cephalad to the occipital bone.(8)
Lower cervical spine (subaxial):

The 5 cervical vertebrae that make up the lower cervical spine, C3-C7, are similar to each other but very different from C1 and C2. Each has a vertebral body that is concave on its superior surface and convex on its inferior surface. On the superior surfaces of the bodies are raised processes or hooks called uncinate processes, each of which articulates with a depressed area on the inferior lateral aspect of the superior vertebral body, anvil. (Figure 1.5).
Figure (1.5): showing subaxial spine, a- a comparison between the fourth and seventh cervical vertebra (superior view), b- a lateral view of the subaxial spine, c- an anteroposterior view of the subaxial spine. (4)
These uncovertebral joints are most noticeable near the pedicles and are usually referred to as the joints of Luschka. They are believed to be the result of degenerative changes in the annulus, which lead to fissuring in the annulus and the creation of the joint. These joints can develop osteophytic spurs, which can narrow the intervertebral foramina. (5)

The spinous processes of C3-C6 are usually bifid, whereas the spinous process of C7 is usually nonbifid and bulbous at its end.

Ligaments of the lower cervical spine:

The anterior longitudinal ligament and the posterior longitudinal ligament are the major stabilizers of the intervertebral joints.

Both ligaments are found throughout the entire length of the spine; however, the anterior longitudinal ligament adheres more closely to the discs than the posterior, and it is not well developed in the cervical spine. The anterior longitudinal ligament becomes the anterior atlanto-occipital membrane at the level of the atlas, whereas the posterior longitudinal ligament merges with the tectorial membrane. Both continue onto the occiput. (9)

The supraspinous ligament runs along the tips of the spinous processes, the interspinous ligaments run between adjacent spinous processes, and the
ligamentum flavum runs from the anterior surface of the superior vertebra to the posterior surface of the inferior vertebra. (9)

The interspinous ligament and the ligamentum flavum control for excessive flexion and anterior translation. The ligamentum flavum also connects to and reinforces the facet joint capsules on the ventral aspect. The ligamentum nuchae is the cephalad continuation of the supraspinous ligament and has a prominent role in stabilizing the cervical spine. (10)

Children have significant anatomical variations in the craniocervical junction compared with adults, that complicates the cervical fusions done in pediatric population. (11)

*Anterior and posterior columns of the subaxial cervical spine:*

The subaxial cervical spine can conveniently be divided into anterior and posterior columns. The anterior column consists of the typical cervical vertebral body sandwiched between supporting disks. The anterior surface is reinforced by the anterior longitudinal ligament and the posterior body by the posterior longitudinal ligament, both of which run from the axis to the sacrum. (10)

Articulations include disc-vertebral body articulations, uncovertebral joints, and facet joints. The disk is thicker anteriorly, contributing to normal cervical lordosis, and the uncovertebral joints in the posterior aspect of the body define the lateral extent of most surgical exposures. The facet joint capsule is weakest posteriorly. Supporting ligamentum flavum, posterior, and interspinous ligaments also strengthen the posterior column. (4)
The spinal cord and spinal canal:

The spinal cord lateral dimension is about 13-14 mm, and the anterior-posterior extent measures 7 mm. An additional 1 mm is necessary for cerebrospinal fluid anteriorly and posteriorly, as well as 1 mm for the dura. A total of 11 mm is needed for the cervical spinal cord.

The spinal nerve and spinal ganglion occupy up to one third of the foraminal space. The neural foramen is bordered anteromedially by the uncovertebral joints, posterolaterally by facet joints, superiorly by the pedicle of the vertebra above, and inferiorly by the pedicle of the lower vertebra. Medially, the foramina are formed by the edge of the end plates and the intervertebral discs. (6)

The spinal nerves exit above their correspondingly numbered vertebral body from C1-C7. Because the numbering of the cervical spinal nerves starts above the atlas, 8 cervical spinal nerves exist, with the first exiting between the occiput and the atlas (C1) and the eighth exiting between C7 and T1. (6)

Intervertebral discs:

Intervertebral discs are located between the vertebral bodies of C2-C7. The discs are composed of 4 parts: the nucleus pulposus in the middle, the annulus fibrosis surrounding the nucleus, and 2 end plates that are attached to the adjacent vertebral bodies. They serve as force dissipators, transmitting compressive loads throughout a range of motion. The disks are thicker anteriorly and therefore contribute to normal cervical lordosis. (4)
Table 1 Differences between the cervical and lumbar discs

<table>
<thead>
<tr>
<th>Cervical intervertebral disc</th>
<th>Lumbar intervertebral disc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained by vertebral bodies</td>
<td>Not contained by vertebral bodies</td>
</tr>
<tr>
<td>Thicker anteriorly than posteriorly</td>
<td>Equal height</td>
</tr>
<tr>
<td>Annulus thicker posteriorly</td>
<td>Annulus weaker posteriorly</td>
</tr>
<tr>
<td>Nucleus in anterior part of disc</td>
<td>Nucleus in posterior part of disc</td>
</tr>
</tbody>
</table>

Blood supply of the cervical spine:

The main blood supply to the cervical spine and related structures is from the vertebro-basilar system. The vertebral arteries originate from the subclavian arteries and finally join to form the basilar artery. During their course they give off the anterior and posterior spinal arteries to the spine and to the spinal cord. (7)

The vertebrobasilar system is a closed circuit, starting below in the subclavian arteries and ending above in the arterial circle of Willis. The vertebral arteries run parallel on both sides of the spinal column through the canal formed by the successive transverse foramina, and are the main blood supply for the cervical spine, the spinal cord and the brain stem. Between the axis and atlas the arteries curve backwards and outwards and run over the posterior arch of the atlas. They
curve upwards again and run cranially into the skull they join to form the basilar artery which then splits into a left and right posterior cerebral artery. (Figure 1.6).

(4)

Unco-arterio-radicular junction:

There is a close connection between the uncovertebral joint, the vertebral artery and the nerve root. The artery is between the uncinate process and the nerve root. The nerve root lies behind the artery and just anterior to the facet joint. Degenerative changes leading to osseous, cartilaginous or capsular hypertrophy may result in compression of artery or nerve root.

