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Chapter

Cervical Arthroplasty

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Abstract

Technological advances have allowed spine surgery to follow the trend toward minimally invasive surgery in general. Specifically, we have seen a corresponding rise in the popularity of cervical arthroplasty. For the treatment of cervical disc disease, arthroplasty is a less invasive option than the gold standard of cervical discectomy and arthrodesis, which by nature is more disruptive to surrounding tissues. Arthroplasty preserves the facets, maintains motion, and reduces the rate of adjacent segment breakdown. These factors counteract the negative impacts of fusion while maintaining the benefits. Arthroplasty implants themselves have become more streamlined to implant as well with less native bone destruction, and biomechanics more compatible with the native disc. While initial implants were ball and socket devices with complex fixation and plane-specific movements, later devices incorporated such motions as translation and compression. Viscoelastic components and materials more closely resembling native tissues afford a more biocompatible implant profile. Until cell-based therapies can successfully reproduce native tissue, we will rely on artificial components that closely resemble and assimilate them.

Keywords: cervical disc replacement, arthroplasty, cervical fusion, artificial disc, implants

1. Introduction

In the trend toward minimally invasive surgery, operations for the cervical spine have followed a similar tendency. While microsurgery has been in the lexicon of neurosurgery for ages, one of the earliest uses of the term “minimally invasive” in spine surgery was used by Probst in 1989 to discuss lumbar microdiscectomy [1]. While the term “minimally invasive” has become somewhat of a generic moniker for many different approaches, its intent is to be less traumatic to the patient with lower complication rates.

In the cervical spine, midline sparing posterior procedures such as lateral [2] and far later posterior approaches have afforded the opportunity to use smaller incisions and even endoscopic [3] approaches. Anterior foraminotomy, a disc preserving approach, has also been proposed [4] with favorable results [5]. However, these approaches have given limited access to midline pathologies and offer little benefit for cases with central herniation or instability.

Anterior discectomy alone allows central pathology to be addressed with reasonable success but high reoperation rates [6]. The addition of fusion stabilizes the spine in addition to maintaining distraction and neural foramen patency. Interbody grafts were instrumental in providing this indirect decompression and additional stability. Fusion halts further disc degeneration, preserves sagittal
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balance, and eliminates segmental instability. Cervical fusion surgery, particularly anterior approaches has followed this minimally invasive trend and become more streamlined.

The anterior cervical discectomy and fusion (ACDF) was first reported in 1955 by Robinson and Smith [7], and this approach quickly became the dominant approach. While the competing Cloward technique [8] offered a high cancellous surface area for fusion, it had a high rate of graft collapse [9] and subsidence rates of up to 9.6% [10]. The shape of the graft provides some intrinsic stability but endplate preparation is more invasive requiring significantly more native bone removal which also predisposed patients to kyphosis [9, 11] at rates up to 9.6% [10]. Furthermore, higher complication rates include up to 4.8% of neurologic injuries [10].

The Smith-Robinson technique [12] is less invasive given that it is endplate sparing and causes minimal vertebral body destruction. It also provides better visualization of the decompression, particularly the uncovertebral joints. Arthrodesis by either technique has proven an effective treatment for cervical spondylosis and disc herniation [9, 13–15]. Anterior discectomy with fusion has been the prominent surgical treatment for symptomatic cervical spondylosis for over 60 years. Traditionally, bone dowels or spacers were harvested from autologous iliac crest contributing to hip pain rates of up to 39% [16]. This additional procedure has contributed to the relatively longer hospital stays of ACDF patients [17].

Allograft iliac crest provided a respite from further surgical trauma at a second site and was thus less invasive. However, fashioning an appropriate size graft added additional operating time on the back table. Pre-cut fibular strut grafts offered a more convenient and efficient option but are limited in terms of footprint size and have a high cortical to cancellous bone concentration. Machined structural allograft was the next iteration providing greater surface area of the graft and a higher percentage of cancellous bone contact, albeit at a greater cost.

Nonunion and graft subsidence still occurred and titanium plating developed as a more stable option [18]. The plate and four screw construct provided a solid fixation for arthrodesis to occur. With fusion rates of up to 100% [19], this technique became the gold standard for 20+ years. While the uniplate had some early adopters [20], high pseudofusion rates were reported [21].

