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The Future of Arthroplasty in the Spine

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ABSTRACT

The evolution of spinal arthroplasty, a significant journey that began in the 1960s and 1970s, has seen remarkable progress. Initially designed to preserve motion at spinal segments and avoid complications associated with fusion surgeries, early designs faced setbacks due to rudimentary concepts and limited materials. However, the 1980s marked a turning point with the development of modern total disc replacement concepts, utilizing advanced materials such as titanium and polyethylene to improve implant longevity and integration. The early 2000s saw crucial approvals by the U.S. Food and Drug Administration, leading to broader clinical adoption.

By the 2010s, cervical disc arthroplasty (CDA) had been refined through innovations such as patient-specific implants and the integration of robotics and surgical navigation. Cervical disc arthroplasty and lumbar disc arthroplasty are effective alternatives to fusion, particularly in preserving motion and reducing adjacent segment disease. Ongoing research continues to focus on viscoelastic arthroplasty and the integration of biologics to enhance outcomes, providing reassurance about the continuous improvement in spinal arthroplasty and instilling optimism about its future.

Selecting patients for arthroplasty is a critical process that requires careful consideration. Ideal candidates display symptoms unresponsive to conservative treatments, have adequate disc height, and possess good bone quality. As arthroplasty typically preserves motion, it is less suited for patients with severe joint diseases or significant spinal stiffness. This emphasis on patient selection underscores the need for thorough evaluation and the importance of considering individual patient factors.

Despite its benefits, the adoption of disc arthroplasty faces barriers such as high costs, stringent inclusion criteria, and the need for specialized surgical training. Overcoming these barriers requires advocacy, improved training, and potentially revising inclusion criteria to ensure more patients can benefit from these advanced treatments. The future of spinal arthroplasty looks promising, with potential advancements in biokinetics, biomaterials, and the broader application of minimally invasive techniques. This ongoing evolution promises to improve clinical outcomes and significantly enhance patient quality of life, offering hope for a better future in spinal arthroplasty.

Focus Issue Article

Keywords: arthroplasty, cervical disc arthroplasty, lumbar disc arthroplasty, evolution, future directions

KEY POINTS

- Evolution of spinal arthroplasty from rudimentary designs to modern total disc replacement concepts.
- Criteria for selecting patients for arthroplasty, emphasizing thorough patient evaluation and individual factors.
- Advantages of arthroplasty over fusion, including spinal motion preservation and faster recovery times.
- Barriers to disc arthroplasty adoption include high costs and specialized surgical training.
- Future directions and prospects in spinal arthroplasty advancements and research regarding better outcomes.

THE FUTURE OF LUMBAR DISC ARTHROPLASTY

History and Evolution of Spinal Arthroplasty

The history of spinal arthroplasty dates back to the 1960s and 1970s, marked by initial attempts to preserve motion at spinal segments with rudimentary designs.[1] The primary objective was to avoid adverse events associated with fusion, such as pseudoarthrosis and adjacent segment degeneration. However, these early efforts often fell short due to the limited availability of advanced materials and a lack of comprehensive biomechanical understanding.[1,2] The 1980s witnessed a significant leap forward with the emergence of modern concepts of total disc replacement.[2] Researchers and surgeons designed implants that could better mimic the natural motion of the spine while providing necessary stability.[3,4] The 1990s witnessed remarkable progress in

materials science and biomechanics with the development of biocompatible materials such as titanium and polyethylene, which significantly improved implant longevity and integration.[5–7]

The early 2000s marked a milestone with several vital clinical trials and approvals of novel implants by the U.S. Food and Drug Administration (FDA), such as the Charité artificial disc in 2004[8,9] and the ProDisc-L in 2007,[10,11] enabling broader clinical adoption.[12–19] The 2010s encompassed further refinement and innovation in cervical disc arthroplasty (CDA), including patient-specific implants, minimally invasive techniques, and integration of robotics and surgical navigation.[20–28]