**Figure (1.6): showing vertebro-basilar system and circle of Willis. (4)**
Disc morphology:

The normal disc:

The intervertebral discs lie between the vertebral bodies, linking them together. They are the main joints of the spinal column and occupy one-third of its height. Their major role is mechanical, as they constantly transmit load arising from body
weight and muscle activity through the spinal column. They provide flexibility to this, allowing bending, flexion and torsion. (12)

The intervertebral disc is a cartilaginous structure that resembles articular cartilage in its biochemistry, but morphologically it is clearly different. It shows degenerative and ageing changes earlier than does any other connective tissue in the body. It is believed to be important clinically because there is an association of disc degeneration with back pain. (13)

The intervertebral discs are complex structures that consist of a thick outer ring of fibrous cartilage termed the annulus fibrosus, which surrounds a more gelatinous core known as the nucleus pulposus. The nucleus pulposus is sandwiched inferiorly and superiorly by cartilage end-plates. (14)

The central nucleus pulposus contains collagen fibres, which are organised randomly, and elastin fibres (sometimes up to 150 mm in length), which are arranged radially. These fibres are embedded in a highly hydrated aggrecan-containing gel. Outside the nucleus is the annulus fibrosus, with the boundary between the two regions being very distinct in the young individual (<10 years). The annulus is made up of a series of 15–25 concentric rings, or lamellae, with the collagen fibres lying parallel within each lamella. Elastin fibres lie between the lamellae, possibly helping the disc to return to its original arrangement following bending. (15)
The cartilage end-plate is a thin layer, usually less than 1mm thick, of hyaline cartilage. This interfaces the disc and the vertebral body. The collagen fibres within it run horizontal and parallel to the vertebral bodies, with the fibres continuing into the disc. (16)

The healthy adult disc has some nerves, mainly restricted to the outer lamellae, some of which terminate in proprioceptors. (17)

The cartilaginous end-plate, like other hyaline cartilages, is normally totally avascular and aneural in the healthy adult. Blood vessels present in the longitudinal ligaments adjacent to the disc and in young cartilage end-plates (less than about 12 months old) are branches of the spinal artery. (18)

Nerves in the disc have been demonstrated, often accompanying these vessels, but they can also occur independently, being branches of the sinuvertebral nerve or derived from the ventral rami or grey rami communicantes. Some of the nerves in discs also have glial support cells, or Schwann cells, alongside them. (19)
**Figure (2.1):** showing a schematic view of a spinal segment (including the intervertebral disc). The figure shows the organization of the disc with the nucleus pulposus (NP) surrounded by the lamellae of the annulus fibrosus (AF) and separated from the vertebral bodies (VB) by the cartilaginous end-plate (CEP). The figure also shows the relationship between the intervertebral disc and the spinal cord (SC), the nerve root (NR), and the apophyseal joints (AJ). (20)
The degenerated disc:

During growth and skeletal maturation the boundary between annulus and nucleus becomes less obvious, and with increasing age the nucleus generally becomes more fibrotic and less gel-like. With increasing age and degeneration the disc changes in morphology, becoming more and more disorganized. Often the annular lamellae become irregular, and the collagen and elastin networks also appear to become more disorganized. (21)

Figure (2.2): The figure shows a normal intervertebral disc on the left. The annulus lamellae surrounding the softer nucleus pulposus are clearly visible. In the
highly degenerated disc on the right, the nucleus is desiccated and the annulus is disorganized. (20)

There is frequently cleft formation with fissures forming within the disc, particularly in the nucleus. Nerves and blood vessels are increasingly found with degeneration. (22)

Boos et al. demonstrated an age-associated changes in morphology, with discs from individuals as young as 2 years of age having some very mild cleft formation and granular changes to the nucleus. With increasing age comes an increased incidence of degenerative changes, including cell death, cell proliferation, mucous degeneration, granular change and concentric tears. It is difficult to differentiate changes that occur solely due to ageing from those that might be considered pathological. (23)

**Biochemistry:**

**Normal discs:**

The mechanical functions of the disc are served by the extracellular matrix. The main mechanical role is provided by the two major macromolecular components
(collagen and aggrecan). The collagen is formed mostly of type I and type II collagen fibrils and making up approximately 70% and 20% of the dry weight of the annulus and nucleus, respectively. The collagen provides tensile strength to the disc and anchors the tissue to the bone. (24)

Aggrecan is the major proteoglycan of the disc responsible for maintaining tissue hydration through the osmotic pressure provided by the chondroitin and keratan sulphate chains in the aggrecan. The proteoglycan and water content of the nucleus is greater than in the annulus. (25)

In addition, there are many other minor components, such as collagen types III, V, VI, IX, X, XI, XII and XIV; small proteoglycans such as lumican, biglycan, decorin and fibromodulin; and other glycoproteins such as fibronectin and amyloid. The functional role of many of these additional matrix proteins and glycoproteins is not yet clear. (26)

The matrix is a dynamic structure. Its molecules are continually being broken down by proteinases such as the matrix metalloproteinases and aggrecanases, which are also synthesized by disc cells. The balance between synthesis and breakdown determines the quality and integrity of the matrix, and thus the mechanical behaviour of the disc itself. The integrity of the matrix is also important for maintaining the relatively avascular and aneural nature of the healthy disc. (27)
**Biochemical changes associated with disc degeneration:**

The most significant biochemical change that occur in disc degeneration is loss of proteoglycan. The aggrecan molecules become degraded, with smaller fragments being able to leach from the tissue more readily than larger portions. This results in loss of glycosaminoglycans; this loss is responsible for a fall in the osmotic pressure of the disc matrix and so a loss of hydration. (28)

The collagen of the disc also changes with degeneration of the matrix but the changes are not as obvious as those of the proteoglycans. The absolute quantity of collagen changes little but the types and distribution of collagens can alter. Type II collagen, become more denatured, apparently because of enzymic activity. (29)

Collagen cross-link studies indicate that, new collagen molecules may be synthesized, at least early in disc degeneration, possibly in an attempt at repair.(30)

Other components can change in disc degeneration in either quantity or distribution. For example, fibronectin content increases with increasing degeneration and it becomes more fragmented. Fibronectin fragments enhances the degenerative cascade because they have been shown to down-regulate aggrecan synthesis. (20)
The enzymatic activity also contributes to the disc degeneration. Several families of enzymes are capable of breaking down the various matrix molecules of disc, including cathepsins, metalloproteins and aggrecanases. Cathepsins have maximal activity in acid conditions (e.g. cathepsin D is inactive above pH 7.2). In contrast, MMPs and aggrecanases have an optimal pH that is approximately neutral. All of these enzymes have been identified in disc, with higher levels in advanced degeneration. (31)

**Effect of degenerative changes on disc function and pathology:**

The loss of proteoglycan in degenerated discs has a major effect on the disc’s load-bearing behaviour. With loss of proteoglycan, the osmotic pressure of the disc falls and the disc is less able to maintain hydration under load so the degenerated discs have a lower water content than do normal age-matched discs. Thus when the degenerated discs are loaded they lose height and fluid more rapidly, and the discs tend to bulge. (20)

Loss of proteoglycan and matrix disorganization have other important mechanical effects; because of the subsequent loss of hydration, degenerated discs no longer
behave hydrostatically under load. (32) Loading may thus lead to inappropriate distribution of stress along the endplate or in the annulus. This may have a role in the discogenic backache clinically. (33)

This stress distribution change in disc behaviour have a strong influence on other spinal structure. The facet joints may be subject to abnormal loads due to the disc height loss and may eventually develop osteoarthritic changes. (32) Loss of disc height can also affect other structures. It reduces the tensional forces on the ligamentum flavum and hence may cause remodelling, thickening and loss of elasticity. (34)

Loss of proteoglycans also influences the movement of molecules into and out of the disc. Aggrecan, because of its high concentration and charge in the normal disc, prevents movement of large uncharged molecules such as serum proteins and cytokines into and through the matrix. The fall in concentration of aggrecan in degeneration may accelerate the degenerative cascade due to increased penetration of large molecules such as growth factor complexes and cytokines into the disc. (20)

