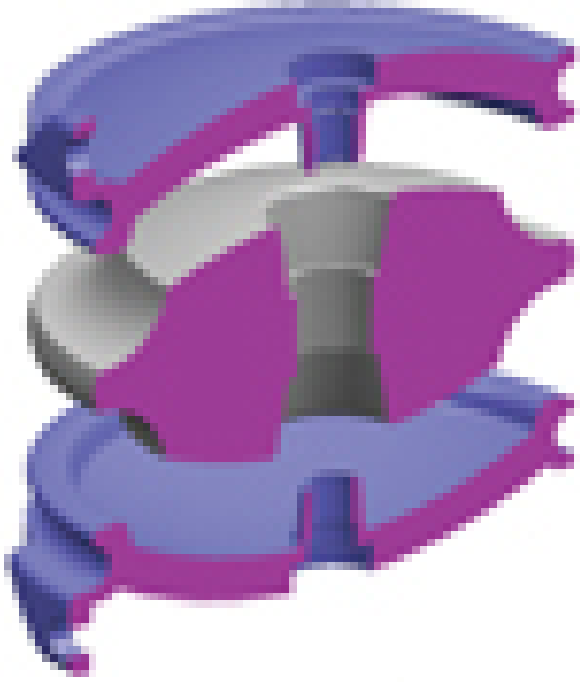

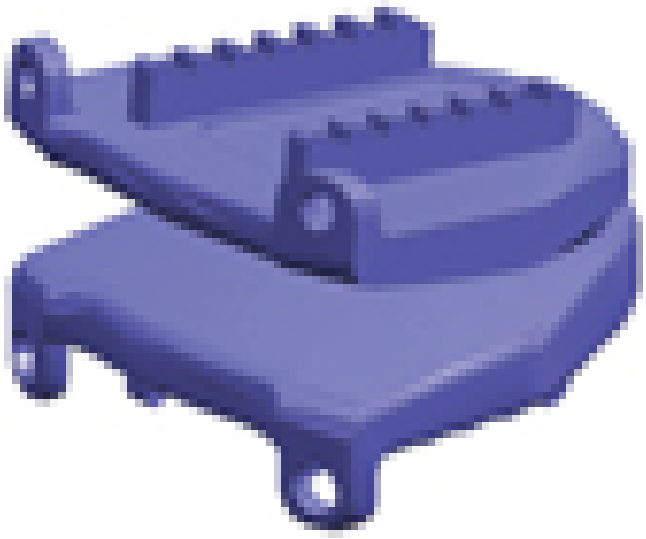

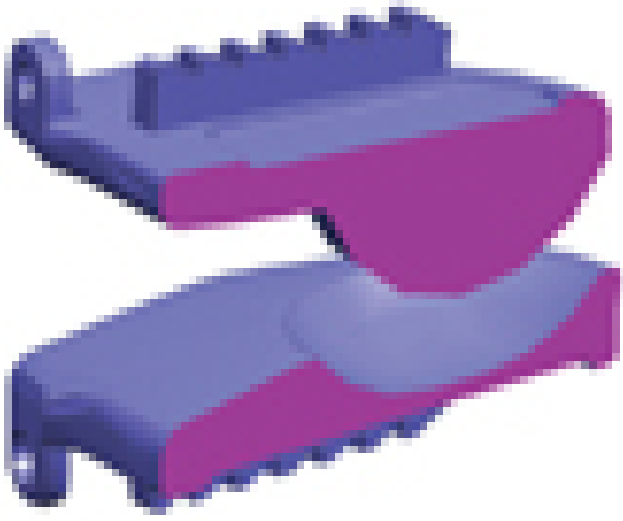

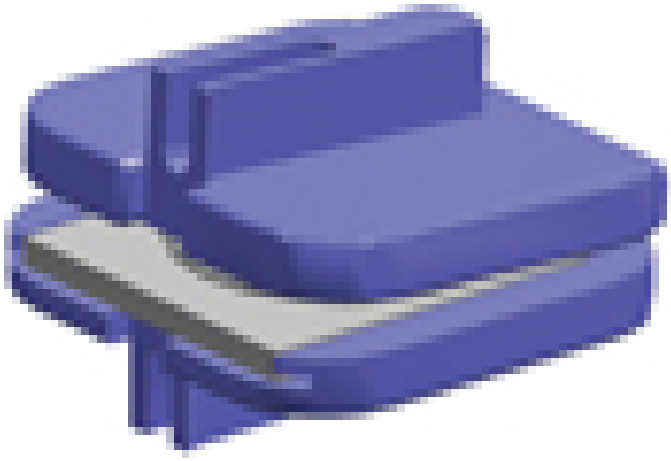

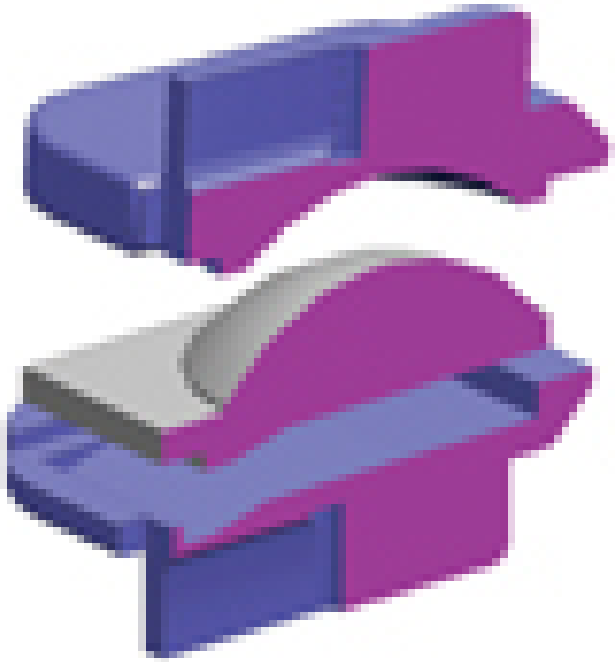

Neurosurg Focus 28 (6):E1, 2010

Introduction

Dynamic stabilization

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The traditional treatment of neurosurgical spinal disorders involved decompression of the spinal cord and/or nerve roots. Fusion was utilized to stabilize segments that became unstable due to either progressive degenerative changes or iatrogenic changes resulting from a decompressive surgical procedure. An alternative, newer treatment has emerged in the form of dynamic stabilization, which provides more stability than is present following a decompression surgery and less rigidity than occurs following a fusion procedure. The value of dynamic stabilization is evaluated in this edition of *Neurosurgical Focus*.

An additional concept to be explored is the use of disc arthroplasty procedures in either the cervical or lumbar spines. In arthroplasty surgery, the pathological disc is excised and replaced by an artificial disc that allows preservation of motion at the operated segment.

Both arthroplasty and dynamic stabilization are being increasingly used to treat disorders of the cervical and lumbar spines. In this edition of *Neurosurgical Focus*, the articles explore the indications, results, complications, and clinical outcomes of a variety of treatment methods. A large number of well-written, high-quality manuscripts were submitted, and the 5 highest-rated cervical and the 5 highest-rated lumbar papers were chosen by multiple reviewers for publication in this edition.

These areas of treatment are quite new, and thus, there is little currently available in the medical literature on these topics. We hope that following review of these articles, the reader will have gained an appreciation for the possibilities that exist, between decompression and fusion, for treatment of disorders of the spine. *(DOI: 10.3171/2010.6.FOCUS.Intro)*

Neurosurg Focus 28 (6):E2, 2010

The use of a hybrid dynamic stabilization and fusion system in the lumbar spine: preliminary experience

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Object. The authors report the use and preliminary results of a novel hybrid dynamic stabilization and fusion construct for the surgical treatment of degenerative lumbar spine pathology.

Methods. The authors performed a retrospective chart review of all patients who underwent posterior lumbar instrumentation with the Dynesys-to-Optima (DTO) hybrid dynamic stabilization and fusion system. Preoperative symptoms, visual analog scale (VAS) pain scores, perioperative complications, and the need for subsequent revision surgery were recorded. Each patient was then contacted via telephone to determine current symptoms and VAS score. Follow-up was available for 22 of 24 patients, and the follow-up period ranged from 1 to 22 months. Clinical outcome was gauged by comparing VAS scores prior to surgery and at the time of telephone interview.

Results. A total of 24 consecutive patients underwent lumbar arthrodesis surgery in which the hybrid system was used for adjacent-level dynamic stabilization. The mean preoperative VAS score was 8.8, whereas the mean postoperative VAS score was 5.3. There were five perioperative complications that included 2 durotomies and 2 wound infections. In addition, 1 patient had a symptomatic medially placed pedicle screw that required revision. These complications were not thought to be specific to the DTO system itself. In 3 patients treatment failed, with treatment failure being defined as persistent preoperative symptoms requiring reoperation.

Conclusions. The DTO system represents a novel hybrid dynamic stabilization and fusion construct. The technique holds promise as an alternative to multilevel lumbar arthrodesis while potentially decreasing the risk of adjacent-segment disease following lumbar arthrodesis. The technology is still in its infancy and therefore follow-up, when available, remains short. The authors report their preliminary experience using a hybrid system in 24 patients, along with short-interval clinical and radiographic follow-up. *(DOI: 10.3171/2010.3.FOCUS1055)*

Key Words • dynamic stabilization • motion preservation • lumbar spine • degenerative disc disease

Over the past decade, spinal arthrodesis with or without instrumentation has become a common technique in the surgical treatment of symptomatic degenerative disease of the lumbar spine. Technological advances such as transpedicular instrumentation have resulted in increased fusion rates, while decreasing the need for postoperative immobilization and brace therapy, and have fueled a seemingly inexorable (recently estimated as 4-fold) increase in the number of spinal fusions performed each year.[9] However, while many patients have benefited from fusion procedures, successful (that is, solid) fusion has not always been accompanied by clinical improvement.[2] This apparent disconnect between surgical and clinical outcomes raises important questions. Does this subset of patients represent a failure of patient selection and should these patients have been offered a different surgery more likely to address their particular pathology? Might spinal fusion lead in some cases to secondary, delayed effects that negatively affect the final clinical outcome?