Viscoelastic arthroplasty, a novel approach in spine surgery, has emerged as an alternative to traditional fusion and total disc replacement techniques, especially for the cervical and lumbar regions.[29–31] This technique utilizes a viscoelastic implant designed to mimic the natural properties of the intervertebral disc, aiming to preserve motion while providing stability to the spinal segment.[30] In the 2020s, incorporating biologics and regenerative medicine has enhanced outcomes with stem cells, growth factors, and tissue engineering.[31,32] Despite ongoing challenges, such as the need for long-term data and cost considerations, spinal arthroplasty has demonstrated substantial benefits in pain relief and motion preservation, establishing itself as a viable alternative to spinal fusion. The story of spinal arthroplasty is far from over, and the significant advancements in the field offer reassurance about its progress and promising future.[33]

Current State and Significance

CDA has become a widely accepted alternative to anterior cervical discectomy and fusion (ACDF) for treating cervical disc degenerative disease.[34,35] Similarly, lumbar disc arthroplasty (LDA) is recognized as a practical option for patients with symptomatic lumbar disc disease who did not respond to conservative treatments or lumbar fusion.[36] The primary advantage of CDA and LDA over traditional fusion techniques is preserving spinal motion at the operated segment.[34,36] This preservation of motion is crucial in preventing or delaying the onset of adjacent segment disease (ASD), a common complication following spinal fusion surgeries. Recent advancements in materials and design have led to the development of more sophisticated implants, including biocompatible materials such as titanium and polyethylene, which offer better integration and longevity.[37] Additionally, incorporating minimally invasive surgical techniques and robotic assistance has improved the precision and safety of these procedures, leading to faster recovery times and reduced complication rates.[36,37] The long-term efficacy and safety of both CDA and LDA are supported by an abundance of research that has shown significant improvements in pain relief, functional recovery, and patient satisfaction.[36–39]

When performing CDA, the nearby vessels, such as the carotid and vertebral arteries, do not require mobilization, simplifying the procedure. In contrast, LDA involves mobilizing significant vessels, adding complexity and difficulty to the surgery. This increased complexity needs a higher level of surgical expertise, which most spine surgeons, whether neurosurgeons or orthopedic surgeons, may not acquire during their training.[36] Consequently, access surgeons, often vascular surgeons, must perform the approach for medicolegal reasons. Moreover, the availability of more straightforward minimally invasive surgical techniques, such as transforaminal lumbar interbody fusion, serves as a disincentive to perform LDA. These factors contribute to the higher frequency of CDA procedures compared with LDA.[36,38]

Integrating biologics and regenerative medicine is an emerging frontier in spinal arthroplasty. Researchers are exploring using stem cells, growth factors, and tissue engineering to enhance the healing and integration of arthroplasty implants.[40] This approach aims to further improve the outcomes of spinal disc replacement by promoting tissue regeneration and reducing the risk of implant failure. Despite the significant advancements, there are still challenges in spinal arthroplasty. Long-term data on the durability and effectiveness of disc implants are required, with ongoing concerns about the higher cost of these procedures compared with traditional fusion surgeries. Additionally, managing complications such as implant migration, wear, and the need for revision surgeries is another crucial area of focus. Future efforts will aim to advance implant designs, improve surgical techniques, and integrate future technologies for enhanced patient outcomes.[32,40]

Criteria for Selecting Patients for Arthroplasty

Selecting suitable patients for CDA and LDA is pivotal to achieving the best outcomes. Ideal candidates typically include those suffering from symptomatic degenerative disc disease, characterized by significant neck or back pain, radiculopathy, or myelopathy that has not responded to conservative treatments such as physical therapy, medications, or injections. Motion preservation at the affected spinal segment is imperative,

making arthroplasty less suitable for patients with significant spinal stiffness or ankylosis.[41] Adequate disc height and good bone quality are essential, as severe osteoporosis or other bone-weakening conditions may contraindicate the procedure. Additionally, the absence of severe facet joint disease is critical, given that significant facet arthropathy can negatively impact arthroplasty outcomes, rendering such patients better candidates for fusion procedures. Typically, candidates with single- or 2-level disc disease are preferred, whereas multilevel degeneration may necessitate alternative surgical approaches such as fusion.[42–47] Young patients or those in good general health are often ideal candidates due to their likely better adaptation to motion-preserving techniques and lower risk of complications.[48]