With load-bearing limitations, limited allograft supply, and concerns over disease transmission from cadaveric bone, titanium cages had a simultaneous rise in popularity particularly in the lumbar spine. The imaging artifact and subsidence of titanium as well as its limited machining options increased the demand for synthetic polymers such as poly ether ether ketone (PEEK). In the cervical spine particularly, PEEK offered the ability to have a number of footprint options as well as height options for corpectomy and multilevel constructs.

The latest stage of cervical fusion has allowed titanium mini plates to incorporate with PEEK spacers as a stand-alone option with internal fixation (Figure 1). This integral plate allows for less bony exposure and potentially less issues with longus colli bleeding, recurrent laryngeal paresis, and sympathetic chain injury at lower levels. Furthermore, the zero- or low-profile interbody plate, as opposed to an on-lay plate, has been shown to have shorter surgical times and lower rates of dysphagia [22]. In addition, these implants have been shown to have lower rates of adjacent segment degeneration (ASD) [23–25]. However, these implants have been associated with increased rates of kyphosis [26, 27].

While the technological advances in arthrodesis have given rise to faster procedures and shorter stays, there has been a concordant rise in cost from zero-dollar autograft to modern-day single-level constructs costing $5–6 K a level. At a time when physician reimbursement is diminishing this rise in per case cost is concerning, although the cost–benefit may be worth it for reduced surgeon’s time.
2. Problems with fusion

Cervical fusion is known to alter spinal biomechanics by creating abnormal loads and affecting segmental motion at adjacent vertebrae [28, 29]. These changes may accelerate adjacent disc degeneration through the increased stress on the adjacent disc [29–31].

Multiple studies have documented evidence of adjacent segment level disease including radiographic findings of new anterior osteophyte formation or enlargement, increased narrowing of an interspace, new DDD, and calcification of the anterior longitudinal ligament [31]. Fusion has shown an increased rate of these compared to arthroplasty. Similarly, the rate of symptomatic disease along with the need for medical treatments related to such was also greater in the fusion cohort.

Multilevel fusion constructs demonstrate even greater stress [32]. These multilevel procedures had higher rates of reoperation, pseudoarthrosis, and complications [33, 34] compared to single-level constructs.

3. The case for arthroplasty

While the ACDF has been the gold standard for years, the well-known effects of motion loss and adjacent segment breakdown have been driving factors for cervical arthroplasty. One such mechanism is the neighboring intradiscal pressure. Fusion
constructs produce greater neighboring intradiscal pressure [30] compared to arthroplasty which preserves physiologic intradiscal pressures at neighboring levels.

In essence, arthroplasty is itself less invasive than fusion because of maintained motion and reducing the need for adjacent level surgery. Like the ACDF, cervical arthroplasty has followed a similar trend toward less invasiveness with a more streamlined process and less procedural time. The nomenclature for this procedure has varied markedly to include: anterior cervical discectomy and arthroplasty (ACDA, and abbreviated ACA), artificial disc replacement (ADR), total disc replacement (TDR), cervical total disc replacement (cTDR), cervical disc replacement (CDR), and cervical disc arthroplasty (CDA).

4. Design rationale

An arthroplasty device must replicate the native disc as much as possible. Three primary considerations include: maintaining intervertebral spacing, allowing for motion with the segment, and maintaining stability with the bones neighboring the segment. The initial stability with screw fixation was the primary focus of early implants while more recent implants relied on press-fit, teeth, and/or keels as well as ligamentum taxis for initial stability. Long-term stability involves ingrowth of bone into porous endplates while at the same time allowing for revision.

The placement of an artificial disc should be done with limited disruption of surrounding anatomy. Arthroplasty by nature relies on the integrity of the neighboring facet joints and ligaments for stability. Likewise, the functioning arthroplasty device should not overload the facets nor unload them.

Replicating motion in all planes but also constraining motion means the device has to mirror physiologic tissue in terms of biomechanics. In addition to allowing loading, flexion/extension, rotation, and lateral bending, the arthroplasty device should optimally allow for translation as well (Figure 2). Ideally, the device would have some natural shock absorption for axial forces. This proved to be a limiting factor in early devices but more modern devices have incorporated this.