Evidence is growing that fusion may in fact have undesirable long-term effects on the remainder of the spine, particularly on the immediately adjacent motion segments.[3,4] This adjacent-level degeneration is typically seen rostral to a fused segment but may also occur caudal to a fusion, especially when the fusion occurs at the L4–5 level. The phenomenon is thought to be due to the altered biomechanics of the fused spine, wherein abnormal forces acting upon the intervertebral discs and facet joints adjacent to the fused segment precipitate the accelerated failure of these stabilizing elements.[5] From this evidence for adjacent-segment degeneration emerged the concept of "dynamic" or nonfusion stabilization of the lumbar spine.

Posterior dynamic stabilization, in which pedicle screw fixation is coupled with a flexible longitudinal connecting system, presumably allows for the normalization of intersegmental motion.[6–8] This stands in contrast to traditional fusion surgery, in which the goal is complete

Abbreviations used in this paper: DTO = Dynesys-to-Optima; VAS = visual analog scale.

Fig. 1. Photograph of the DTO implant, which is a hybrid construct with dynamically stabilized segment (at left) and rigidly fixated segment (at right). Image used with permission from Zimmer Spine.

and immediate elimination of motion and, ultimately, arthrodesis. While both strategies seek to address the underlying pathology of microinstability, the dynamic stabilization approach promises to do so in a more physiological manner. By "restoring" normal motion, mobility is theoretically preserved rather than eliminated, and the forces acting above and below the construct are altered to a lesser extent, reducing the potential undesirable effects of fusion.

Nearly a dozen such systems are currently available, and all employ a variety of motion-preserving technologies ranging from semirigid rods to ball-and-socket joints.[1] Of note, due in large part to the exigencies of the medical device approval process, FDA approval of these systems has thus far been for their use as an adjunct to fusion in the lumbar spine, a decision based on the demonstration of noninferiority of the approved systems compared with traditional pedicle screw/rod–based fusion. Nevertheless, "off-label" use for motion-preservation surgery is widespread, and several investigational device exemption studies for nonfusion applications are ongoing.

At our institution, we have been using one of these systems—the Dynesys Dynamic Stabilization System (Zimmer Spine)—for motion-preservation surgery for nearly 5 years. Recently available is a hybrid system (DTO, Zimmer Spine; Fig. 1) in which dynamic stabilization may be performed immediately above (or less commonly, below) a fusion. The system is intended for use in patients in whom fusion is desired—whether to treat gross instability or severe, advanced degeneration—at one or more levels, and in whom one or more adjacent segments exhibit degenerative changes that are thought to be contributing to the patient's symptoms but are not of a severe-enough degree to warrant arthrodesis. This study was performed to evaluate the preliminary experience with the DTO hybrid construct.

Methods

We performed a retrospective review of all DTO posterior lumbar hybrid dynamic stabilization and fusion procedures at the University of Pittsburgh Medical Center, Presbyterian Hospital. Patients with degenerative lumbar disc disease were chosen to undergo the procedure if they were candidates for fusion and had symptomatic adjacent-level pathology in which dynamic stabilization was thought to be more appropriate than arthrodesis. The DTO procedure involves placement of standard transpedicular instrumentation and fusion utilizing the Zimmer Optima system at segments deemed to require rigid fixation and fusion. A unique Dynesys screw is then placed in the superior pedicle of the segment believed to be at risk for subsequent degeneration adjacent to the fusion. A transitional screw is placed in the intervening pedicle that allows the 2 systems to be connected. An intertransverse process fusion is then performed at the levels to be fused and is typically supplemented with interbody fusion via a transforaminal approach. Autograft bone, obtained from the same incision in the course of the bony decompression, is supplemented with demineralized bone matrix and laid down between the decorticated transverse processes.

TABLE 1: Summary of demographics

Variable	Value
sex	
male	12
female	12
age (yrs)	
range	29–66
mean	49
prior lumbar op	
yes	15
no	9

Medical records were reviewed to determine preoperative VAS pain scores (with 1 being very little pain and 10 being very severe pain) obtained at the time of surgical consent, to assess clinical outcomes at follow-up (including the need for reoperation), and to record complications. Postoperative imaging studies, including radiographs, CT scans, and MR images, were reviewed when available. Patients were contacted via telephone at the time of chart review to assess their current level of back and leg pain. In all cases, patient permission was obtained for this review.

Results

A total of 24 patients underwent the DTO procedure between March 2008 and December 2009. The mean patient age was 49 years (range 29–66 years). There were 12 men and 12 women. Fifteen patients had undergone previous lumbar surgery at one or more of the surgically treated levels. Patient demographics are summarized in Table 1. Figure 2 shows a representative case, including a preoperative provocative discogram and postoperative lateral radiograph.

Clinical Outcomes

Postoperative VAS scores were available for 22 (92%) of the 24 patients. The mean follow-up duration was 8

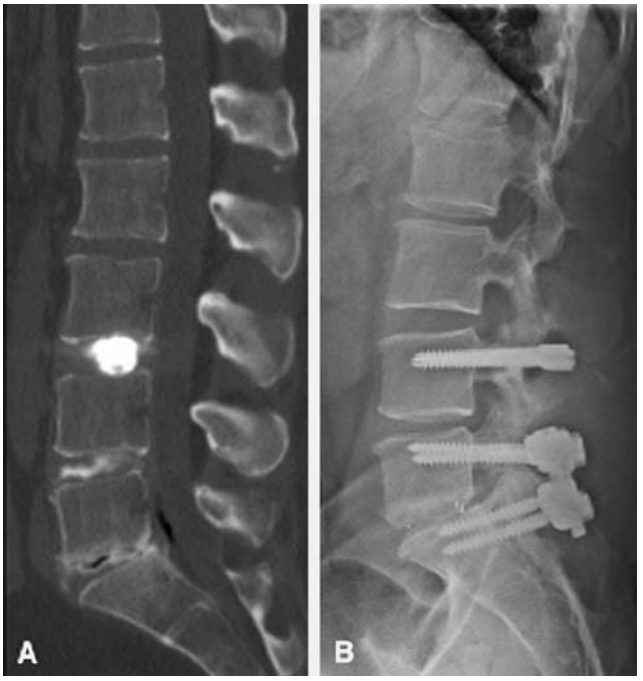

Fig. 2. Radiographs obtained in a 43-year-old man with a 5-year history of disabling low-back pain and in whom nonsurgical therapy had failed. **A:** A preoperative blinded provocative discographic study was performed and demonstrated severe disc degeneration with contrast extravasation and concordant pain replication at L5–S1. Less severe disc degeneration with an anular tear but nonconcordant pain replication was demonstrated at the L4–5 level. The L3–4 level was found to be completely normal on CT scanning. **B:** A postoperative lateral radiograph demonstrating the hybrid construct with a dynamically stabilized segment (L4–5) above a rigid fused segment (L5–S1).

months (range 1–22 months). For the entire group, the mean preoperative VAS score was 8.8, and the mean postoperative VAS score was 5.3. Pain in 3 patients improved by 7 points, in 2 patients by 6 points, in 3 patients by 5 points, in 3 patients by 4 points, in 3 patients by 3 points, in 4 patients by 2 points, and 4 patients rated their pain unchanged. Of the 4 patients who experienced no improvement in pain, one case was notable for the patient having a complicated postoperative course requiring reoperation after 8 months for a disc herniation at the stabilized level, which was further complicated by a wound infection requiring irrigation and debridement and long-term antibiotics. The other 3 patients had an uneventful postoperative course.

Complications

There were 5 perioperative complications. These included 2 dural tears for which primary repair was performed. In 1 of the patients with a dural tear, a persistent CSF leak developed and required wound revision. One patient awoke with new radicular pain that was attributable to a medially placed L-4 pedicle screw. This patient was taken back to the operating room and underwent revision of the screw. In 2 patients a postoperative wound infection developed, in both of whom the incisions healed following irrigation and debridement of the wound. All of these cases were believed to be unrelated to the DTO system itself and were thought to be rather typical for lumbar arthrodesis surgery with instrumentation. There were no cases of hardware failure.

TABLE 2: Summary of pain scores, complications, and treatment failures*

Factor	Value
mean VAS score	
preop	8.8
postop	5.3
no. of complications	
dural tear	2†
symptomatic screw misplacement	1
wound infection	2
no. of treatment failures	
symptomatic degeneration at the DSS‡	1
symptomatic degeneration above the DSS‡	2

* DSS = dynamically stabilized segment.
† One of the 2 patients required operative wound revision for a persistent CSF leak.

Treatment Failures

Treatment failure was defined as persistent pain or the need for further surgery at either the surgically treated or adjacent levels. Three patients (12%) underwent extension of their fusion for adjacent-level disease during this follow-up period. In one patient, persistent pain attributed to the dynamically stabilized level prompted revision with interbody fusion at that level. In 2 other patients adjacent-level disease developed immediately rostral to the dynamically stabilized segment. Results are summarized in Table 2.

Discussion

The phenomenon of adjacent-segment disease, referring to accelerated degenerative changes occurring at the ends of the fused spine, has received increasing attention as ever more spinal fusions are performed and long-term follow-up data become available.[3,7] While the time course and prevalence of adjacent-segment disease are not fully known, there is increasing evidence in the spine literature that its effects may be seen soon after fusion surgery and in as many as 30% of patients.[3,4] In a recently published large retrospective analysis Cheh et al.[3] reported a rate of clinical adjacent-segment disease of 30.3% and showed that patients in whom adjacent-level disease developed had significantly worse Oswestry Disability Index scores than those without adjacent-level disease. They further identified age > 50 years at time of surgery, increasing length of fusion, and extension of the fusion to L1–3 as significant risk factors for the development of adjacent-level disease. No significant difference was identified between posterior and circumferential fusion.