Arthroplasty Vs Spinal Fusion

Compared with spinal fusion, disc arthroplasty offers several advantages, notably in preserving spinal motion. This is instrumental in reducing the risk of ASD and maintaining natural spinal mechanics.[49,50] Arthroplasty is associated with quicker recovery times and a faster return to normal activities due to less disruption of spinal mechanics. In contrast, fusion often entails a more extended recovery period and extensive rehabilitation. Long-term studies underscore the favorable outcomes of arthroplasty in pain relief and functional improvement, with the added benefit of mitigating the progression of degeneration at adjacent segments. Despite potential complications such as implant wear and migration, advancements in implant technology have significantly reduced these risks.[51] Conversely, fusion is associated with risks such as nonunion, hardware failure, and increased stress on adjacent segments. Therefore, arthroplasty is best suited for patients with well-preserved motion and minimal facet joint disease, particularly younger and more active individuals. At the same time, fusion is still more suitable for patients with severe facet joint disease, instability, deformities, or multilevel degenerative conditions.

Overcoming Barriers to Disc Arthroplasty Adoption

The initial introduction of disc arthroplasty devices captured substantial attention, resulting in an increased frequency of disc replacement procedures.[52] Despite this early enthusiasm, a noticeable decline in the prevalence of these procedures was observed several years following the FDA approval of the initial device.[53] This downward trend can be attributed to multiple factors, including the escalating financial burden associated with hospitalization, stringent inclusion criteria, patient eligibility, and a lack of provider familiarity and comfort with the procedure.[54]

Disc replacement procedures, when successful, can significantly improve the quality of life for patients suffering from degenerative disc disease.[55,56] However, the economic considerations cannot be understated, given that insurance may not fully cover the costs associated with these procedures. This imposes a significant financial strain on healthcare systems and patients.[57] Additionally, the rigorous patient selection criteria have limited the applicability of disc replacement, potentially excluding a substantial subset of individuals who might benefit from the procedure.[13,58] The familiarity and comfort of healthcare providers with disc arthroplasty also play a crucial role; a lack of widespread training and experience may deter practitioners from adopting this surgical technique.[59]

Due to these challenges, disc arthroplasty's predicted prevalence and potential impact have yet to be fully explored.[60] However, significant potential remains for an expanded role in the modern management of degenerative disc disease. With advancements in device technology, improved provider training and education, and potential revisions to inclusion criteria, we can envision a future where this procedure is more widely applicable.[61] Such advancements, coupled with enhanced economic models that address cost-effectiveness and insurance coverage, are crucial for the sustainability of the procedure. They could further support its adoption, positioning disc arthroplasty as a valuable alternative in the contemporary treatment paradigm for discogenic pain secondary to degenerative disc disease.[62,63]

Insurance companies are critical in hindering the adoption of proven technologies such as CDA and LDA despite Class 1A evidence proving their efficacy and safety.[64] These companies often prioritize profit optimization, leading to restrictive coverage policies that limit patient access to advanced treatments. This cost-containment strategy may result in adverse outcomes. Patients who could benefit from CDA and LDA are frequently denied coverage, compelling them to opt for less effective treatments or incur significant financial burdens.[65] Although insurance companies may achieve short-term savings by denying coverage for these procedures, the long-term costs associated with alternative therapies can be higher due to prolonged recovery times, higher rates of complications, and the need for additional surgeries. These factors ultimately increase the overall cost of care.[66]

Furthermore, the reluctance of insurance companies to cover innovative technologies stifles innovation in the medical field. Manufacturers and healthcare providers may be less inclined to invest in developing and adopting new technologies if there is uncertainty about insurance reimbursement, thereby slowing the advancement of medical treatments.[67] This scenario highlights a discrepancy between scientific research and clinical practice, where insurance coverage decisions undermine high-quality evidence supporting the efficacy of CDA and LDA. Such denials can erode trust in the healthcare system and the value of evidence-based medicine. Physicians, aware of the denial of coverage, may be deterred from recommending or performing these procedures, thus limiting patient options and constraining the ability of healthcare providers to offer the best possible care.[68]

Addressing this issue requires a multifaceted approach. Advocacy by professional medical societies, patient advocacy groups, and continuous dialog with insurance companies is undoubtedly critical. This advocacy can help bridge the gap between evidence and coverage policies. Demonstrating the long-term cost-effectiveness and superior patient outcomes associated with CDA and LDA through health economic studies may persuade insurance companies to reconsider their positions.[69] Regulatory bodies and policymakers have a fundamental role in ensuring that coverage decisions are aligned with the best available evidence, promoting broader access to proven beneficial technologies for patients with degenerative disc disease.[70,71]

Despite this ongoing multifaceted advocacy approach, insurance companies still need to listen.[72] Thus, additional strategies need to be considered. Legislative actions, such as lobbying for changes that mandate insurance coverage for procedures with proven efficacy, can create a regulatory environment. This could compel insurance companies to cover CDA and LDA based on existing Class 1A evidence.[70] Legal challenges, including class-action lawsuits and individual cases, can highlight the disparity between evidence-based medicine and insurance practices, potentially resulting in court rulings that enforce coverage.