Aggrecan has been shown to inhibit neural ingrowth. Thus in degenerated disc, there is an increase in the neural and vascular ingrowth which may be linked to chronic discogenic pain. (35)
Aetiology of disc degeneration:

A-Nutritional pathways to disc degeneration

One of the primary causes of disc degeneration is thought to be failure of the nutrient supply to the disc cells. Like all cell types, the cells of the disc require nutrients such as glucose and oxygen to remain alive and active. The activity of disc cells is sensitive to extracellular oxygen and pH, with matrix synthesis rates falling steeply at acidic pH and at low oxygen concentrations. Thus, a fall in nutrient supply could affect the ability of disc cells to synthesize and maintain the disc’s extracellular matrix and could ultimately lead to disc degeneration. (20)

The disc is large and avascular and the cells depend on blood vessels at their margins to supply nutrients and remove metabolic waste. The nutrient supply to the nucleus cells can be disturbed at several points. Factors that affect the blood supply to the vertebral body such as atherosclerosis, sickle cell anaemia, Caisson disease and Gaucher’s disease all appear to lead to a significant increase in disc degeneration. (36)
Even if the blood supply remains undisturbed, nutrients may not reach the disc cells if the cartilaginous end-plate calcifies. Intense calcification of the endplate is seen in scoliotic discs. (37)

There is a relationship between loss of cell viability and a fall in nutrient transport in scoliotic discs with subsequent disc degeneration. (38)

**B-Mechanical load and injury**

Abnormal mechanical loads are also thought to provide a pathway to disc degeneration. For many decades it was suggested that a major cause of back problems is injury, often work-related, which causes structural damage. It is believed that such an injury initiates a pathway that leads to disc degeneration and finally to clinical symptoms and back pain. (20)

Further support for the role of abnormal mechanical forces in disc degeneration comes from findings that disc levels adjacent to a fused segment degenerate rapidly. (39)
Epidemiological studies that have found associations between environmental factors and development of disc degeneration, with heavy physical work, lifting, truck-driving, obesity and smoking found to be the major risk factors for back pain and degeneration. (40)

**C-Genetic factors in disc degeneration:**

Disc degeneration may have important genetic components.

Battie et al. found that magnetic resonance images in identical twins, who had no major risk factors such as smoking or heavy work, were very similar with respect to the spinal columns and the patterns of disc degeneration. (41)

Genetic predisposition has been confirmed by findings of associations between disc degeneration and gene polymorphisms of matrix macromolecules. (42)

In summary, the findings from these genetic and epidemiological studies point to the multifactorial nature of disc degeneration.
Chapter 3

Biomechanics of the cervical spine

Normal biomechanics

1. Functional anatomy and its relation to biomechanical behavior of the cervical vertebrae

For descriptive purposes, the cervical spine can be divided and perceived as consisting of four units, each with a unique morphology that determines its kinematics and its contribution to the functions of the complete cervical spine. In anatomical terms the units are the atlas, the axis, the C2-3 junction and the remaining, typical cervical vertebrae. In metaphorical, functional terms these can be perceived as the cradle, the axis, the root, and the column. (43)

1-The cradle
The atlas vertebra serves to cradle the occiput. Into its superior articular sockets it receives the condyles of the occiput. The union between the head and atlas, through the atlanto-occipital joints, is strong, and allows only for nodding movements between the two structures. In all other respects the head and atlas move and function essentially as one unit. Under normal conditions, however, flexion is limited by tension in the posterior neck muscles and by impaction of the submandibular tissues against the throat. Extension is limited by the occiput compressing the suboccipital muscles. Axial rotation and lateral flexion are not physiological movements of the atlanto-occipital joints. (43)  

Figure (3.1): showing right lateral views of flexion and extension of the atlanto-occipital joints. The central figure shows the occipital condyle resting in the atlantial socket in a neutral position. The dots are reference points. In flexion the head rotates forwards but the condyle also translates backwards, as indicated by the displacement of the references dot. In extension, the reverse happens. (43)
2- Axis

After weight-bearing, the cardinal function of the atlanto-axial junction is to permit a large range of axial rotation. The articular cartilages both of the atlantial and the axial facets of the joint are convex, rendering the joint biconvex. (44)

The spaces formed anteriorly and posteriorly, where the articular surfaces diverge, are lined by intra-articular meniscoids. (45)

In the neutral position the summit of the atlantial convexity rests on the convexity of the axial facet. As the atlas rotates, however, the ipsilateral atlantial facet slides down the posterior slope of its axial fact, and the contralateral atlantial facet slides down the anterior slope of its facet. As a result, during axial rotation the atlas descends, or nestles into the axis. Upon reversing the rotation the atlas rises back onto the summits of the facets. (Figure 3.2).

The mechanism of paradoxical movements of the atlas, the atlas acts as a passive washer, interposed between the head and the cervical spine proper. Its movements are essentially passive and governed essentially by the muscles that act on the head. Accordingly, rotation of the atlas is brought about by splenius capitis and sternocleidomastoid acting on the head. Torque is then transferred from the head, though the atlanto-occipital joints, to the atlas. The passive movements of the atlas are most evident in flexion/extension of the neck where, indeed, the atlas exhibits
paradoxical motion. At full flexion of the neck, the atlas can extend, and usually does so. (46) (Figure 3.3).

**Figure (3.2):** showing Atlanto-axial rotation. A: top view. The anterior arch of the atlas (shaded) glides around the odontoid process. B: right lateral view. The lateral mass of the atlas subluxates forwards across the superior articular process of the axis. (43)

This arises because the atlas, sandwiched between the head and axis, and balanced precariously on the summits of the lateral atlanto-axial facets, is subject to compression loads. If the net compression passes anterior to the contact point in the lateral atlanto-axial joint, the lateral mass of the atlas will be squeezed into flexion. Conversely, if the line of compression passes behind the contact point, the atlas will extend; even if the rest of the cervical spine flexes. If, during flexion, the chin is tucked backwards, paradoxical extension of the atlas is virtually assured, because retraction of the chin favours the line of weight-bearing
of the skull to fall behind the centre of the lateral atlanto-axial joints. (46) (Figure 3.4).
Figure (3.3): showing a lateral view of a right lateral atlanto-axial joint (central figure) showing the biconcave structure of the articular cartilages. Upon forward or backward displacement, the lateral mass of the atlas settles as it slips down the slope of the cartilage. (43)
3- the root:

The C2-3 junction is regarded as the beginning of the typical cervical spine. the C2-3 junction differs from other segments in a subtle way. Unlike the typical facet joints whose planes are transverse, the superior articular processes of C3 face not only upwards and backwards but also medially, by about 40°. (Figure 3.5) Morphological and biomechanical properties of the vertebro-axial joint (C2-C3) results into a difference in the motion during axial rotation of the neck, the direction of coupling with lateral flexion at C2-3 is opposite to that seen at lower segments. Instead of bending towards the same side as rotation, C2 rotates away from that side. (43)

Figure (3.4): showing the mechanism of paradoxical movements of the atlas. In the neutral position (central figure) the atlas is balanced on the convexities of its articular cartilages. If the atlas is compressed anterior to the balance point, it flexes. If compressed behind the balance point, it extends. (43)
**Figure (3.5):** showing a tracing of a pillar view of the upper cervical spine, showing the unique morphology of C2 (shaded). A pillar view is a radiographic projection of the cervical spine obtained by directing the beams upwards and forwards from behind the cervical spine, essentially along the planes of the lower cervical facet joints.