Over the past 20 years, an array of posterior pedicle fixation–based motion preservation systems have been introduced as many in the spine community have sought to

decrease the incidence of adjacent-level disease.[1] One of these systems—the Dynesys Dynamic Stabilization System—has been in use at our institution for the past 5 years. More recently, we have begun to use a hybrid system in which Dynesys dynamic stabilization is performed above (or less commonly, below) a traditional pedicle screw–augmented fusion. The DTO hybrid construct has proven useful in the treatment of the patient in whom decompression and fusion are required at one or more levels, but in whom there is also the potential for symptomatic degenerative changes at one or more adjacent levels. In our series, clinical improvement, as measured by changes in VAS pain scores, was seen in 18 (82%) of 22 patients. Three (12%) of the original 24 patients developed symptomatic degenerative changes at or above the dynamically stabilized levels and subsequently underwent revision with fusion—a not insignificant rate of adjacent-segment degeneration whose cause is the subject of an ongoing investigation. Finally, 5 (21%) of 24 patients experienced a complication, including 2 dural tears, 2 wound infections, and a single screw misplacement requiring revision. However, these complications were not believed to have been related to the actual DTO system itself.

Conclusions

The DTO hybrid system represents a unique new technology that allows for the coupling of arthrodesis with dynamic stabilization at adjacent levels in the lumbar spine. Application of the technique is in the early stages, and long-term follow-up data are therefore scarce. However, based on preliminary results in 24 patients, the technique merits further investigation as an alternative to multilevel lumbar arthrodesis.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: PC Gerszten, MB Maserati, MJ Tormenti. Acquisition of data: MB Maserati, MJ Tormenti, CM Bonfield, DM Panczykowski. Analysis and interpretation of data: PC Gerszten, MB Maserati, MJ Tormenti. Drafting the article: MB Maserati, MJ Tormenti. Critically revising the article: PC Gerszten. Reviewed final version of the manuscript and approved it for submission: PC Gerszten. Statistical analysis: MB Maserati, MJ Tormenti, DM Panczykowski. Administrative/technical/material support: PC Gerszten. Study supervision: PC Gerszten.

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Degenerative lumbar spinal stenosis with neurogenic intermittent claudication and treatment with the Aperius PercLID System: a preliminary report

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Object. The aim of this study was to evaluate whether clinical improvement is noticeable after a minimally invasive procedure such as that used with the Aperius PercLID System in patients with degenerative lumbar spinal stenosis (DLSS) and neurogenic intermittent claudication (NIC).

Methods. The patients were treated with the aforementioned system at 3 different centers. The initial requirement to be included in the study was a minimum follow-up of 12 months. The authors studied 40 cases of DLSS in patients with NIC (age 72.7 ± 8.08 years). Symptom severity, physical function, quality of life, and self-rated pain were assessed preoperatively and at the 12-month follow-up using the Zurich Claudication Questionnaire (ZCQ) and a visual analog scale. The procedure was conducted under spinal (35 patients) or local (5 patients) anesthesia, using biplanar fluoroscopy for visualization.

Results. Single-level treatment was performed in 28 patients and 2-level treatment was performed in 12 patients. Based on time recordings in 24 cases, the mean procedural time was 19.9 ± 5.0 minutes. The mean pain visual analog scale score improved significantly from 8.1 ± 2.19 at baseline to 3.44 ± 2.89 at the 1-year follow-up. The ZCQ score for patient satisfaction showed 90% of the patients being satisfied with the procedure. The mean rates of improvement in ZCQ score for symptom severity and physical function at 1 year were 38.7 ± 33.3% and 33.8 ± 29.7%, respectively, and both proved to be statistically significant. Most improvement was seen in mobility, pain/discomfort, and ability for self-care.

Conclusions. In this preliminary study, the Aperius system provided clinically significant improvement after 1 year of follow-up in patients older than 65 years with DLSS and NIC. *(DOI: 10.3171/2010.3.FOCUS1034)*

Key Words • lumbar spinal stenosis • neurogenic claudication • Aperius PercLID System • treament • interspinous process device

In an older or high-risk population, a short minimally invasive procedure may represent an added value when treating lumbar spinal stenosis. For that purpose, a variety of spinal devices have been developed. Interspinous process devices for the lumbar spine are intended to mechanically distract the spinous processes to increase the size of the spinal canal and neural foramina. However, the alleged treatment objectives are quite variable, including management of degenerative spinal stenosis, discogenic low-back pain, facet syndrome, disc herniations, and instability. A hard dynamic stabilization system designed in 1986 to congeal unstable operated degenerative lumbar segments with an interspinous blocker and to limit extension, the device also had a tension band around the spinous processes to secure the implant and limit flexion.[28] The procedure was reversible and if low-back pain persisted or recurred, the device was removed and stability was achieved using fusion. Since this prototype other interspinous extension-limiting devices—also referred to as interspinous process devices—have been developed, their use has been rapidly increasing in recent years. Different extension-limiting devices, from static spacers to dynamic devices, composed of various different materials, are now available for the treatment of lumbar spine diseases. A landmark technical advance is attributed to Minns and Walsh,[21] who in 1997 first reported a novel soft implant design for resisting the instability of the lumbar spine in the sagittal plane. Meanwhile, the development of a less invasive approach has favored the acceptance of these techniques by patients and treating physicians.[7,12] These devices represent an effective treatment option for a variety of lesions, including lumbar spondylosis and lumbar spinal stenosis, as recognized by

Abbreviations used in this paper: DLSS = degenerative lumbar spinal stenosis; NIC = neurogenic intermittent claudication; NSAID = nonsteroidal antiinflammatory drug; VAS = visual analog scale; ZCQ = Zurich Claudication Questionnaire.

TABLE 1: Summary of modified Macnab criteria outcome

Outcome	Description
excellent	free of pain; no restriction of mobility; able to return to normal work & activities
good	occasional nonradicular pain; relief of presenting symptoms; able to return to modified work
fair	some improved functional capacity; still handicapped &/or unemployed
poor	continued objective symptoms of root involvement; additional op intervention needed at index level irrespective of repeat op or length of postop period

some experts in the field.[9] All have in common that, at the treated level, they increase the interspinous space, limit extension movement while reducing loading on the disc, anulus, and the facet joints. The results of an MR imaging study conducted in cadaveric spine samples in extension[26] demonstrated that insertion of an interspinous device resulted in an increase in the spinal canal area of 18%, spinal canal diameter of 10%, and subarticular diameter of 48%. The exit space of the nerve root was remarkably enlarged, showing an increase of 25% in foramen area and of 41% in foramen width. This was achieved without significant modification of the adjacent spinal levels.

A percutaneous technique for the Aperius PercLID System (Medtronic) was introduced to the market about 3 years ago.[20] The minimally invasive procedure may represent a treatment option in older or high-risk patients with DLSS and NIC with or without low-back pain.

Methods

Three different centers played a role in the study. Of 116 patients treated with a percutaneous system for NIC, we found 40 patients older than 65 years and with a minimum follow-up of 1 year. Fifty patients had a follow-up of less than a year—20 of them less than 6 months. Twenty-two of 62 patients with 1 year of follow-up were younger than 65 years. Four patients were lost to follow-up. All patients had undergone a previous course of conservative treatment, including pain and physical rehabilitation, which failed to provide adequate NIC and pain relief.

We selected 40 patients with DLSS and NIC with a minimum of 1 year of follow-up after treatment with the Aperius PercLID System. Data were collected prospectively, and clinical outcomes were graded using modified Macnab criteria (Table 1).[24] Also, symptom severity, physical functioning, quality of life, and self-rated pain were assessed preoperatively and at 12 months after surgery using the ZCQ and the VAS.[18,26,27] The study group comprised 19 men and 21 women whose mean age at operation was 72.7 ± 8.08 years. Relevant medical history included hypertension (38 patients), heart valvulopathy (12 patients), chronic vascular disease (8 patients), diabetes (8 patients), asthma (4 patients), chronic lung disease (4 patients), and thyroid disease (4 patients).

Single-level treatment was performed in 28 patients and 2-level surgery in 12 patients. In 11 patients a single-level procedure was performed at L3–4; in 12 at L4–5; and in 7 at L5–S1 (Fig. 1). In 6 patients a 2-level procedure was performed at L3–4 and L4–5 and in 6 at L4–5 and L5–S1. Based on time recordings in 24 cases, the mean procedural time was 19.9 ± 5.0 minutes. No drainage was necessary at the implant site and blood loss was minimal. The Aperius implantation procedure was conducted under general spinal (35 cases) or local (5 cases) anesthesia using continuous biplanar fluoroscopy for visualization (Fig. 2).

Fig. 1. Photographs showing the Aperius PercLID System. The system is composed of a set of color-coded distraction trocars of increasing sizes (8, 10, 12, and 14 mm) **(left)**, and of the preassembled inserter devices with implants **(right)**. There are 4 individually packaged color-coded inserters for adequate implant deployment and release, each with implants of 8, 10, 12, and 14 mm, respectively. Each device is for a single use. The 8-mm distraction trocar *(yellow)* has a sharp pointed tip to facilitate piercing of the interspinous ligament for the subsequent trocars and for the implant. Each trocar and each inserter has a curved shape, which facilitates convenient access to the target level and optimal positioning of the implant. Each implant is preassembled on the inserter so it can be inserted without intermediate steps once the desired distraction is achieved. The implant core is made of titanium (TiAl6V4) alloy, whereas the external shell is composed of commercially pure titanium. Both of these materials are MR imaging compatible and offer resistance over time to keep the interspinous space open.