Public awareness campaigns can raise public consciousness about the benefits of CDA and LDA and the obstacles posed by insurance companies, generating public pressure for policy changes.[73] Collaborating with large employers to include CDA and LDA in employee health plans can bypass traditional insurance company barriers, as employers can be educated on the long-term benefits and cost savings associated with these procedures, leading to more inclusive coverage options for their employees. Increasing transparency around insurance company decision-making processes is not just a suggestion but a necessity. This transparency can hold insurance companies accountable by publicly sharing data on approval and denial rates for specific procedures, pressuring them to align their policies with evidence-based practices.[74]

Exploring alternative payment models, such as bundled payments or value-based care, can incentivize insurance companies to cover procedures demonstrating long-term cost savings and improved patient outcomes, shifting the focus from short-term cost savings to the overall value in healthcare delivery.[75] Additionally, collaborating directly with medical device companies to provide compelling data and case studies can strengthen the argument for coverage. These companies can also support efforts through funding research, advocacy initiatives, and patient education programs. By employing these added strategies, stakeholders can intensify their efforts to ensure that insurance companies recognize the value of CDA and LDA and provide the necessary coverage for patients with degenerative disc disease.[76] Table 1 provides a summary of strategies

Table 1. Strategies to overcome challenges in the adoption of spinal arthroplasty.

Broader Insurance Coverage
Offer alternatives to single out-of-pocket payments
Fund health economic studies to explore value-based care
Set inclusive patient eligibility criteria
Collaboration between medical device companies and large organizations
Public Awareness Campaigns
Educate the public on benefits of arthroplasty and challenges posed by insurance
Build public pressure to drive policy changes
Optimized Patient Selection
Focus on patients with single- or 2-level disc degeneration
Exclude those with severe facet joint disease, spinal stiffness, ankylosis, or significant comorbidities
Prioritize younger patients with good disc height and bone quality
Widespread Surgical Training
Ensure ongoing provider training and education
Periodically conduct complex case meetings and surgical technique workshops to enhance surgical expertise
Patient Advocacy
Foster dialogue among professional medical societies, patient advocacy groups and insurance companies
Advocate for legal change through petitions, lawsuits, and meetings with regulatory bodies and policymakers
Scientific Advances
Integrate biologics and regenerative medicine to enhance treatment outcomes
Conduct further research on bioactive materials and intelligent devices
Create implants personalized to the patient's anatomy
Consider application of AI and robotics in surgical planning and execution

Abbreviation: AI, artificial intelligence.

to address current challenges and accelerate the adoption of spinal arthroplasty.

Future Directions and Prospects

Spinal arthroplasty is advancing into a transformative era fueled by significant innovations and robust research efforts, promising patients and medical professionals an improved future. This field is experiencing technological advancements like bioactive materials and intelligent implants. These innovations enhance the integration and longevity of spinal implants and bring tools such as real-time biomechanical monitoring, augmented reality, and virtual reality into the fold. Such technologies are poised to revolutionize preoperative planning and surgical training, resulting in more precise and less invasive spinal surgeries.[77]

On the biological front, integrating biologics and regenerative medicine is enhancing tissue integration and pushing the boundaries of stem cell therapies.[78] These advancements are expected to dramatically improve postsurgical outcomes by accelerating healing processes and tissue regeneration.[78] Regarding policy and economics, spinal arthroplasty is proving its cost-effectiveness, encouraging policymakers and insurers to adapt. This is a noticeable shift toward value-based care models, which emphasize long-term cost savings and sustainability, making spinal arthroplasty more accessible.