The facet joints at lower levels (arrowed) are orientated transversely, whereas at C2-3 they are inclined medially. (43)

4-the column (typical cervical vertebrae)

The vertebral bodies are stacked on one another, separated by intervertebral discs. The opposing surfaces of the vertebral bodies are not flat as they are in the lumbar spine, but, they are gently curved in the sagittal plane. The anterior inferior border of each vertebral body forms a lip that hangs downwards towards the anterior superior edge of the vertebra below. (46)

The superior surface of each vertebral body slopes greatly downwards and forwards. As a result, the plane of the intervertebral disc is set not perpendicular but somewhat oblique to the long axes of the vertebral bodies. This structure indicates that flexion-extension are the cardinal movements of typical cervical segments. The vertebral bodies are also curved from side to side. This curvature is only apparent if sections are taken through the posterior ends of the vertebral
bodies, either parallel to the planes of the facet joints, or perpendicular to these planes. The appearance is that of a saddle joint suggesting that rocking could occur between the typical cervical vertebral bodies. (47)

This description appears to be agreeable with traditional ideas that typical cervical segments exhibit flexion/extension, lateral flexion, and axial rotation; but it is not. Rather it allows flexion/extension but stipulates that the only other pure movement is rotation around an axis perpendicular to the facets. Since the facets are orientated at about 45° to the transverse plane of the vertebrae. (47)

Horizontal rotation is coupled with lateral flexion and vice-versa. If horizontal rotation is attempted, the inferior articular process must ride up this slope. As a result, the vertebra must tilt to the side of rotation. Downward movement of the ipsilateral inferior articular process is arrested by the upward facing superior articular process; but is permitted if the inferior process slides backwards down the slope of the superior process. As a result, the vertebrae must rotate to the side of lateral flexion.

3-Normal biomechanics of the intervertebral disc:
The cervical intervertebral discs are not like lumbar discs; they lack a concentric anulus fibrosis around their entire perimeter. (48)

The cervical anulus is well developed and thick anteriorly; but it tapers laterally and posteriorly towards the anterior edge of the uncinate process on each side. This structure arises in adults through the development of transverse fissures across the back the cervical discs. The fissures commence, at about the age of nine years, as clefts in the uncovertebral region. Progressively, they extend medially across the disc, ultimately to form transverse clefts by the third decade. This allows, or facilitates, axial rotation. (49)

The disc main function in the spine is to maintain flexibility and motion. Along with the facet joints, it is responsible for carrying all different types of tensile, compressive and shear stresses. The nucleus carries the compressive loads and the annulus the tensile stresses. This changes with degeneration as the hydration of the disc is less and the tensile stresses in the collagen fibers of the inner annulus become compressive stresses. (50)

The biomechanical behavior of the intervertebral disc is time-dependent. The intradiscal pressure is determined by the recent disc loading not only the current load alone. The prolonged dynamic loading causes a decrease in the intradiscal pressure and disc height, and an increase in the compressive stiffness. (51)
4- Biomechanics of Disc Degeneration

The nucleus pulposus in the early life or in slightly degenerated discs acts like a gelatinous mass. A compressive load decreases disc height due to a decrease in the volume of gelatinous mass. This also increases the hydrostatic pressure which leads to a bulging of outer annulus. During the day, the compressive load reduces the disc height mainly because of water being squeezed out of the disc, and in part due to the creep of the viscoelastic annulus collagen fibers. (52)

Both effects are reversible in healthy discs like unloading of the spine during a night’s bed rest. (53)

Disc degeneration alters the structure and function. The risk of prolapse is highest in the posterior and posterolateral annulus, especially in normal and mildly degenerated discs, while moderate or strongly degenerated discs have a lower risk for a prolapse. (54)
Some factors affecting the disc degeneration:

1. Prolonged sitting results in sustained axial compressive loading which may alter the viscoelastic properties of the disc and vertebra. (55)

b- The resonant frequency can increase the load on the the intervertebral disc. The resonant frequency can occur during driving and postures that are common in occupational workplace. (56)

2. Muscle dysfunction destabilizes the spine by reducing the role of facet joints in transmitting load and shifting loads to the discs and ligaments. (57)

3. Disc degeneration may cause increased tension and shearing forces at the adjacent normal discs. Thus, disc degeneratin alters the facet joint motion at the degenerated and adjacent levels leading to further adjacent level degeneration. (58)

Panjabi et al. found that any damage to disc alters the biomechanics of facet joints by disproportionately sharing the facet loads. (59) The stress distribution in the intervertebral disc uniform, isotropic for normal disc; nonuniform and anisotropic for the degenerated disc. (60)
Chapter 4

Cervical disc arthroplasty

Background:

The anterior cervical discectomy and fusion (ACDF) is a well established procedure associated with a high degree of patient satisfaction and excellent outcomes. Adverse effects can occur such as pseudarthrosis, severe dysphagia, or heterotopic ossification. (61)

Furthermore, adjacent segment degeneration after successful ACDF has been widely reported in both cephalad and caudad motion segments. (62)
Cervical disc arthroplasty (CDA) offers a biomechanical advantage over anterior cervical discectomy and fusion (ACDF) in preserving motion at the disc space after an adequate decompression. In theory, by retaining physiologic motion at the disc space and posterior elements, adjacent level disease can be prevented. In addition, cervical disc arthroplasty may allow an earlier return to function and/or work by eliminating the need for postoperative bracing or restrictions. (61)

Goffin et al prospectively followed a series of ACDF patients who underwent the procedure for either a degenerative or traumatic condition. Follow-up was for five to nine years. Sixty percent of the patients developed ASD, equally distributed between the older degenerative population and the younger traumatic population, providing evidence that fusion may accelerate degenerative changes. They also reviewed a larger series of ACDF patients followed for an average of 8 years. In this group, 90% of the patients developed ASD, though they had a much lower rate of additional surgical procedures. (63)

**Rationale of cervical disc arthroplasty studying:**

Although motion-sparing procedures have led to great improvements in the treatment of degenerative joint disease in the hip, knee, and shoulder, such technology would only warrant use in the cervical spine if superiority over fusion was proven.
Cervical disc prostheses are unable to replace the healthy, physiologic properties of a hydrated disc completely; however, studies have demonstrated their ability to absorb vibrational and impact loads. Dahl et al tested dynamic response and compared biomechanical properties of the intact cervical spine specimens and those treated with either the Bryan disc or fusion. Fusion segments were found to increase disc pressures at the adjacent segments significantly during loading compared with the intact spine and with implanted constructs. The authors suggested that the energy absorbed at the treated prosthesis level was dissipated through the implant devices rather than absorbed by deformation. (64)