Figure 2.
Flexion/extension views of the Centinel spine ProDisc-C at C5–6 show arthroplasty device flexing and extending with the spine.
The movement within the implant must be balanced by a stable bone-implant interface anchoring the implant. While a fusion allows for the remodeling of bone, arthroplasty is not afforded such long-term stability. The endplates must allow for a proper degree of bony on-growth while maintaining physiologic loads at this interface to reduce implant failure and endplate failure. The resilience of the implant over the patient's life span is also an important factor. In the event of implant failure, the design should allow for minimal impact from this failure and ideally offer a radiographic cue to its existence.

Implant material is another factor that must be considered in normal usage. Materials should be chosen that are biocompatible, durable, minimize wear debris, and have a minimal inflammatory response. Additionally, materials should be selected that minimize diagnostic imaging artifact at the index level, but certainly preserving visualization of the adjacent segments is essential.

5. History of arthroplasty

While fusion has been the gold standard for over sixty years, arthroplasty designs have been developing over a similar time frame. Dr. Ulf Fernstrom studied a spherical intercorporeal endoprosthesis, or simply a stainless-steel ball, placed in the disc space in the late 1950s. He implanted 191 of his “Fernstrom Balls” in the cervical and lumbar spines of 101 patients [35]. The procedure was later abandoned over high failure rates with subsidence, migration, and hypermobility. Methylmethacrylate [36] was used as an alternative to the steel ball but did not gain much traction in the spine world.

Arthroplasty progress was somewhat dormant for approximately 30 years until the stainless-steel ball and socket implants from Bristol/Cummins were developed [37]. These advanced into a ball and trough design that allowed for translational movement to become the commercially available Prestige line from Medtronic. Charite was approved in 2004 as the first FDA-approved commercial spinal arthroplasty device (lumbar spine). Prestige ST was approved in 2007 as the first cervical arthroplasty device. This steel on steel implant was simple but its stainless-steel construction caused significant artifact on MR imaging. Some patients reported clicking sounds from the saddle joint (personal experience). The esthetics and dysphagia of an on-lay plate (Prestige-ST) as well as time-consuming implant procedure with four screw fixation.

Prestige LP was first marketed OUS in 2004 and approved by FDA in 2014. It was a less invasive approach in terms of fixation. As named, the LP design relied on lower-profile press-fit rales and antimigration teeth for fixation. It also had a titanium plasma spray for additional fixation. The implant was also made with a titanium ceramic composite material that provided better imaging characteristics. Arthroplasty implants designed up to this point allowed motion but no elasticity. The elasticity component is key for load-damping properties.

Early arthroplasty devices like the Bristol and Prestige-ST had a prominent four screw construct with a locking mechanism. Subsequent revisions like the Prestige-LP had a lower profile as so named along with no need for screw fixation.

Similar to the trends toward less invasive, more modern implants have also followed the trend toward more physiologic motion. Early arthroplasty devices mirrored general orthopedic implants with two articulating surfaces. In this spine, these first-generation implants relied on metal articulations attached to the endplate above and below the index disc (Bristol and Prestige). The early Bristol disc was a ball and socket which allows lateral bending, rotation, and flexion/extension but not translation. Prestige was created with a trough on the lower articulating surface in order to allow anterior/posterior translation.
General orthopedic implants evolved to incorporate a plastic spacer in hopes of reducing metallic wear debris while also providing better wear characteristics and a minor degree of shock absorption. A high molecular weight polyethylene core was juxtaposed between the metal surfaces. These second-generation devices reduced some of the metal-on-metal concerns but still lacked elasticity like a native disc. The ProDisc returned to a ball and socket approach with the bottom half of the polyethylene core anchored to the inferior endplate. The subsequently released Secure-C preserved the superior ball and socket design but had a saddle design on the inferior endplate articulating surface. This allowed for translation.

6. Arthroplasty 2.0

The first generation of arthroplasty implants replicated conventional orthopedic implants with metal-on-metal articulating surfaces. These types of implants allow rotation, lateral bending, flexion and extension, and in some cases (Prestige-ST) anterolisthesis.