The trajectory of spinal arthroplasty also heavily relies on targeted research, which is essential for exploring personalized medicine approaches, improving implant longevity, and refining minimally invasive techniques.[79] Addressing existing knowledge gaps, including the need for standardized outcome measures and assessing the economic impacts of new technologies, is crucial for maximizing the potential of spinal arthroplasty. The field is on a fast development track, driven by breakthroughs that promise enhanced clinical outcomes and aim to significantly improve patient's quality of life.[80] This ongoing evolution in spinal health care is setting the stage for a new era of medical excellence characterized by more effective, personalized, and advanced treatments.[66]

THE FUTURE OF CDA

From an ontogenetic perspective, the cervical spine has evolved for multiplanar motion, which is essential for daily activities.[81] Significant motion occurs at the subaxial cervical spine, where degenerative disc disease is more common. ACDF, previously the gold standard, results in motion loss and neck stiffness. In contrast, arthroplasty preserves biomechanical features such as an intact spine.[82]

Clinical Outcomes

CDA devices are among the most scrutinized in the spine arena. High-quality data (Level 1 evidence) from 9 completed prospective randomized controlled trials (RCTs) by the U.S. FDA show that CDA outcomes are at least noninferior to the "gold standard" ACDF. Furthermore, the data are highly reproducible across multiple devices.[83] Despite issues like heterotopic calcification and potential loss of mobility at the index level, long-term follow-up at 10 years highlights differences in clinical outcomes between CDA and ACDF.[84,85]

Kim et al[86] analyzed 10-year follow-ups of 1- and 2-level FDA trials at the 9 highest enrolling centers (n = 187; 75% follow-up rate) and found that 88.8% of patients were "delighted" with their outcomes. Significant improvements were sustained at 7 years or enhanced at the 10-year follow-up.[86] Not a single clinical study showed CDA to be inferior to ACDF.[83–86] Future research will focus on clinical and radiological outcomes and prosthesis survival indicators beyond 10 years, which is crucial for long-term cost-effectiveness studies.

Range and Quality of Motion Preservation

The original argument for cervical arthroplasty was preserving motion in an inherently highly mobile spine segment. Gornet et al[87] and Kim et al[86] showed long-term range of motion (ROM) conservation despite 43% heterotopic ossification (HO). Achieving the correct postoperative location of the center of rotation (COR) in the pathological intervertebral space is equally critical for a favorable outcome. An altered COR negatively affects both segmental and global ROM.

Using the same third-generation mobile core device in various clinical scenarios (hybrid constructs, single-level, and multilevel cervical arthroplasty), it was found that postoperative CORs at the index level tend to be located superiorly and posteriorly at 6 months. However, it normalizes after 1 year, compared with healthy volunteers.[88] A more "physiological" location of the COR can potentially reduce the mechanical load on adjacent discs and facet joints. This assumption needs validation from future clinical studies.

Adjacent-Segment Protection

When performed according to rigorous technical principles, which involve perfectly centering the device to achieve the best biomechanical performance, CDA

protects against adjacent segment degeneration, both radiologically and clinically. The protective mechanism on adjacent segments is based on less hypermobility and reduced intradiscal pressure with CDA constructs compared with ACDF.

In a biomechanical study by Patwardhan and Havey,[89] an increase in cervical sagittal vertical axis (cSVA), typical of the aging process, significantly increased intradiscal pressure on the adjacent segment in the context of a 2-level fusion ($r = 0.47$; $P < 0.01$). Many clinical reports corroborate these biomechanical findings. With a follow-up of 84 months, Lanman et al[90] demonstrated the absence of hypermobility in their series of CDA patients, resulting in lower reoperation rates at adjacent levels compared with ACDF. This difference widens with more extended follow-up periods, regardless of any potential bias from patients or surgeons regarding the indication for reoperation.[89,90]

Badhiwala et al[91] showed no significant difference in adjacent-level surgery between CDA (1.7%) and ACDF (3.4%) at 2 years. However, at 7 years, CDA had significantly fewer reoperations (4.2% vs 13.5%, $P < 0.001$).[91] In a study involving 1,334 CDA patients and 1,061 ACDF patients from 8 RCTs with 48 to 120 months follow-up, the reoperation rate for ASD was significantly lower with CDA (3.6% vs 9.5%, $P < 0.001$).[92]

A meta-analysis of 8 clinical trials (15 studies; n = 1,440 CDA patients and 1,237 ACDF patients) confirmed a significantly lower reoperation rate for CDA compared with ACDF (5.8% vs 13.4%, $P < 0.00001$). No differences in adverse event rates between the groups were found.[93] Interestingly, no difference in results was observed between RCTs ($n = 9$) and 28 observational studies, according to Jee et al.[94] The mean time from index surgery to reoperation is longer for CDA than ACDF (54.6 months vs 31.1 months, $P < 0.01$, level 2 evidence). Only 2 subsequent surgeries were reported after 7 years. Notably, no single study indicates a higher reoperation rate with CDA.