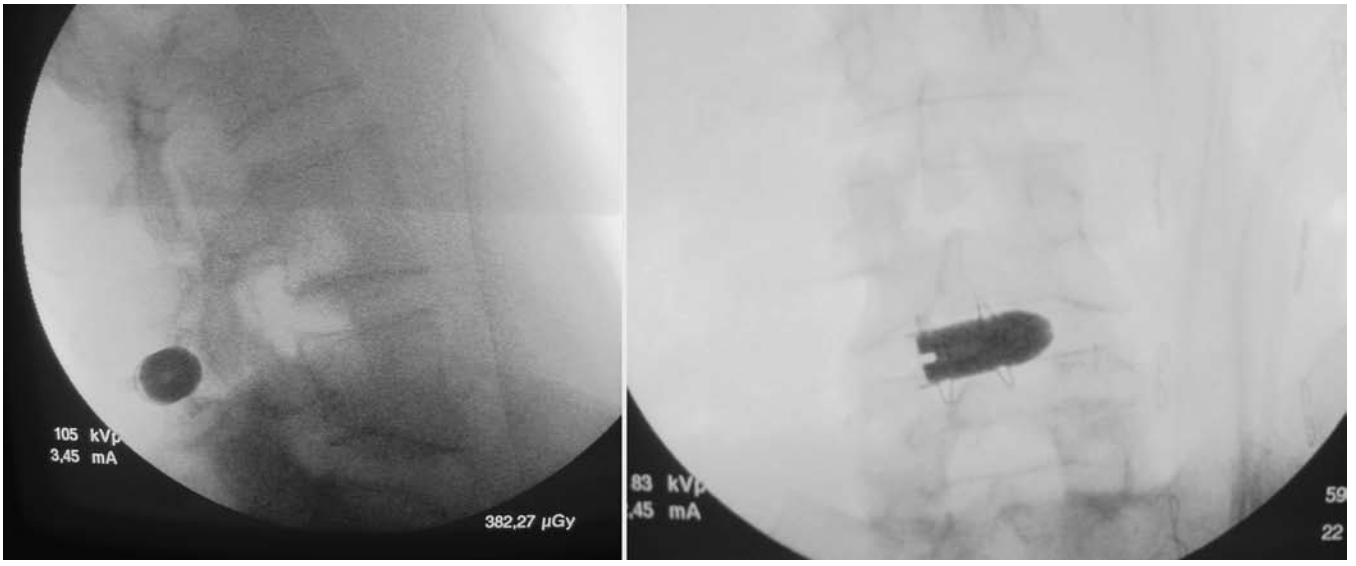

Fig. 2. Lateral **(left)** and anteroposterior **(right)** radiographs of the lumbar spine obtained intraoperatively, showing the inserted device at the L3–4 level.

Results

Postoperatively, the type of analgesic agent required, the frequency of analgesic agent use, and the time to ambulation were recorded to classify the degree of wound pain. Patients who needed only oral NSAIDs for pain relief and who were ambulatory on the day of surgery or the 1st postoperative day were classified as having mild wound pain (25 patients); those requiring an NSAID and 4 or fewer narcotic injections for pain relief and who were ambulatory on the 2nd postoperative day were classified as having moderate pain (15 patients); and those needing an NSAID and 5 or more narcotic injections and who were ambulatory only on or after the 3rd postoperative day were classified as having severe wound pain, which was not seen in any case.

Patients were mobilized 6–12 hours postoperatively or as soon as possible and allowed to ambulate on the same day or on postoperative Day 1 to be discharged home on postoperative Day 2. All patients were advised to wear a lumbosacral nonrigid vest for 40 days. In addition most patients received rehabilitation for pain and lower-extremity motor function.

Follow-up durations ranged from 12 to 18 months (mean 16 months). Postoperative clinical status was rated according to the modified Macnab criteria.[24] Overall results were excellent in 70% of the cases, good in 20%, and fair in 10%. No poor results were seen. Dynamic spinal radiography was performed at 2, 6, and 12 months postoperatively to measure lumbar stability and the extent to which preexisting instability, if it existed, worsened after the operation, but this was not seen. No implant migration was reported.

The mean overall pain VAS score improved significantly from 7.1 ± 2.19 at baseline to 3.44 ± 2.89 at 1 year ($p < 0.0001$).

Mean rates of improvement in ZCQ score for symptom severity and physical function at 1 year were 38.7 ± 33.3% ($p = 0.0002$) and 33.8 ± 29.7% ($p < 0.0001$), respectively, and both proved to be statistically significantly. The ZCQ score for patient satisfaction showed that 90% of the patients were satisfied with the procedure.

Discussion

We report our preliminary experience from 3 different centers using the Aperius system to treat patients with DLSS. Symptomatic DLSS with NIC represents the most common, and rapidly increasing, surgical indication in patients older than 65 years.[32] Nearly 8% of the adult population presents with DLSS;[10] of these, 5% of patients with low-back pain consulting a general medical practitioner present with DLSS,[11,32] whereas 15% of patients with low-back pain who consult a medical specialist present with DLSS.[14] It is worthy of recognition that surgical procedures for DLSS in patients older than 65 years have shown an 8-fold rise in number in the last 20 years.[14,16,17,32]

Clinical Findings and Relevance

Lumbar spinal stenosis was first described by Verbiest[34,35] in the early 1950s, after he observed that laminectomy relieved sciatic symptoms in 4 patients with narrowed spinal canals in the absence of disc herniations. Graded cauda equina or radicular syndromes can also be exacerbated by acute disc intrusions.[19–35] Patients typically present with complete or near-complete canal or lateral recess obliteration before development of classic NIC or activity-induced leg pain. Therefore, the diagnosis of lumbar stenosis should be reserved for those patients in whom the classic features are demonstrated on clinical examination and diagnostic imaging.[2,6] Patients with predominant complaints of low-back pain or atypical or nonradicular leg pain, and in whom moderate stenosis is evident on spinal imaging, respond poorly to surgery and should probably not be considered to have a diagnosis of lumbar stenosis.[18] This is reflected in the fact that many patients will require reintervention for persistent symp-

TABLE 2: The rate of reintervention due to persistent symptoms in lumbar spine surgery*

Authors & Year	No. of Patients Needing Reintervention	Follow-Up (mos)	Rate of Reintervention (%)
Caputy & Luessenhop, 1992	16 of 88	60 yrs	18
Markwalder, 1993	12 of 100	33	12
Jönsson & Strömqvist, 1994	19 of 105	6–54	18
Katz et al., 1996	20 of 88	96	23
Atlas, 1996	5 of 76	12	6
Hansraj et al., 2001	4 of 103	24–60	5
Atlas, 2005	NA	98–120	23
Jansson et al., 2005	628 of 9664	120	11

* NA = not applicable.

toms. Conservative treatment success rates vary from 15 to 50%.[1,14,16,17,33] In the past, failure of conservative therapy has generally occurred 4–6 years after the onset of DLSS symptoms, leaving decompression surgery as the only treatment alternative.[6,17,32,37] Reoperation rates vary from 5 to 23% indicating that the initial surgery is often not the last.[1,8,10,16] This is depicted in Table 2. To date, our patients have not required reoperation, although admittedly our follow-up period is still short.

Age-Related Complications of Spinal Surgery

The postoperative morbidity and mortality rate following traditional lumbar surgery, predominantly for lumbar stenosis and disc disease, is highest in the geriatric population, which may be defined as comprising patients older than 70 years of age. Risks for hospitalized patients, along with hospital charges, similarly increased with advancing years. Fusions in geriatric patients carried the highest complication rate and demanded the greatest hospital resources.[10,16,23,33] In a series reported by Smith and Hanigan[30] of 78 patients undergoing lumbar laminectomies for stenosis or herniated disc without fusions, 85.2% experienced improvement after discectomy, whereas 81.4% with stenosis had fair to good outcomes. Those at greatest risk harbored 3 or more preoperative medical risk factors (for example, cardiovascular or pulmonary disease, diabetes, and hypertension). All our patients have some relevant medical history including heart or lung disease.

On the other hand, Quigley and colleagues[25] reported on 143 patients older than 70 years of age who underwent 155 operations. Averaging 74.9 years of age, most patients had disc disease together with stenosis, or had stenosis alone. Hospital stay was not prolonged by advanced age, and the overall incidence of major morbidity without mortality was 6.9%. All our patients were older than 65 years, and we did not have morbidity associated with surgery. Most patients left the hospital on the 1st postoperative day.

Stand-Alone Treatment

In 2007 Palmer et al.[23] introduced a posterior dynamic stabilization system that was tested in human cadaveric spines dissected from L-2 to L-5, and leaving all ligamentous structures intact. Neuroimaging analysis showed 84% less compression of the posterior disc of the instrumented spines during extension, and no difference during flexion, compared with intact spines. The main conclusion was that the posterior dynamic stabilization system has the benefit of being a completely percutaneous technique, which can be used at all levels of the lumbar spine, including S-1. This system, similar to the open surgical technique,[5,36] limited spinal motion,[5,23] enlarged the foramina,[29] and achieved disc decompression.[30]

Similarly, the Aperius PercLID System is a standalone percutaneous interspinous decompression system that achieves neural element decompression solely through interspinous process distraction. The system offers, by limiting extension, a percutaneous procedure without open decompression surgery.[20] The ipsilateral and contralateral wings prevent lateral migration, minimizing the risk of neural damage. Additionally, the procedure can be carried out using a local anesthetic with sedation when general anesthesia represents a high risk to the patient.

The typical profile of a candidate for Aperius PercLID System is generally a patient older than 50 years of age with mild to moderate symptom severity in whom initial conservative treatment has failed, and who is experiencing NIC symptoms—with or without back pain—exacerbated by prolonged standing or by activities in the upright posture, and relieved by a flexed position of the lumbar spine. There is imaging evidence of DLSS with clinical confirmation of NIC, and the interspinous process spaces from L-1 to L-5 are anatomically suitable for placement of the device.