Artificial cervical disc devices maintain sagittal motion, translation, and coupled motion in lateral bending compared with preoperative or intact states. (65)

Dmitriev et al used cadaveric cervical specimens to compare intradiscal pressures at adjacent segments after arthroplasty, allograft dowel, or allograft dowel and anterior instrumentation. They demonstrated a 50% increase in intradiscal pressure with fusion compared with intact specimens, an effect mitigated by arthroplasty. (66)

**Design considerations of cervical disc arthroplasty:**
The concepts of arthroplasty design remain similar regardless of the joint treated: provide a safe, stable, durable, and biomechanically efficient artificial joint to replace degenerative cartilage that can serve as pain generators. However, unlike appendicular arthroplasty, cervical disc arthroplasty presents a number of unique considerations. First, bone stock in the cervical spine is limited, allowing less flexibility when making bony cuts to accommodate implant prosthesis. Second, in contrast to the knee and hip joints, the intervertebral disc contributes substantially to spinal stability by restoring balance to the anterior and middle columns. Finally, although the patient population for cervical disc arthroplasty is typically younger, the transferrable loads are much lower compared with those in the lower extremity.

With a longer expected lifespan (between 30 and 50 years), an estimated total of 100 million flexion cycles can be expected throughout the lifetime of such an implant. The proximity of the spinal cord and critical anterior neck structures makes an inflammatory reaction secondary to wear debris in cervical disc arthroplasty potentially more life-threatening.

Current devices available are unconstrained in the physiologic range (neutral zone); they provide little or no restraint to motion. During extremes of motion, implant devices experience edge contact, which can lead to abnormal wear. However, each implant is different in the degree of coupled angulation and translation it allows.
Two basic designs are available: variable axis and single axis of motion.

a-The variable axis devices allow coupled translation with rotation in all planes during motion. Examples to accomplish this are a mobile bearing and a ball-and-trough design, used in the Prestige ST Cervical Disc System.

b-The single-axis prostheses, ball-and-socket designs, do not allow translation. These devices provide greater inherent stability by resisting excessive motion and preventing translation during rotation. However, these implants fix the center of rotation throughout the motion cycle, which can lead to impact loading and higher wear rates, and impart undue stress on the adjacent levels.

The clinical and long-term implications of the different designs are currently unknown. (1)

The critical biomaterial considerations include durability, incidence of fatigue/fracture, and wear characteristics. In addition, biomechanical properties such as stiffness, biocompatibility, and resistance to corrosion must be accounted for.
Unique to the cervical spine, the use of different metals must be compatible with MRI to allow for follow-up evaluation of the neural elements. Stainless steel is the most inexpensive and widely available material but has disadvantages compared to that of titanium and chromium. For example, steel has greater ductility but less biocompatibility. (1)

Imaging artifacts with both CT and MRI make long-term evaluation difficult. (67)

Common types of cervical disc arthroplasty:

Currently, 6 cervical total disc replacement devices have been approved by the FDA for single-level anterior cervical disc procedures: Prestige ST (Medtronic), ProDisc-C (Synthes), Bryan (Medtronic), Kineflex-C (Spinal Motion), Mobi-C (LDR Spine), and Secure-C Artificial Cervical Disc (Globus Medical). (1)

1. Prestige

Prestige I, the initial ball and socket design which was entirely fabricated from stainless steel, was converted to a ball and trough design, allowing limited translation. The anterior flanges were diminished in size and a locking screw added to prevent bone screw backout.
Prestige II was further modified by again reducing the anterior flange and modifying the endplates to allow bone ingrowth.

Prestige ST was the design evaluated in the United States as part of the Food and Drug Administration (FDA) investigational device evaluational (IDE) study. This arthroplasty incorporates the features of Prestige II with further shortened anterior flanges.

The final design is Prestige LP, a major change from its predecessors. Instead of stainless steel, the Prestige LP is made from a titanium ceramic composite, preserving the ball and trough bearing design. It has a titanium plasma spray on the endplates for bone ingrowth. The flange and locking bone screws have been removed. The Prestige LP, being made of titanium, has a better compatibility than stainless steel in MRI imaging. (Figure 4.1)
2. **Bryan Cervical Disc Prosthesis**

Bryan Cervical Disc Prosthesis (Medtronic) consists of a nucleus made of polyurethane between two titanium alloy endplates in a clamshell configuration.
There are two bearing surfaces in the arthroplasty at the interfaces between the nucleus and the endplates. A polyurethane sheath attaches to the endplates and surrounds the nucleus. Sterile saline is injected between the outer sheath and the nucleus as lubricant. (Figure 4.2).

The endplates have a titanium porous coating for bone ingrowth and a small flange anteriorly to prevent posterior migration.
Thus, the Bryan cervical disc is a biarticulating device consisting of a polyurethane nucleus and sheath surrounded by 2 titanium alloy shells. Polyurethane is a softer bearing surface than polyethylene, which theoretically leads to inferior wear characteristics; however, investigation of wear rates reveals that wear particles produced do not provoke inflammatory reaction. In addition, polyurethane has been shown to significantly lower stiffness, with greater energy absorption and damping characteristics than polyethylene and titanium materials, suggesting polyurethane may provide shock absorption similar to physiologic disc anatomy. (68)

3. **ProDisc-C**

ProDisc-C Cervical Disc Prosthesis (Synthes) has a ball and socket design, with endplates made of a cobalt-chrome alloy. The bearing surface has an articulating dome of ultra high molecular weight polyethylene (UHMWPE) attached to the inferior endplate and a concave polished socket integral to the superior endplate. It has a plasma sprayed titanium for biological fixation. (1)
Figure (4.3): showing a ProDisc-C Cervical Disc. (1)
The ProDisc-C prosthesis contains 2 cobalt–chromium alloy components with a polyethylene insert (Figure 4.3). Titanium alloys, characterized by a Young’s modulus most similar to bone, have been identified as biocompatible, inert materials that are used on design surfaces in porous coatings to promote ingrowth of bone. (63)

Titanium oxidizes to form Titanum oxide on the surface, thereby offering excellent resistance to corrosion. Titanium alloy also demonstrates the advantage of reduced imaging artifact on MRI compared with other metals. (69) (Figure 4.3)

4. **Porous-Coated Motion (PCM) Cervical Arthroplasty**

The Porous-Coated Motion (PCM) Cervical Arthroplasty (Cervitech, Rockaway, New Jersey) consists of two cobalt-chrome-molybdenum (CoCrMo) endplates that have a titanium calcium phosphate porous coated backing for bone ingrowth.

The device is inserted by a press-fit method, but the endplates have transverse serrated rows of teeth that resist migration.