Cervical Sagittal Balance Preservation and Correction

Sagittal imbalances, translated as kyphosis or increased cSVA, lead to neck pain, facet joint, and adjacent disc degeneration, as well as myelopathy progression. Suppose cervical arthroplasty is used on a larger scale besides motion preservation and adjacent level protection. In that case, it should also harbor a beneficial effect on the index and global sagittal balance. Our unpublished data on 35 patients demonstrate a significant mean increase at the index-level lordosis of 3.37° ($P < 0.01$) that influenced the increase in global lordosis ($r = 0.374$; $P = 0.029$), especially in patients in low T1 slope. This observation aligns with a meta-analysis demonstrating a favorable global alignment after CDA compared with ACDF.[95] CDA can correct preoperative global sagittal imbalance at the adjacent segment or the global cervical spine.[95] Publication of studies elaborating on sagittal balance and the interrelation with the different parameters after CDA are needed.

Cost-Effectiveness, Implant Costs, and Surgeon's Reimbursement

Besides reflecting safety, device failure, and outcomes, reoperations can significantly affect a procedure's long-term cost and related cost-effectiveness. In a 2015 retrospective study with a matched cohort analysis of prospectively collected data from a "real-world" national insurance database reflecting patients with broader indications than FDA studies, Radcliff et al[96] clearly showed that CDA was 12% cheaper. A statistically significant lower cumulative incidence of reoperation (5.7% vs 10.5%, $P = 0.0214$) explained the savings over time despite higher overall hospital costs. Likewise, CDA effectively reduced the monthly cost of care compared with ACDF. A tendency for earlier return-to-work was also sizeable.[97] In a meta-analysis (based on 8 studies with a minimum of 4-year follow-up), Wu et al[98] demonstrated a significantly higher index-level reoperation rate with ACDF (16.8%) when compared with CDA (7.4%). CDA is a cost-effective surgery over a patient's lifetime, assuming a 5-year follow-up analysis or a 20-year prosthesis survival.[99,100]

On the side of manufacturers and companies, devices could reduce their cost, so this technology could be accessible to further patients, especially in low- and middle-income countries. In an international survey, surgeons acknowledged that device cost was a significant barrier to implementing cervical arthroplasty despite recognizing intrinsic benefits.[101] Also, from a surgeon's perspective, the reimbursement of cervical arthroplasty must be equalized to ACDF. CDA is a more technically demanding and time-consuming surgery, as surgeons cannot rely on indirect decompression alone, as with cages in ACDF. Thus, it should be better valued. Complete osteophyte and posterior longitudinal ligament removal to decompress correctly, avoid HO, and take advantage of the biomechanics of the disc, along with bilateral uncus removal beyond the compressive pathology to prevent recurrent radicular pain, are factors that entail arduous labor and risks. At some point, excellent quality studies on a value-based

perspective are indispensable to persuade stakeholders to endorse CDA surgery on a broader scale. Studies on the long-term durability and functionality of CDA are required to validate the econometrics of this technology.[102]