Relative and absolute contraindications are the following: lumbar degenerative spondylolisthesis greater than Grade 1 (on a scale of 1–4) at the affected level; significant hypermobility observed during radiological imaging; proven allergy to device material (titanium and titanium alloy);[20] scoliotic deformity with a Cobb angle higher than 25°; proven radiological ankylosis of the affected level; kyphosis that requires surgical correction; proven spinous process fracture at the affected level; Paget disease; and active infection or tumor of the spine.

There are certain precautions that the surgeon must take—for example, a patient with a fixed motor deficit, or angina pectoris, active rheumatoid arthritis, peripheral vascular disease, advanced diabetes, or any other systemic disease that may affect directly or indirectly the am-

bulatory capabilities of the patient, may not benefit after insertion of an Aperius device. Additionally, patients with severe osteoporosis (bone mineral density of the spine or hip of –2.5 T-score) may be at risk for unsuccessful standalone treatment.

Most of our patients did not have osteoporosis, and of those who did have some, none was of the severe type.

Conclusions

Increasing life expectancy has made lumbar spinal stenosis a common pathology in the elderly. Also, the number of old or high-risk patients requiring neurosurgical intervention for the treatment of NIC is rapidly increasing. In this preliminary report of 40 patients older than 65 years with DLSS, NIC, and a minimum follow-up duration of 1 year, treated with the Aperius PercLID System in 3 hospitals, we observed adequate clinical improvement for degenerative spinal disease. The system's dynamic or reversible condition allows, if necessary, for subsequent conventional arthrodesis in selected cases. A caveat of this study is the relatively short follow-up period. Although all our patients underwent a previous course of conservative treatment, we did not study a comparative cohort of patients who had undergone either traditional open surgery or other minimally invasive technique.

Disclosure

Dr. Fabrizi is a senior consultant for Medtronic. All other authors do not have any commercial interest with the product described in this study.

Author contributions to the study and manuscript preparation include the following. Conception and design: M Galarza. Analysis and interpretation of data: M Galarza, R Gazzeri. Drafting the article: M Galarza. Critically revising the article: M Galarza, R Gazzeri, JF Martínez-Lage. Reviewed final version of the manuscript and approved it for submission: all authors.

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Cervical motion preservation using mesenchymal progenitor cells and pentosan polysulfate, a novel chondrogenic agent: preliminary study in an ovine model

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Object. There is an unmet need for a procedure that could generate a biological disc substitute while at the same time preserving the normal surgical practice of achieving anterior cervical decompression. The objective of the present study was to test the hypothesis that adult allogeneic mesenchymal progenitor cells (MPCs) formulated with a chondrogenic agent could synthesize a cartilaginous matrix when implanted into a biodegradable carrier and cage, and over time, might serve as a dynamic interbody spacer following anterior cervical discectomy (ACD).

Methods. Eighteen ewes were divided randomly into 3 groups of 6 animals. Each animal was subjected to C3–4 and C4–5 ACD followed by implantation of bioresorbable interbody cages and graft containment plates. The cage was packed with 1 of 3 implants. In Group A, the implant was Gelfoam sponge only. In Group B, the implant consisted of Gelfoam sponge with 1 million MPCs only. In Group C, the implant was Gelfoam sponge with 1 million MPCs formulated with the chondrogenic agent pentosan polysulfate (PPS). In each animal the cartilaginous endplates were retained intact at 1 level, and perforated in a standardized manner at the other level. Allogeneic ovine MPCs were derived from a single batch of immunoselected and culture-expanded MPCs isolated from bone marrow of outbred sheep (mixed stock). Radiological and histological measures were used to assess cartilage formation and the presence or absence of new bone formation.

Results. The MPCs with or without PPS were safe and well-tolerated in the ovine cervical spine. There was no significant difference between groups in the radiographic or histological outcome measures, regardless of whether endplates were perforated or retained intact. According to CT scans obtained at 3 months after the operation, new bone formation within the interbody space was observed in the Gelfoam only group (Group A) in 9 (75%) of 12 interbody spaces, and 11 (92%) of 12 animals in the MPC cohort (Group B) had new bone formation within the interbody space. Significantly, in the MPC & PPS group (Group C), there were only 1 (8%) of 12 levels with new bone formation ($p = 0.0009$ vs Group A; $p = 0.0001$ vs Group B). According to histological results, there was significantly more cartilaginous tissue within the interbody cages of Group C (MPC & PPS) compared with both the control group (Group A; $p = 0.003$) and the MPC Group ($p = 0.017$).

Conclusions. This study demonstrated the feasibility of using MPCs in combination with PPS to produce cartilaginous tissue to replace the intervertebral disc following ACD. This biological approach may offer a means preserving spinal motion and offers an alternative to fusion to artificial prostheses. *(DOI: 10.3171/2010.3.FOCUS1050)*

Key Words • anterior cervical discectomy • pentosan polysulfate • mesenchymal stem cell • tissue engineering • sheep • Gelfoam

Cervical discectomy is a common procedure, which is usually performed for neural decompression in patients experiencing radiculopathic or myelopathic symptoms. Cloward, Smith, and Robinson[7,8,30,34] introduced ACDF in the 1950s to address this problem and modifications of their techniques are still widely used today.

Regardless of the cervical fusion technique employed, a long-term sequela of adjacent segment disease can be recurrent pain from adjacent nerve root compression.[14] The incidence of symptomatic adjacent segment disease in a group of 374 patients followed for a maximum of 21 years after anterior cervical fusion was found to be 2.9% per year and up to 25.6% at 10 years.[13] Other

Abbreviations used in this paper: ACD = anterior cervical discectomy; ACDF = ACD and fusion; ICRS = International Cartilage Repair Society; MPC = mesenchymal progenitor cell; PPS = pentosan polysulfate.

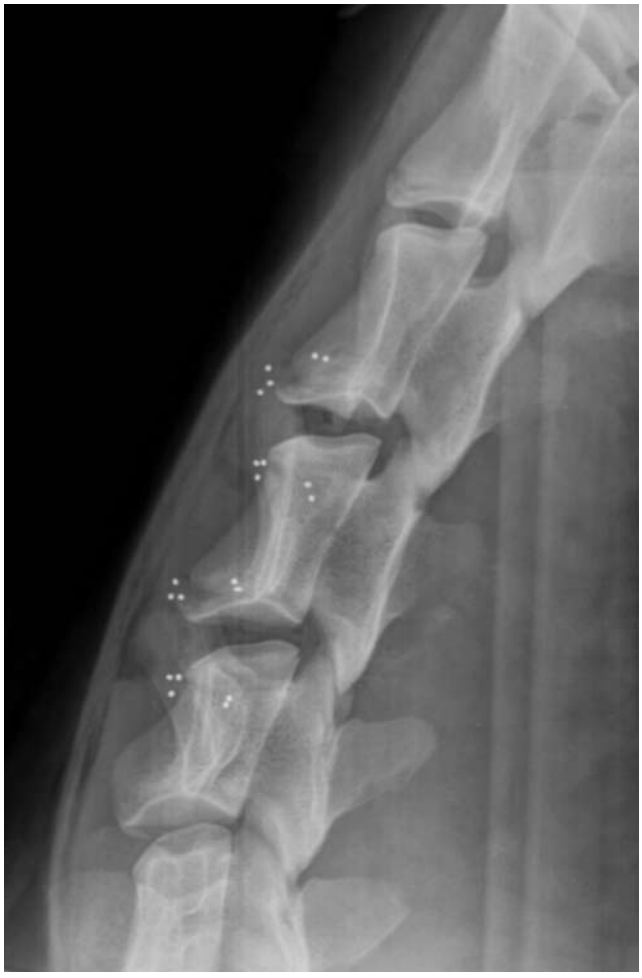

Fig. 1. Lateral radiograph showing modified Cornerstone HSR cervical cage and Mystique Hydrosorb cervical plate at C3–4 and C4–5. The white dots are the radiolucent markers on the proximal and distal screws and plates (top and bottom); thus there are 5 points at each attachment point.

studies also report increased intradiscal pressure at adjacent levels to fused vertebrae, which may account for the adjacent segment disease.[11,28] Many patients requiring ACDF also exhibit signs of preexisting spondylosis at other levels and it has been shown that an even higher incidence of symptoms may develop in these patients following ACDF.[20]

In an attempt to minimize the long-term problems associated with adjacent segment disease, a variety of motion preservation techniques and devices have been evaluated in select patient groups. For example, cervical disc arthroplasty has been evaluated in comparison with conventional interbody fusion in prospective trials, but the results have been mixed.[2,9,10,22,26,27,29,31] Recently, one investigative group performed allograft disc transplants in humans in an attempt to provide a biological alterative to artificial disc prosthesis.[32] Cervical discs, together with endplates and uncovertebral joints, were removed from donors and stored in 10% dimethyl sulfoxide with 10% calf serum and frozen in liquid nitrogen. In a series of 5 patients with a 5-year follow-up period, 1 patient displayed radiological evidence of fusion across the transplanted disc space, whereas sagittal motion was maintained in 4 of 5 patients. As assessed by MR imaging, preservation of disc hydration was present in 2 of 5 patients, and although the authors were unable to provide evidence that the anulus and nucleus cells of the transplanted discs survived, they suggest that their approach led to no adjacent segment disease at 5 years.

There are clearly many practical difficulties associated with human disc transplantation and it is unlikely to become part of routine clinical practice in the immediate term. Nevertheless, there is an unmet need for a procedure that could generate a biological disc substitute, while at the same time preserving the normal surgical practice of achieving cervical spine decompression. The objective of the present study was to test the hypothesis that adult allogeneic MPCs formulated with a chondrogenic agent could synthesize a cartilaginous matrix when implanted into a biodegradable carrier and cage, which over time might serve as a flexible interbody spacer. It should be emphasized that in this preliminary experimental study, the objective was not to produce a new intervertebral disc, but rather a cartilaginous tissue within the body of the resorbable cage.