The bearing surface is an ultra high molecular weight polyethylene (UHMWPE) convex insert of large radius of curvature attached to the inferior endplate which articulates with the polished concave surface of the superior endplate. (Figure 4.4)
Figure (4.4): showing Porous Coated Motion (PCM) Cervical Arthroplasty (1)

New designs:

Newer cushion designs have a prosthetic annulus with a deformable prosthetic nucleus. The aim of this design is to reduce translation of moving parts, reducing particulate wear particles, and capturing wear particles within the prosthetic annulus in an attempt to avoid secondary osteolysis. (70)
INDICATIONS

The current FDA-approved indication for cervical disc replacement is single-level cervical degenerative disc disease causing radiculopathy and/or myelopathy in adult patients. (71)

Additional indications include radiculopathy caused by disc herniation (soft or hard) or foraminal osteophytes, myelopathy because of a soft disc herniation, and failure of conservative management of a single-level spondylosis meeting the appropriate criteria. The use of a motion-sparing implant in patients with congenital spinal canal stenosis has been reported to lead to recurrent myelopathy. (72)

Riew et al demonstrated that in patients with single-level cervical disease causing myelopathy, similar clinical outcomes were achieved after treatment, compared with those with radiculopathy. (73)

Thus, for cervical myelopathy not caused by retrovertebral compression such as ligamentum flavum hypertrophy, ossification of the posterior longitudinal ligament, or congenital stenosis, a total disc prosthesis accompanied with a meticulous decompression is a reasonable treatment alternative.
Other reported uses for CDA include multilevel disease, treatment at adjacent segments to fusion or ankylosis, and discogenic neck pain. However, currently, these indications are off-label in the United States and should be considered experimental. (1)

**Contraindications to cervical disc replacement**

These include instability (greater than 3.5 mm of translation or more than 11 degrees of kyphosis), severe disc degeneration (more than 50% loss of disc height), severe osteoporosis, history of infection in the cervical spine, severe facet arthrosis, ankylosis, allergy to components of the prosthesis, and congenital spinal stenosis. (64)

In addition, because the presence of functional or intact posterior elements is essential to stability with a cervical disc prosthesis, prior laminectomy or excessive removal of the facet joints is a contraindication.

Relative contraindications include rheumatoid arthritis, renal failure, cancer, and preoperative corticosteroids. (74)

**Future of cervical disc arthroplasty**
The release of the ideal cervical disc arthroplasty is yet to come. Complications of present disc arthroplasty devices continue to challenge device makers to create a disc that recreates the native cervical motion, treats the index level disease, and yet will last the lifetime of the recipient. (75)

Chapter 5

Biomechanical changes following cervical disc replacement:

Background:
It is essential to evaluate the clinical outcomes in terms of an artificial disc’s ability to provide normal kinematics following cervical total disc replacements. Several parameters like center of rotation, range of motion, stiffness and hysteresis are used to assess the quality and the quantity of motion in a spinal segment.

The clinical experience of more than 50 years in the area of lower extremity joint replacements suggests that the long-term success of any total arthroplasty system is a function of three primary factors:

1. implant design parameters (geometry, material, kinetics, ROM in all 6 degrees of freedom)
2. patient related parameters (weight, kinematics, age)
3. surgeon related factors such as surgical procedures. (76)

Effects of implant related parameters:

A-The design:
Faizan et al. simulated three distinct philosophies of designs in the finite element model. These were as follows:

1. Ball and Socket (BS) design: The design consisted of two metallic components (superior ball and inferior socket) and placed such that the BS articulation was towards the posterior region of the disc space.

2. Sandwich design (SND): The sandwich design possessed three components where the core polyethylene ball was sandwiched between the superior and inferior metallic components. The size of the ball component was larger in the sandwich design when compared to the BS design.

3. Elastomer design with ALL replacement (ELST): This is a single piece type artificial disc design (Abbott Spine, Houston, TX). The disc implant replaces the intervertebral disc and the anterior longitudinal ligament (ALL). (77) (Figure 5.1)

The load-displacement characteristics of the flap are very close to cervical anterior longitudinal ligament in the elastomer design. The sandwich design and the elastomeric design produced motions higher than intact (55 and 15% greater than intact, respectively). The total facet loads at the C4–C5 level during extension were similar for BS and elastomeric designs. The facet load for sandwich design was lower than intact. Among the three disc designs, the facet loads with the elastomeric design were closer to the intact facet loads. Overall,
the elastomeric disc reproduced intact segment behavior better than the other two designs. (76)

**Figure (5.1):** showing the simulated three distinct philosophies of cervical disc replacement designs. BS is the ball and socket design. SND is the sandwich design. ELST is the elastomer design. (76)

B-Sagittal balance following TDR:

In Johnson et al study, there was a 4.5 degree mean reduction in lordosis for those who underwent single level disc replacement. (78)

It was found that only about 35% of patients are able to maintain lordosis immediately following Bryan artificial disc surgery. The overall sagittal alignment
of the cervical spine was preserved in 85% of cases at the final follow up. Preoperatively kyphotic functional spinal unit results in lordotic functional spinal unit in 15% of patients during the late follow up, and preoperatively kyphotic overall cervical alignment results in lordosis in 35% of the patients postoperatively. (79)

Disc replacement can alter the spine alignment. In particular, resection of the anterior longitudinal ligament and the anterior portion of the annulus fibrosus, combined to an increase of the intervertebral space height, induces an alteration of the segmental lordosis regardless of the mechanics of the prosthesis itself. (80)

Thus, spinal alignment after TDA is related to the surgical technique and the design of the specific prosthesis. The use of the Bryan prosthesis can result in a kyphotic orientation of the implanted level, probably due to its lack of structural lordosis in the resting position and other surgical variables as the loss of intervertebral space and the angle of insertion while the total cervical lordosis is generally preserved. Disc prostheses consisting of components with articulating surfaces, both semi-constrained and unconstrained, may allow the preservation of the lordotic curve, or even restoration in the case of a preoperative incorrect spinal alignment. (81)

C-Range of motion after cervical TDR: (quality and quantity)
The most studied parameter of spinal kinematics after TDA is the range of motion (ROM), that is the rotation from one extreme to the other of the physiological range of rotation of a specific motion. In vitro and in vivo motion studies suggest that the range of motion of the cervical spine differs with level, gender, degree of degeneration and subject. (82)

These facts lead to the rise of several questions: Should the TDR be gender, level and subject specific? Should we restore the motion (quantity and quality) to a normal person or to the adjacent degenerated level motion of that patient? Coupling, an association of translation/rotation in one plane with the translation/rotation in the other plane, is another motion parameter of importance. These questions remain as a challenge to the cervical disc arthroplasty up till now. (83)

The cervical spine exhibits a significant degree of coupled motion. Should TDR restore coupled motion behavior? To examine this aspect, Puttlitz et al conducted an in vitro study using ProDisc-C (Synthes). There were no significant differences in coupling between the intact and implanted conditions. (84)

There is a general motion preservation at the implanted level, with range of motion nearly similar to the physiological values, regardless of the specific prosthesis design. Thus, prosthesis design appears to be more strongly related to the quality of motion, e.g. the site of the axes of rotation, than to the quantity.
Some authors investigated the motion compensation at the adjacent levels, which was found to be very limited, thus resulting in a preservation of the physiological motion.

Chang et al. observed an increase in the range of motion at the treated segments after implantation of both the semi-constrained ProDisc-C and the unconstrained Prestige. (85)

On the contrary, Nabhan et al. described a reduction of the range of motion at the implanted segment after cervical disc arthroplasty in radiographic studies. (86)

Thus there is some controversy in the literature regarding the motion at the implanted level.