Expansion of Indications

Two-Level Degenerative Disc Disease

Multilevel (>2-level) ACDF exacerbates many of the adverse biomechanical effects of single-level fusion, namely the increased stiffness and the hypermobility of adjacent levels.[103] The effects of 3- and 4-level fusion on neck motion negatively impact the cervical spine's global functional status.[103] They are poorly tolerated when assessing the quality of life, especially in younger patients with higher life expectancy. Furthermore, complication rates occur in multilevel ACDF in a magnitude not seen with CDA.[103] At the index level, Gornet et al[104] reported on the reoperation rate and found rates of 3.6% (5/116) in the 3-level CDA group and no reoperations for the 4-level CDA group. Meanwhile, Laratta et al[105] saw a 26% reoperation rate only for pseudarthrosis for 3- and 4-level ACDF. Adding cervical disc prosthesis devices in a construct does not affect the biomechanical function of each disc prosthesis, as shown by Huppert et al.[106] Since the clinical effectiveness of CDA vs ACDF becomes more apparent as treatment increases from 1 to 2 levels, it seems logical to consider CDA in multilevel (>2-level) disc disease.[81,107] In a single surgeon cohort using a single device in 32 patients with a mean age of 47 years (range, 42–57) presenting with multilevel disc disease with a mean follow-up of 44.5 months (range 19–70), a significant increase in ROM was observed at the index-level and globally, nicely coupled with the restoration of adequate sagittal balance.[107] Despite the restricted indication for >2-level cervical arthroplasty, as degenerative disc disease matures dissimilarly at various levels, more studies on 3- and 4-levels with more significant cohorts of patients and longer follow-ups should be published.

Kyphosis at Index Level

A study by Kim et al[86] revealed that only 13% of preoperative kyphotic index levels become lordotic after CDA, whereas global kyphosis resulted in lordosis in 33% of patients. Thus, CDA is more efficient in correcting global than index-level kyphosis. Our unpublished data concerning 23 patients presenting with 25 kyphotic levels with a mean age of 47 ± 7.12 years and followed up for a mean of 21 months (range 6–40 months) showed that all levels become lordotic with an increase in index angle of +5.7° ($P > 0.001$). Whenever the intrinsic properties of the device are not enough to recover lordosis, an osteotomy to reformat a preoperative wedge-shaped vertebra will help to confer a lordotic configuration to the disc space.[108]

Degenerative Cervical Myelopathy

A growing number of young patients are presenting with symptoms of myeloradiculopathy due to multilevel compressive collapsed ("slit") discs, often in the context of congenital canal stenosis (CCS) without instability. These patients become suitable candidates for multilevel cervical arthroplasty once their facet joints are confirmed to be nonankylosed through intraoperative intervertebral motion assessment following disc and osteophyte removal. Chang et al[109] demonstrated that hybrid CDA, a partially motion-preserving surgery, provided similar clinical improvements to 3-level ACDF in younger patients with myelopathy caused by CCS.

Our unpublished data that analyzed 28 patients with a mean age of 48 years (range 30–68) and a mean follow-up of 28 months (range 12–50) showed significant results for 39 "slit" discs (defined as disc height <3 mm), with a mean increase in disc height of 5.74 ± 1.01 mm and a mean increase in index-level ROM of 3.0 ± 7.04 degrees. Future studies should focus on motion-preserving surgery for myelopathic patients with compressive disc disease, specifically those without facet joint ankylosis or hypermobility contributing to their myelopathy.[109]

Improved Biokinetics and Biomaterials

The evolution of cervical disc prosthesis design has been remarkable. Still, a considerable margin for kinematics improvements exists. The likelihood of achieving ROM in physiological ROM (5°–16°) depends on prosthesis design ($P < 0.01$). Six degrees of freedom devices show the highest proportion of implanted segments in the physiological motion range compared with the cohort average (79% vs 65 %; $P < 0.01$).[110] The COR's location varies according to patient age, disc and facet joint degeneration, and overall sagittal alignment. Additionally, the COR location for a C3- to C4-disc level differs for a C6 to C7 level. However, we are implanting the same device profile in those levels when compressive pathology stands. Preoperative studies on individual patients' location of COR in pathological and normal levels matched to big data from healthy volunteers or similar pathological cases managed by artificial intelligence will open an entirely new world with the

potential for better clinical results and fewer complications.[110] However, wear, debris, and long-term survival are valid concerns for every motion preservation device. Equally, the materials used so far affect the ability to image both the prosthesis and the adjacent neural tissues postoperatively. Future research on biomaterials could provide helpful information for building better devices.

Preservation of Compensatory Mechanisms While Aging

A seminal biomechanical study by Patwardhan et al[111] highlighted the existence of compensatory mechanisms during the cervical ages. In the setting of an increase in the cSVA, a compensatory flexion at the C2-7 level and hyperextension at the C0-1-2 level develop over the years. Cervical fusion, especially multilevel, inexorably abolishes these functional and adaptive mechanisms. This can be the most compelling argument for cervical arthroplasty, assuming the survival of the prosthesis. Cervical arthroplasty may represent a window of opportunity to treat younger patients as compensatory mechanisms are preserved, contrary to fusion surgery. Future clinical studies are needed to validate these laboratory studies.