Methods

Study Design

Eighteen Border-Leicester/Merino ewes (2 years old) were divided randomly into 3 groups of 6 animals. Each animal was subjected to C3–4 and C4–5 ACD following the standardized surgical procedure.[19] A custom-modified noncrystalline polylactide copolymer with a 70:30 ratio of poly(L-lactide) to poly(D,L-lactide) (Hydrosorb Cornerstone HSR, Medtronic), was packed with 1 of 3 implants then inserted into each disc space. In Group A, the implant consisted of Gelfoam only (Pharmacia & Upjohn Co.). In Group B, the implant was composed of Gelfoam containing 100 μl of 1 million immunoselected MPCs (Mesoblast Ltd.) suspended in 1.0 ml Profreeze (Lonza Ltd.).[21] The implant in Group C was Gelfoam containing 100 μl of 1 million MPCs/ml Profreeze formulated prior to cryopreservation with 100 μg/ml of PPS (Proteobioactives Pty Ltd.). Group C was designated the "MPC & PPS" group.

Anterior plating to each level was then performed using a Mystique Hydrosorb cervical plate (Medtronic) and screws (Fig. 1). In total, 36 cervical spinal levels were included in the study. Animals were killed at 3 months. The study was approved by the Animal Research Ethics Committee of the School of Biomedical Sciences, Monash University, Victoria, Australia.

Endplate Treatment

The retention of the cartilaginous endplates, while potentially inhibiting fusion and promoting chondrogenesis within the interbody space, could also inhibit nutrition to the implanted cells. In the light of this possibility, 1 random level in each animal was selected and the endplates were perforated in a standardized manner using a

Fig. 2. Photographs of custom-made instrument used for standardized perforation of endplates.

custom-made tool (Fig. 2). This procedure ensured that 16 holes (0.5-mm wide × 0.5-mm deep) were made through the endplates into the vertebral bone at the designated levels. Each animal had the identical implant placed at both C3–4 and C4–5 levels, but 1 level was randomly assigned to have the endplates perforated and the other endplates were retained intact (Table 1).

Cervical Plate, Interbody Cage, and Carrier

The cages, plates, and screws were made from polylactic acid and were bioresorbable. The Mystique Cornerstone interbody cage (6-mm high × 11-mm long × 14-mm wide) was specifically modified to increase the internal volume to 472 mm^3. This cage was packed with the same volume of Gelfoam carrier in every case. In the cell-treated groups, the MPCs were added to the carrier within the cage (Fig. 3 left) and allowed to soak into the sponge, avoiding spillage (Fig. 3 right). The Mystique Hydrosorb cervical plate (25 mm) was secured to each operated level using 4 Mystique (3 × 13 mm) screws (Fig. 4).

Surgical Technique and Postoperative Care

The surgical procedure has been previously described.[19] Animals were fasted 12–24 hours before surgery and were allowed water ad libitum. Sheep were positioned supine on the operating table and anesthetized by intravenous injection of thiopentone (20 mg/kg); anesthesia was maintained using isoflurane (1–3%) inhalation. Local anesthetic (0.5% bupivacaine with 1:200,000 adrenaline) was injected prior to a right anterolateral approach through a longitudinal neck incision. The longus colli muscle was elevated bilaterally using diathermy and the position of the C3–4 and C4–5 levels were confirmed with fluoroscopy. Distraction was achieved with 16-mm Caspar pins followed by a total discectomy, but the cartilaginous endplates were carefully preserved. No attempt was made to open the posterior longitudinal ligament. All cages were inserted and countersunk by approximately 3 mm. As per the manufacturer's instructions, the Mystique plates were then molded using hot saline to reconstruct the anterior column and to act as a graft containment device. The longus colli muscle was then approximated by suture, followed by layered closure and subcuticular suture to skin.

A fentanyl patch was administered postoperatively. Following extubation, the sheep were transferred to a metabolic cage for observation. After 3 days, the sheep were transferred to open pastures for the duration of the study and observed regularly. The sheep were allowed to graze ad libitum and supplemented with Lucerne chaff.

TABLE 1: Summary of study design and number of operated levels

Treated Levels	No. of Operated Levels		
	MPC Group (B)	MPC & PPS Group (C)	Control Group (A)
C3–4 perforated	3	3	3
C4–5 intact	3	3	3
C3–4 intact	3	3	3
C4–5 perforated	3	3	3

Postmortem Analysis

All sheep were killed at 3 months by overdose using 150 mg/kg of pentobarbitone sodium. Clinical veterinarians performed autopsy examinations on the sheep in a blinded fashion.

Radiographic Analysis

Plain lateral and selected anteroposterior digital radiographs were obtained in all animals (Radlink Atomscope HF 200A) of the cervical spine preoperatively, within 24 hours following surgery, and at 1-, 2-, and 3-months postoperatively. The radiography was performed while the sheep were under sedation using metomidine (0.025 mg/kg intravenously) and reversed using atipamezole (0.125 mg/kg intravenously). After the sheep were killed at 3 months, multislice CT (Siemens Sensation 64) was performed on the isolated spine, and multiplanar images were acquired with 0.6-mm collimation on a 64-slice-scanner and reconstructed in the sagittal, axial, and coronal planes. Fusion, or lack thereof, was assessed by plain radiography and fusion was defined by continuous bridging of the trabecular bone and the absence of ra-

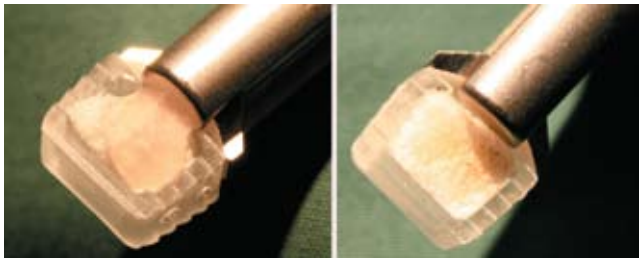

Fig. 3. Modified Cornerstone HSR cervical cage packed with Gelfoam with MSCs added **(left)** and after MSCs have soaked in **(right).**

diolucent lines at 3 months on CT.[3,5] The interbody space was assessed, in a blinded manner, for the presence or absence of new bone formation (Fig. 5).

Histological Analysis

Following extraction, the spine was placed in 10% normal buffered formalin. The C3–4 and C4–5 motion segments were then cut from the remainder of the spine using a band saw. These 2 segments were cut in the midsagittal plane into 2 blocks, each containing the cage, with 3 mm of the superior and inferior vertebral bodies on either side. Decalcification was performed using 10% formic acid for 2 weeks. The blocks were then dehydrated in ascending concentrations of ethanol before being placed in neat chloroform overnight to dissolve the polylactic acid cage and plates. Dehydration was again performed in ascending concentrations of ethanol under agitation before clearing in xylene prior to embedding in paraffin. Six-micron sections were then cut in the sagittal plane and stained with H & E, Alcian blue, toluidine blue, or Masson trichrome. A modified scoring system based on the ICRS scoring system (Table 2) was used for scoring the sections (Fig. 6).[25] A board-certified veterinary pathologist blinded to treatment condition scored each section.

Statistical Analysis

Data were analyzed using 1-way ANOVA followed by the Dunnett multiple comparison test where significant differences were observed. The 2-tailed Student t-test was used for comparison of parametric data and the

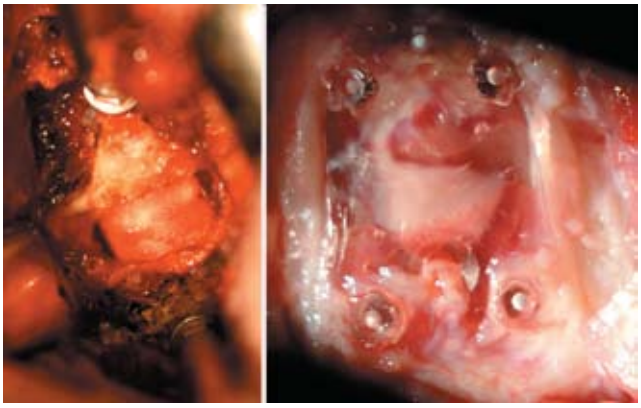

Fig. 4. Left: Intraoperative photograph showing interbody cage and carrier in disc space following discectomy. **Right:** Photograph at 3 months postmortem showing plate, screws, and cage with its contents.

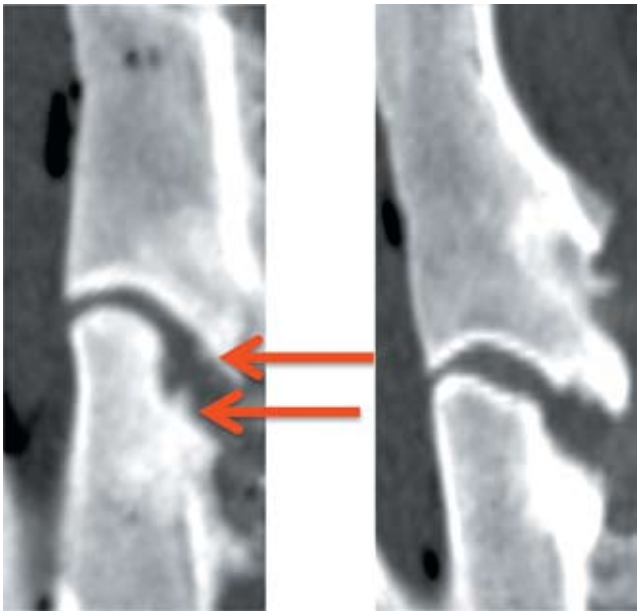

Fig. 5. Sagittal CT scans showing an example of new bone formation **(left)** within the interbody space *(arrow)* and no new bone formation within the interbody space **(right)**. Note anterior subperiosteal bone formation in both images.