Implants with a polyethylene core have offered more physiologic movement and less concern over metallic deposition and blood levels. These second-generation implants like ProDisc offered a fixed core while the subsequently released Secure-C offered a sliding arthrodesis.

Figure 3. The Zimmer Mobi-C was the first arthroplasty device to gain FDA approval in the United States for two-level indications.
Keel base implants like the ProDisc and Secure-C had no additional fixation hardware relaying on press-fit, bony on-growth, and keel anchoring stability. Even within the keel-based implants, the Secure-C introduced a shorter, wider keel which required even less exposure in a cranial-caudal direction.

The Nuvasive PCM disc allowed similar translation while also incorporating an arrow-shaped row of teeth as the primary fixation modality. When Mobi-C was released, the mindset was to perform as little endplate preparation as needed. Mobi-C went a step further to offer a circumferentially mobile center of rotation and obtained FDA approval as a two-level implant in 2013 (Figure 3).

While Mobi-C provided even more range of motion, concerns arose regarding hypermobility [38, 39] of the joint and the inability to adequately visualize the mobile core. With a mobile core, there was now a superior and inferior articulating surface to be concerned with, especially in shear force loading.

7. Arthroplasty 3.0

Third-generation implants have allowed for translation and compression forces that more closely resemble physiologic motion.

The Bryan cervical disc was under development as early as 1997 by Spinal Dynamics Corporation. This implant relied on the preservation of the natural vertebral concavities with convex titanium shells matching them. The convex portion of the implant has a rough porous coating for bony on-growth. The concave surface of the implant is surrounded by a flexible membrane and lubricant to reduce friction and prevent migration of wear debris. The inner polymer nucleus provides a full range of motion while also allowing for a full range of motion but without loading. The Bryan disc eliminated the need for chiseling of keels but required a complex endplate preparation rig and procedure to shape the vertebral endplates. Subsequent implants like M6 likewise require only a small amount of chiseling for stability.

The Orthotic M6 implant has additional design components that allow more physiologic motions and replicate the physiological phenomenon of progressive resistance to motion in all six degrees of freedom (Figure 4). This design enables the disc to move in all six degrees, with independent angular rotations (flexion-extension, lateral bending, and axial rotation) along with independent translational motions (anterior–posterior and medial–lateral translations), as well as axial compression. This unique compressive ability has been thought to reduce adjacent segment disease specifically.

The M6 is a complex, multi-component implant that contains an artificial nucleus made of Viscoelastic polymer (PCU) designed to simulate the native nucleus structure. It lies adjacent to but is not fixated to two inner titanium endplates. This core nucleus is retained circumferentially between the titanium endplates by a fiber annulus matrix.

This Ultra High Molecular Weight Polyethylene (UHMWPE) fiber matrix is designed to simulate the native annular structure and is wound in a specific pattern, with multiple redundant layers. The matrix is wound around the core and through slots in the two Ti6Al4V titanium alloy inner endplates. Surrounding the flexible portions of the implant is a jacket of viscoelastic polymer (PCU) designed to minimize tissue in-growth and debris migration.

The inner plates are welded to outer plates the surface of which includes low profile fins and are coated with titanium plasma spray (TPS).
8. Arthroplasty benefits

Numerous IDE studies have shown the benefits of arthroplasty over fusion, particularly in the cervical spine. In addition to being motion sparing, arthroplasty’s perhaps greater value is in the reduction of adjacent segment breakdown. Several studies have shown lower rates of ASD in patients having undergone arthroplasty compared to their ACDF cohorts. The Secure-C study showed a 4x greater risk of having adjacent segment surgery in the ACDF group.

Lower rates of adjacent segment surgery, not only benefit patients could lower total health care costs. Ironically, this advantage has not been a motivating factor in insurance approval. The author spoke with the Medical Director of one major health insurance provider extolling the benefits of arthroplasty for a 24-year-old patient for whom a single-level ACDF was already approved. In an attempt to get authorization for an artificial disc at C5–6, I said, “I am fighting to get paid less for an operation that will potentially save the patient another surgery and in the end save you money on all accounts.” Their response was, “We don’t care. Our data shows most patients will change insurance carriers in the next five or six years and that doesn’t help us.” (Jason Highsmith, personal communication January 2009.)