Complications

Heterotopic Ossification

CDA device design, technical details, or patient characteristics were noted as causative factors of HO. However, HO occurrence does not disrupt clinical outcomes. A systematic review of 38 studies found HO rates from 16.1% to 85.7%, implying that causative factors still need to be understood. The development of HO is time dependent, but a ceiling effect is observed at 5 years postoperatively.[112] More studies in the future should bring further insights into how to prevent HO in CDA patients.

Osteolysis

Anterior osteolysis following CDA is a critical concern in spinal surgery, as highlighted by an increasing number of reports in recent literature.[113] Characterized by a decline in periprosthetic bone density, osteolysis poses significant diagnostic challenges due to its largely asymptomatic nature and uncertain etiology.[113,114] Potential causes include indolent infections, stress shielding, implant site micromotion, and wear debris immune reactions.[115–117] Specifically, studies such as those conducted by Scott-Young et al[118] and Häckel et al[116] have identified polyethylene wear debris as a significant contributor to periprosthetic osteolysis. Despite these identified factors, the precise mechanisms underlying osteolysis remain elusive. This condition rarely manifests clinically, but when symptomatic, it can lead to complications such as subsidence, kyphosis, or neck pain.[118] Furthermore, there is a notable discrepancy in the reported prevalence of osteolysis, ranging from 3.13% to 91.89% across 6 studies encompassing 440 patients and 536 operated segments.[118] This variability underscores the need for refinement in measurement techniques. It suggests that our understanding of osteolysis's origins, mechanisms, risk factors, actual incidence, and temporal development is still in its infancy.[119] Nevertheless, with the potential for progress in these areas, we can look forward to a better understanding of osteolysis and improved patient outcomes.

Revision Strategies

The number of implanted cervical disc prostheses of different generations is in the order of 100,000.[120,121] Over 10 years, the rate of revision surgery for CDA among different devices was low (2.1%).[120,121] Ninety percent of revision cases were due to either cervical spondylosis or mechanical complications. Strict adherence to surgical indications, contraindications, and technical performance is crucial to avoid the failure of CDA. After the removal of CDA, different procedures were performed: ACDF with or without decompression (69.6%), combined anterior/posterior fusion/decompression (11.6%), and replacement of CDA (7.2%).[120,121] Patients requiring revision surgery for mechanical complications or those who underwent a combined surgical approach were at significantly higher risk for subsequent short-term complications ($P < 0.05$).[120,121] Although the prosthesis survival is meager compared with ACDF, we still need valuable information on planning revision cases.[122] Future directions and prospects that can further propel the employment of cervical arthroplasty are outlined in Table 2.

CONCLUSIONS

CDA has already proven its efficacy in clinical use, and we are on the brink of significant advancements that will further refine the technology and enhance clinical outcomes. Ongoing research in kinematics and biomaterials is set to substantially improve implant efficiency, minimize complications, and reduce costs. The evolution of CDA is expected to be supported by robust laboratory and clinical data, expanding its indications to include complex conditions such as

Table 2. Future developments in cervical arthroplasty.

Expansion of Indications
>2 levels
Index level kyphosis
Collapsed discs
Cervical spondylotic myelopathy
Congenital canal stenosis
Improved Biokinematics Signature and Prosthesis Survival
Custom-made devices to match individual's COR and LDC
Protection of compensatory mechanism while aging
Biomaterials to reduce wear and debris
Understand and Control Complications
Anterior osteolysis: timeline, causes, and management
Heterotopic calcification control
Revision strategies for failed cases
Econometrics
Long-term value-based studies
Device costs
Surgeon's reimbursement

Abbreviations: COR, center of rotation; LDC, load-displacement curves.

multilevel symptomatic disc degeneration beyond 2 levels, degenerative cervical myelopathy, variations in kyphotic indices, collapsed discs, and CCS. Additionally, value-based research is likely to play a pivotal role in promoting the widespread adoption of CDA, improving cost-effectiveness, and facilitating better reimbursement structures for surgeons. This progression promises to broaden the therapeutic scope of CDA and solidify its role in advancing spinal health and patient quality of life, ultimately positioning it as a cornerstone in managing cervical spine disorders.

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