Fisher exact test was used for contingency data. Prism 5.0 (Graph Pad Software) was used for the statistical analysis. Values were expressed as means and SDs unless otherwise stated. A probability value < 0.05 was considered statistically significant.

Results

Adverse Events

No surgical- or cell-related adverse events were observed during the study or at postmortem. All animals were ambulant within 2 hours of surgery. A degree of graft extrusion was noted in all animals by 3 months. This extrusion was generally due to anterior vertebral subperiosteal bone formation above and below the disc space, which elevated the plate and caused migration of the cage (Fig. 7). The cages migrated anteriorly a mean distance of 5 mm (range 3–10 mm) but there were no differences in extent of cage or plate movement between the experimental groups.

Endplate Treatment

There was no significant difference between groups

TABLE 2: Modified ICRS histological scoring system used for this study

Matrix	Score*
bone	0
fibrous tissue	1
fibrocartilage	2
mixed fibro/hyaline cartilage	3
hyaline cartilage	4

* Evidence of ossification within cartilage, subtract 1.

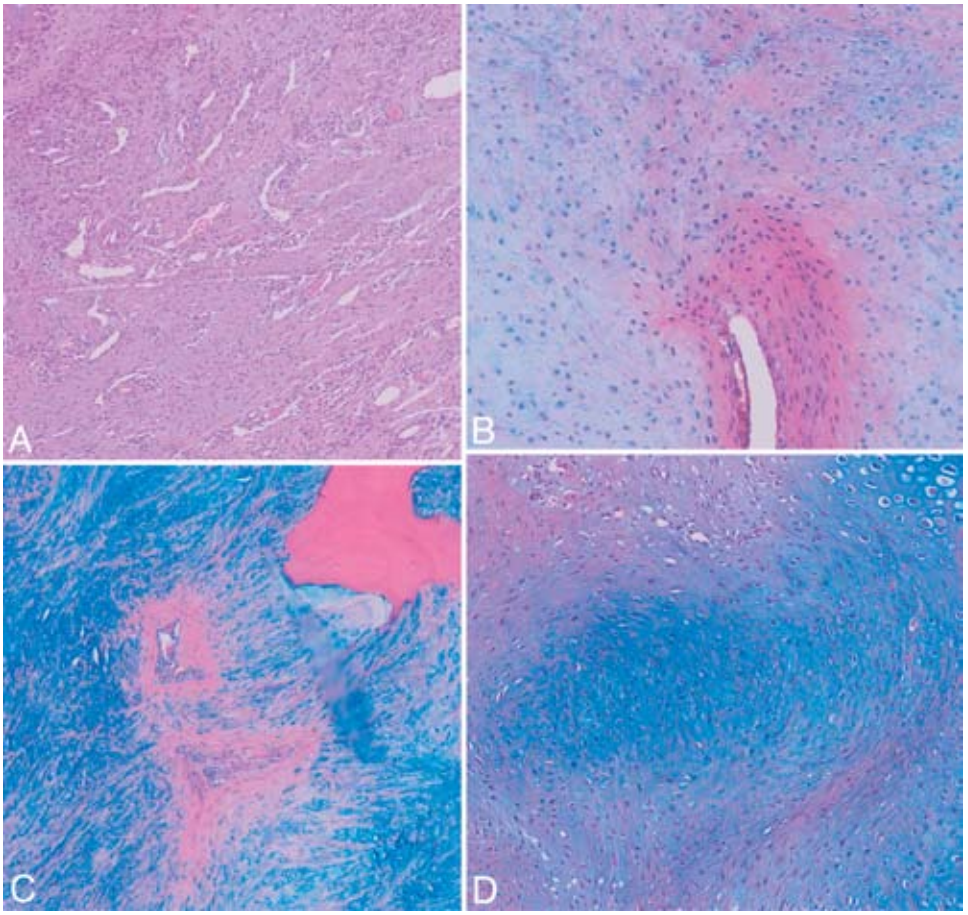

Fig. 6. Photomicrographs showing examples of the modified ICRS histological grading system: **A**, fibrous tissue (score 1); **B**, fibrocartilage (score 2); **C**, hyaline cartilage with ossification (score 3); **D**, hyaline cartilage (score 4). H & E and Alcian blue. Magnification × 4.

in the radiographic or histological outcome measures, regardless of whether endplates were perforated or retained intact.

Radiographic Results

Continuous bridging of trabecular bone was not observed in any animal, at any time point, by plain radiography or by CT scan. According to CT scans obtained at 3 months, new bone formation within the interbody space was observed (Table 3, Fig. 8) in Group A (Gelfoam only) in 9 (75%) of 12 interbody spaces, with 4 of 6 levels having perforated endplates and 5 of 6 with intact endplates. Eleven (92%) of 12 animals in the MPC cohort (Group B) had new bone formation within the interbody space, with 5 of 6 levels having perforated endplates and 6 of 6 with intact endplates. Significantly, in the MPC & PPS group (Group C), there was only 1 (8%) of 12 levels with new bone formation and this occurred in a perforated endplate level ($p = 0.0009$ vs Group A and $p = 0.0001$ vs Group B).

Histological Results

No inflammatory, infective, or neoplastic changes were evident in any specimen recovered from any group. No difference was observed in the modified ICRS histology score between control Group A and MPC Group B; mean scores were 0.92 ± 0.29 and 1.08 ± 0.79, respectively, and were indicative of predominantly fibrous tissue within the interbody cage area. Significantly, in the MPC & PPS group (Group C), predominantly cartilaginous tissue within the interbody cages was found with a mean modified ICRS histology score of 2.28 ± 1.35. This score was significantly higher than the control group ($p = 0.003$) and the MPC group ($p = 0.017$; Fig. 9).

Discussion

The results of the histological studies provide proof of concept for our working hypothesis that it is possible to perform a conventional ACD while at the same time generating, in situ, a cartilaginous tissue that has the potential to form an interbody mobile segment. Moreover, the MPC & PPS group, in contrast to the other experimental groups, failed to deposit bone to any large extent within the confines of the cage.

Although the present studies have shown that it is possible to grow cartilage from MPC & PPS seeded into a collagen scaffold within a Hydrosorb cage placed in a spinal location that normally supports fusion, the duration of the study was too short to determine if complete interbody chondrification occurred after the cage

was resorbed. Furthermore, based on the existing literature,[11,13,14,19,27] we can only speculate as to whether the long-term clinical outcomes would be superior to the current practice of spinal fusion. In particular, the biomechanical characteristics of a cartilaginous tissue as a replacement for the tougher fibrocartilaginous anulus fibrosis must be questioned in relation to maintaining the functional stability of the cervical spine during articulation and axial loading. Additional longer-term multidisciplinary studies are clearly required to address these important issues.

Our previous studies with an ovine model of ACDF using the same allogeneic ovine MPC & Mastergraft hydroxyapatite/tricalcium phosphate granules in a Fidji interbody cage, when evaluated after 12 weeks showed 75% continuous bone bridge formation compared with 33% in the group that received granules alone.[17] On the basis of these results, and notwithstanding the absence of the osteoconductive hydroxyapatite/tricalcium phosphate granules, it might be predicted that a greater amount of new bone formation was deposited within the cage after 12 weeks than was observed by CT in the present study. While it is possible that with time these small bone spurs may advance to frank bone bridging, the radiographic and histological studies clearly showed that after 12 weeks there was an increased frequency of bone spur deposition in cages containing MPC alone compared with the formulation containing MPC & PPS.

The inhibition of new bone formation by MPCs coupled with enhanced cartilage production arises from the ability of PPS to selectively direct the differentiation of MPCs and other mesenchymal stem cells down the chondrogenic lineage. In vitro studies have confirmed the concentration-dependent upregulation of cartilage associated genes SOX-9, aggrecan, and Type II collagen, and downregulation of bone-associated genes, Type I collagen, and RUNX2 gene expression by MPCs cultured in micromass, pellets,[16] or Gelfoam sponges in the presence of PPS (Goldschlager T, Ghosh P, Wu AW, Shimmon S, Abdelkadar A, Jenkin G, et al., unpublished abstract ["Regeneration of the cervical intervertebral disc part 1: enhanced proliferation and chondrogenic differentiation of mesenchymal precursor stem cells (MPC) cultured in collagen sponges in the presence of pentosan polysulfate (PPS)"] presented at the Cervical Spine Research Society Annual Meeting, 2009). These findings were supplemented by biochemical assays that confirmed that PPS also directed chondrogenic differentiation of MPCs at the protein level[16] (Goldschlager T, Ghosh P, Wu AW, Shimmon S, Abdelkadar A, Jenkin G, et al., unpublished abstract ["Regeneration of the cervical intervertebral disc part 1: enhanced proliferation and chondrogenic differentiation of mesenchymal precursor stem cells (MPC) cultured in collagen sponges in the presence of pentosan polysulfate (PPS)"] presented at the Cervical Spine Research Society Annual Meeting, 2009).