Another potential benefit of this reduction of ASD is the ability to only operate on a symptomatic or freshly herniated level and leave other levels with some pathology untreated. In the past, there was a tendency to fuse everything that was
abnormal, which of course exacerbates adjacent segment breakdown. This single-level approach for arthroplasty may lead to lower future costs.

ACDF patients had a higher reoperation rate at the index level in most of the IDE studies. Patients underwent a revision for nonunion as well as hardware revisions for screw pullout and plate fracture. One possible explanation is that most surgeons in the IDE study were highly skilled with ACDF procedures and took more time with the ACA procedure with better carpentry and decompression.

One explanation for this is that with arthroplasty there is only one active surface the articulating surface, whereas in ACDF there are two active surfaces of fusion to account for. Because of the need for additional decompression and resection of the uncovertebral joint, more care may be taken during ACA procedures.

Another positive factor for arthroplasty is certainly patient demand and satisfaction. The nomenclature of fusion is rarely a welcome term in clinical practice. At the same time, some patients with significant facet arthropathy or spondyloarthropathy come wanting disc replacement as the latest innovation regardless of their underlying pathology.

One limitation of the early studies was that the control group consisted of allograft spacers with a four-screw on-lay construct. While this was no doubt standard of care at the time these studies were initiated, and potentially still is, new options exist. Stand-alone devices with a cage and integrated plating are an easier construct to implant than a four screw on-lay plates.

While the clinical inclusion criteria for arthroplasty have been fairly stable over the last 20 years, the trend clinically has been more aggressive in indications. Initially, the ideal candidate was a less than 40-year-old patient with a solitary fresh disc, minimal adjacent segment disease, and little spondylosis. Now we are seeing older patients with more chronic disc issues, absent of facet pathology, undergoing arthroplasty. Based on my experience as a principal investigator for three IDE studies, we are seeing arthroplasty being offered to a broader spectrum of patients as surgeons become more comfortable with the procedure (Figures 5 and 6).

Figure 5.
Sagittal T2 MRI of a 38-year-old woman with worsening neck pain and radiculopathy. Note multi-level cervical disc herniations with cord impingement. Given her age, nerve impingement, isolated soft tissue pathology, and failure of conservative care patient was an ideal candidate for three-level cervical arthroplasty.
9. Pearls

Early in the Globus Secure-C study [40], we observed some heterotopic ossification in spite of oral NSAIDs. This led many surgeons to try additional measures to reduce this phenomenon. Several surgeons sealed the anterior edges of the adjoining bodies with bone wax, particularly where the anterior longitudinal ligament was denuded from the bone. Anecdotally, this appeared to reduce the incidence of HO. In my experience, I’ve had a lower rate of autofusion by incorporating the same technique along the uncovertebral joints. The proximity of neighboring bone in this area after aggressive decompression puts it at risk for heterotopic bone formation. As such I seal the areas of decorticated bone with a thin layer of bone wax even into the joint.

Many devices have keels or teeth that provide initial fixation. I often “set” the implant into the neighboring bone by compressing the implant using the Caspar pins in compression. This helps reduce overdistraction of the facets as well.

When using a keel-based implant such as ProDisc, I recommend using the mill rather than chiseling. There have been case reports [41, 42] of fractures of the vertebral body using the chisel even in the low-profile Prestige-LP [43]. Similar findings have occurred in lumbar cases with ProDisc-L. [44] where there is no milling rig available. Concern over fractures like these should be even greater in multilevel cases [45]. Interestingly, all of these cases used the bone chisels to make the keel cut. While there is no data to support the use of the milling bit, it appears to be a less invasive option (Figure 7).
10. Future design implications

A number of other implant designs have been proposed albeit with little clinical implementation. The hydrogel Prosthetic Disc Nucleus (PDN) is a hydrogel core in a polyethylene shell or jacket meant to only replace the nucleus in the lumbar spine while preserving the annulus fibrosis. This technique relied on the compressed core to be inserted and absorb fluid over the first four or five days allowing it to expand and restore disc height. In the trend toward minimally invasive, there is great potential to become percutaneous. While stem cells have proven useful in osteobiologics, there is still a great need for their development in cartilage and disc replacement. Clearly, the future lies in cellular-based disc repair and reconstruction but for now, that hope is elusive.
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