Some cases of heterotopic ossification have been reported in the literature after implantation of both semi-constrained and unconstrained disc prostheses. This is probably due to the altered mobility and stress distribution induced by the disc arthroplasty, this leads to a total loss of mobility of the implanted segment at a later time. (87)
D- Protection of the biological structures

Although the most investigated issue on disc prosthesis biomechanics is motion preservation, the study of loads and stresses acting on the anatomical structures is gaining increasing attention as these stresses may be a direct cause of early degeneration. (86)

McAfee et al described some extent of spine destabilization with the surgery itself due to resection of the anterior longitudinal ligament and a part of the annulus, this leads to an increase of loads through the facet joints and a decrease in the stresses in the adjacent discs. (89)

Wigfield et al. observed a reduction of the peak stresses in the annulus adjacent to a Bristol disc (an unconstrained ball-and-socket disc prosthesis), measuring the stress profile by means of a pressure transducer in physiological flexion and extension. In that study, stresses were found to be larger for discs adjacent to a plated fusion. However, the authors remarked a strong dependency of the results on the testing conditions and loading protocol, thus a definitive conclusion could not be reached. (90)
Chang et al. found that facet joint forces at the implanted level increased in extension, while no significant changes were recorded in flexion, lateral bending and rotation. (85)

Rousseau et al. compared different configurations of ball and socket constrained disc prostheses by using finite element models. Facet joint stresses were found to be lower for larger, more posterior spherical surfaces. (91)

Based on the currently published studies, a global conclusion cannot be drawn yet; the relationship between the prosthesis design and load sharing patterns is still unclear. A more constrained design may be able to preserve the surrounding biological structures, but a quantitative analysis of this topic is not available yet. (92)

E- Device stability and wear:

With reference to the interface between the disc prosthesis and the surrounding biological system, two topics are primarily discussed in the literature: the osseointegration at the bone–implant surface and the biological response to the possible formation of wear. (92)

A more constrained design may lead to increased loads acting on the disc prosthesis, promoting wear but the dependence of osseointegration and wear
properties on the prosthesis design and kinematics have not been investigated well enough. (92)
Chapter 6

Cervical disc arthroplasty vs anterior cervical discetomy and fusion

Introduction:
Anterior cervical discectomy and fusion (ACDF) has long been the standard surgical treatment for symptomatic cervical disc herniation and spondylosis with radiculopathy or myelopathy. While this procedure is effective at relieving neural compression and providing symptom relief, there is a reported incidence of clinically significant adjacent level degeneration of about 4% per year. Cervical disc replacement (CDR) has been developed as a motion-preserving alternative to fusion, with the hope that retained motion at the operative level may reduce the adjacent level degeneration. (70)

A literature review for comparison between cervical disc arthroplasty and arthrodesis:

A-Biomechanical parameters:

1-Range of motion

In the Arthroplasty:(at the operated level)

Two important definitions are to be mentioned

- angular lax zone (LZ): portion of ROM in which ligaments and hardware are lax
- stiff zone (SZ): portion of ROM in which ligaments and hardware are under tension.

Sagittal plane motion at operated level:
The angular ROM after arthroplasty matched the intact values well at the index level. Similarly, the angular LZ and SZ also matched intact values well at the index level. These findings suggest that the physiological quantity of sagittal cervical motion as defined by the intact spine is well maintained by the arthroplasty device. (93)

Coronal plane motion (lateral bending) at the operated level:

The angular ROM was reduced to 71% of the normal after arthroplasty. Despite this reduction in ROM, the stiff zone component of the ROM actually increased to 142% of intact. The lax zone component of the ROM decreased to 50% of intact. So it overcame the increase in the stiff zone component to lead to the net decrease in ROM. This behavior indicates that after arthroplasty, the earliest resistance to coronal plane motion was met closer to upright than it had been met in the intact condition. However, as motion proceeded, the resistance to further motion was more gradual than it had been in the intact condition. If this behavior persisted postoperatively, it could be a beneficial property clinically if additional lateral bending stability is needed at the index level. (93)

Transverse plane motion (axial rotation) at the operated level:
The angular ROM after arthroplasty matched the intact ROM well. However, although there was no change in the ROM, the stiff zone component of the ROM increased to 173% of intact. The lax zone component of the ROM decreased to 67% of intact overcoming the increase in the SZ component, leading to no net change in ROM. As with lateral bending, this behavior indicates that after arthroplasty, the earliest resistance to transverse plane motion was met closer to neutral. However, as motion proceeded, the resistance to further motion was more gradual than it had been in the intact condition. This biomechanical behavior could be potentially beneficial clinically because the operated level would have greater stability in the lax region near neutral rotation, meaning that the adjacent levels would preferentially move first during low-impact activities. (93)

DiAngelo et al. studied in cadaveric specimens using applied loads mimicking physiological load patterns. They found insignificant increases in ROM during flexion, lateral bending, and axial rotation and a significant decrease in ROM during extension. (94)

Puttlitz et al. observed that disc replacement increased ROM to 149% of intact during flexion-extension, decreased ROM to 60% of intact during lateral bending, and decreased ROM to 70% of intact during axial rotation. (95)

Chang et al. studied changes in ROM in the cervical spine after insertion of ball-and-socket arthroplasty and after anterior plating. They found significant increases
in ROM at the operated level during flexion and extension after ball-and-socket arthroplasty and insignificant increases in ROM during lateral bending and axial rotation. (85)

*In the arthrodesis:* (the range of motion)

As expected, plating reduced ROM and LZ in all directions of loading relative to intact and arthroplasty by significant amounts in almost all comparisons. After fusion occurred in actual patients, the elastic response would become stiffer. (93)

Zhong et al. Concluded that cervical fusion extensively constrained the motion of the operative segment as reflected by about 90% reduction in ROM during all kinematic motions of the spine. (96)

Chang et al. studied changes in ROM in the cervical spine after insertion of ball-and-socket arthroplasty and after anterior plating. They found that plating caused decreased ROM, as expected. (85)

*Angular coupling*

It is known that, in the human cervical spine, there is normally a pattern of strong coupling between lateral bending and axial rotation such that coupled lateral
bending occurs simultaneously during axial rotation and, similarly, coupled axial rotation occurs simultaneously during lateral bending. (97)

It was found in this experiment that the pattern of coupled axial rotation occurring during lateral bending was maintained fairly close to intact, whereas this pattern was altered after plating. (93)

However, the coupling pattern of lateral bending occurring during axial rotation was lost both after arthroplasty and after plating. It is unclear from the design of the device why arthroplasty-implanted spines would match intact kinematics better during lateral bending than during axial rotation. It is also interesting that the opposite was true regarding ROM: arthroplasty-implanted spines matched intact ROM better during axial rotation than during lateral bending. (97)

Puttlitz et al. also measured the coupling pattern with and without cervical disc arthroplasty. They measured coupled lateral bending occurring during primary axial rotation, as well as the coupled axial rotation occurring during primary lateral bending. Although they found no significant differences between intact and disc-replaced conditions with regard to the amount of coupling present, they showed that arthroplasty maintained closer agreement with the intact condition in the case of coupled axial rotation during lateral bending than in the case of coupled lateral bending during axial rotation. (95)
Axis of rotation

It was found that although arthroplasty did not affect the anteroposterior position of the axis of rotation during flexion-extension it shifted the rostrocaudal position of the axis of rotation slightly but significantly rostrally. Anteroposterior position of the axis of rotation is highly dependent on depth of insertion of the device, and the agreement between arthroplasty-inserted and intact this indicates that the motion segment angulated slightly more sharply after arthroplasty than it had done normally.

The single-level arthrodesis treatment produced much more diffuse centers of rotation, with centrodes of motion moving posteriorly and inferiorly compared with the intact condition, particularly at the operative and inferior adjacent levels. (98)

Facet loads

On the basis of the limited data available in the literature covering this topic, neither arthroplasty nor anterior plating seemed to affect load distribution through the facets compared with intact during pure moment loading. The significantly decreased facet loads seen with the implants in place (both after arthroplasty and after anterior plating) compared with intact indicates a shift in the distribution of axial compressive loads along the spine leading to load axis acting more anteriorly.
It is unknown what the clinical consequences of this shift in load transfer would be. More data are still necessary before further conclusions can be drawn.

Adjacent segment biomechanics:

Bryan et al. found that after two-level arthrodesis, the distal adjacent level demonstrated increased ROM compared with the intact condition. These kinematic findings may suggest a biomechanical cause of adjacent-level degeneration secondary to cervical arthrodesis. (98)

After cervical arthrodesis, there is a restriction of the motion at the operated level as discussed before. This restricted motion was compensated by the adjacent motion segment, with up to 30% increase of ROM. The compensatory increase of ROM caused more than 10% increase of intradiscal pressure at the adjacent segments. Thus, this may be a contributor to the adjacent level disease development with the cervical fusion. (96)

Unlike the fusion condition, in the cervical arthroplasty the hyper-mobility of the operative site is reversely compensated by a reduced range of motion at the adjacent site. The reduction is about one-fifth in all direction at the inferior segment, while the superior segment had a reduction ranging from 10 to 35%. The intradiscal pressure is also reduced in the adjacent discs. Thus this reduction in
both the range of motion and the intradiscal pressure may represent an alleviation to adjacent segments. (96)

The reduction of the range of motion and the intradiscal pressure in the adjacent segments associated with the cervical disc arthroplasty should reduce the incidence of adjacent-segment disease. This is yet to be demonstrated in future studies. (85)

B-surgical parameters:

-Operative Time:

Information on the operative time was provided in nine studies, and three of these studies with a total of 575 patients (310 in the arthroplasty group and 265 in the anterior cervical discectomy and fusion group) were eligible for meta-analysis. The operative time was significantly longer in the arthroplasty group. (99)

-Blood Loss:

Information on total blood loss was provided in nine studies, and three of these studies with a total of 575 patients (310 in the arthroplasty group and 265 in the anterior cervical discectomy and fusion group) were meta-analyzed. Blood loss was significantly greater in the arthroplasty group. (99)
-Length of Hospital Stay:

Information on the length of the hospital stay was provided in six studies, and three of these studies with a total of 575 patients (310 in the arthroplasty group and 265 in the anterior cervical discectomy and fusion group) were meta-analyzed. The length of the hospital stay did not differ significantly between the two groups. (99)
Conclusion

Based on the current literature review, cervical disc arthroplasty is generally able to preserve a nearly physiological motion in the cervical spine apart from several alterations in the cervical biomechanics. Most authors reported that the range of motion is nearly similar to the physiological values. Some non-biomechanical problems as wearing and heterotopic ossification have been reported in a significant number of patients. Device stability seems not to be an actual problem,
for any of the currently available disc prostheses. No critical differences between semi-constrained and unconstrained devices in terms of biomechanical effects have been observed so far.

In appropriately indicated patients, the cervical disc arthroplasty appears to be at least as good as anterior cervical discectomy and fusion (the current gold standard surgical treatment for one to two level cervical disc disease with radiculopathy). The improved segmental range of motion, lower re-operation rates and lower rate of radiological adjacent segment disease favor the disc arthroplasty over ACDF. Making the disc arthroplasty an attractive alternative to ACDF in many patients.

Yet, more prolonged studies aiming at the reveal of the long term outcomes of the cervical disc arthroplasty are still needed to fully understand the complexity of this entity.

Boselie et al. provided a systematic review published in the Cochrane Database of Systematic Reviews. They concluded that, while the use of CDR should be restricted to clinical trial settings, there was a tendency for results to be in favour of CDR. They also noted ‘high quality evidence that the goal of preservation of segmental mobility in arthroplasty was met. (100)
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الميكانيكا الحيوية لاستبدال القرص الفقري العنقي

توطنة للحصول على درجة الماجستير في جراحة العظام

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الملخص العربي

يعتبر القرص الفقري مكون رئيسي للعمود الفقري كي يتحمل الاحمال. وقد وجد أن التحويل الميكانيكي على القرص الفقري أحد الأسباب الرئيسية للتفاف الذي يصيبه. وقد وجد أن نظام العلاج للمرضى المزمنين، يتراوح بين العلاج الحفظي إلى العمليات الجراحية، التي تشمل التثبيت بين الفقرات باستخدام أو بدون استخدام أجهزة.

وقد ثبت نجاح هذا التثبيت في الحد من حركة الفقرات. وبالرغم من ذلك، لا تزال مشكلة الاحساس بالألم تواجه غالبية المرضى بعد إجراء جراحات تثبيت الفقرات. وقد لوحظ أن جراحات تثبيت الفقرات قد تؤدي أيضا إلى تلف في الفقرات المتناهمة.

وقد تسبب هذه العيوب في تفكير الباحثون في وضع حلول بديلة مثل التقويم الإجمالي للقرص المفصل على طريق الاستبدال الكلي للقرص الفقري باستخدام قرص اصطناعي الذي من المتوقع أن يحافظ على الحركة ويخفف الألم.
ولذلك، أصبح من الضروري تقييم النتائج السريرية من حيث القدرة على الحركة العادية بعد الاستبدال الكلي للقرص الفقاري بالقرص الاصطناعي.

ولقد أوضحت التجارب السريرية على مدار 50 عاماً في مجال استبدال مفاصل الأطراف السفلي من الجسم أن نجاح التقويم المصلي على المدى الطويل يتوقف على ثلاث عوامل رئيسية: وهي عوامل ترتبط بتصميم البارامترات المنزرعة (الهندسية والمادية وحركية، في درجات حرية)، عوامل ذات صلة بالمريض المعلمات (الوزن، الكينماتيكي، العمر) و عوامل أخرى ذات صلة بالجراح مثل الإجراءات الجراحية. و لذلك أنه من الممكن أن تتوقع على المدى الطويل تأثير مشابه لهذا النجاح لعمليات الاستبدال الكلي للقرص الفقاري بالقرص الاصطناعي.