TABLE 3: Levels with new bone formation within the interbody space

Group	C3–4 Intact	C3–4 Perforated	C4–5 Intact	C4–5 Perforated
Control (A)	2	3	3	1
MPC (B)	3	2	3	3
MPC & PPS (C)	0	1	0	0

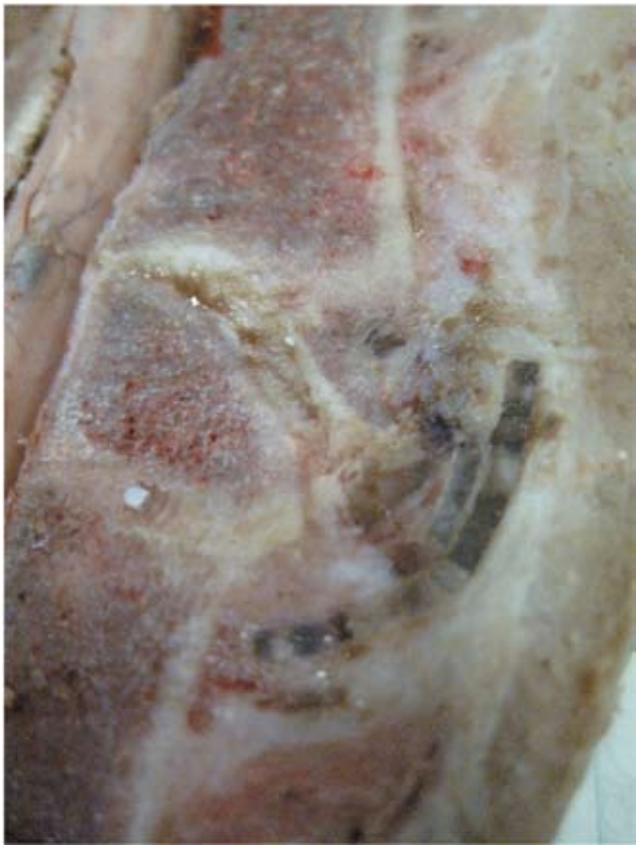

Fig. 7. Sagittal section of the cervical spine after sacrifice at 3 months showing anterior migration of the cage and plate.

In contrast to the majority of previous investigations that have used transforming growth factor–β, bone morphogenetic proteins, or other proteinaceous growth factors to induce chondrogenic differentiation of mesenchymal stem cells,[6,23] PPS is a semisynthetic sulfated polysaccharide that has been used for more than 40 years for

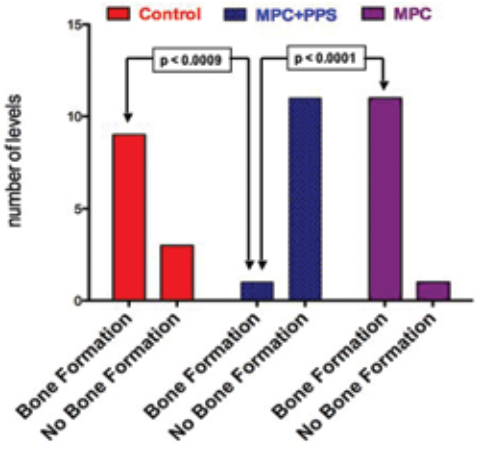

Fig. 8. Graph of new bone formation determined by CT at 3 months in each experimental group. p = 0.002 for ANOVA.

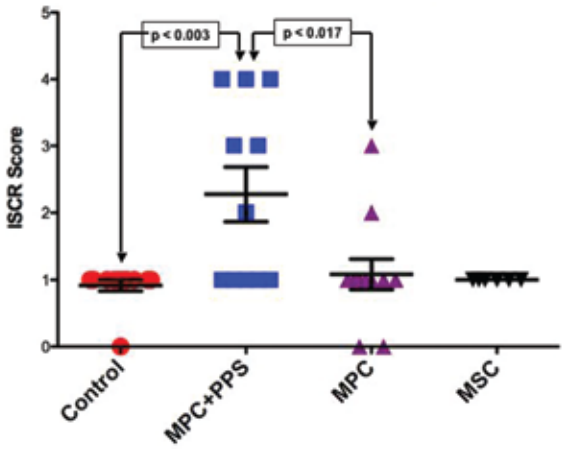

Fig. 9. Graph showing histological assessment of cartilage deposition at 3 months in each experimental group.

a number of clinical applications including osteoarthritis.[12,18] Extensive in vitro and animal model studies have shown that PPS is antiinflammatory, promotes fibrinolysis, and stimulates cartilage matrix synthesis by chondrocytes.[12,13,15] Pentosan polysulfate is also a potent inhibitor of serine proteinases, and it downregulates collagenase production by chondrocytes at the gene promotor level.[1,12] More recently, PPS has been shown to inhibit the cartilage aggrecanases ADAMTS4 and ADAMTS5[35,36] and their binding to the endogenous inhibitor TIMP-3. These data clearly demonstrate the ability of PPS to stimulate the biosynthesis of components of the extracellular matrix while concomitantly limiting their degradation by its direct and indirect anticatabolic effects. These beneficial pharmacological activities of PPS have resulted in its widespread use for the treatment of osteoarthritis in both veterinary[4,12,24] and human practice.[12,14] However, the present study is the first to demonstrate the ability of this drug to induce chondrogenic differentiation of MPC in vivo, thereby highlighting the potential of the MPC & PPS combination in neurological and orthopedic surgery and regenerative medicine.

A major problem encountered in this animal study was the migration or extrusion of the cervical cages and plates. We believe that the retention of the endplates was a likely cause because they reduce friction between the grooves of the cage and the cartilaginous endplate surface. This is less of a problem in the fusion setting where the endplates are removed and the interface between bone and the cage produces a greater degree of friction. However, there are reports of migration of bioresorbable implants in fusion surgery (Lebl DR, Metkar U, Grottkau B, Wood KB, unpublished abstract ["Early failure of bioabsorbable anterior cervical plates"] presented at the Cervical Spine Research Society Annual Meeting, 2009). In the studies described here, the cervical plate was used to contain the cage, as previous testing with a standalone cage in this model resulted in complete extrusion. Periosteal bone formation in the ovine model is well described[33] and caused elevation of the plate, thereby allowing migration of the cage. It is likely that the cage migration negated any potential difference arising from perforating or retaining the endplates. Further studies with custom-made implants for this purpose are in progress. In addition, biomechanical testing will be undertaken 18 months after implantation to ensure complete resorption of the polylactic acid implants occurred, to confirm motion preservation in this model.

Conclusions

This study has demonstrated the feasibility of MPCs in combination with PPS to produce cartilaginous tissue to replace the intervertebral disc following ACD. This biological approach may offer a means of preserving spinal motion and offer an alternative to fusion to artificial prostheses.

Disclosure

The research was partially funded through a sponsored research agreement from Mesoblast Ltd. awarded to Monash University. Peter Ghosh, Stan Gronthos, and Andrew Zannettino are consultants of Mesoblast Ltd. and own stock in this company. Silviu Itescu is an employee of Mesoblast Ltd. and owns stock in the company. Tony Goldschlager has received partial travel support from Mesoblast Ltd. to attend scientific conferences.

Author contributions to the study and manuscript preparation include the following. Conception and design: P Ghosh, T Goldschlager, S Itescu. Acquisition of data: T Goldschlager, G Jenkin. Analysis and interpretation of data: P Ghosh, T Goldschlager, A Zannettino, S Gronthos, G Jenkin. Drafting the article: P Ghosh, T Goldschlager, G Jenkin. Critically revising the article: P Ghosh, T Goldschlager, A Zannettino, S Gronthos, JV Rosenfeld. Reviewed final version of the manuscript and approved it for submission: P Ghosh, T Goldschlager, JV Rosenfeld. Statistical analysis: P Ghosh, T Goldschlager, S Itescu, G Jenkin. Administrative/technical/material support: A Zannettino, S Gronthos, S Itescu, G Jenkin. Study supervision: JV Rosenfeld, G Jenkin.

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A systematic review of randomized trials on the effect of cervical disc arthroplasty on reducing adjacent-level degeneration

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Object. Anterior cervical discectomy and fusion had been considered a safe and effective procedure for radiculopathy and myelopathy in the cervical spine, but degeneration in adjacent spinal levels has been a problem in some patients after fusion. Since 2002, cervical disc arthroplasty has been established as an alternative to fusion. The objective of this study was to review data concerning the role of cervical arthroplasty in reducing adjacent-level degeneration.

Methods. A systematic review was performed using the MEDLINE, EMBASE, Cochrane, and LILACS databases, focusing on a structured question involving the population of interest, types of intervention, types of control, and outcomes studied.

Results. No study has specifically compared the results of arthroplasty with the results of fusion with respect to the rate of postoperative development of adjacent-segment degenerative disease. One paper described a rate for adjacent-level surgery. The level of evidence of that paper was classified 2b, and although its authors found a statistically significant between-groups difference (arthroplasty vs fusion) using log-rank analysis, re-analysis according to number needed to treat (in the current paper) did not reveal statistical significance.

Conclusions. Adjacent-level degeneration has not been adequately studied in a review of the available randomized controlled trials on this topic, and there is no clinical evidence of reduction in adjacent-level degeneration with the use of cervical arthroplasty. *(DOI: 10.3171/2010.3.FOCUS1032)*

Key Words • cervical arthroplasty • fusion • systematic review • adjacent-level degeneration • randomized controlled trial

Cervical radiculopathy and myelopathy are conditions in which cervical spine surgery is frequently performed to alleviate signs and symptoms. Anterior cervical discectomy and fusion had been considered a safe and effective procedure for radiculopathy and myelopathy in the cervical spine, but some patients have been found to develop newly affected areas in adjacent spinal levels after fusion. It has not been proven whether the changes observed in these newly affected levels are, in fact, caused or accelerated by fusion or are a result of the natural history of the degenerative process.[8]

The first paper related to CDA was published in 2002.[5] The author's arguments for CDA development were that accelerated degeneration would occur in intervertebral discs adjacent to immobilized spine segments (as a result of fusion) and the maintenance of movement by CDA could prevent ALD.

Since 2002, the results of several RCTs have been published. In all of these RCTs, the proponents of CDA stated that its rationale was to decrease the likelihood of adjacent-segment degeneration.[7,14–16,18]

The theoretical advantage of arthroplasty, a long-term reduction in ALD, should be demonstrated conclusively for CDA to be considered a viable alternative to ACDF.[4]

Abbreviations used in this paper: ACDF = anterior cervical discectomy and fusion; ALD = adjacent-level degeneration; CDA = cervical disc arthroplasty; LILACS = Literatura Latino Americana e do Caribe em Ciências da Saúde; NDI = neck disability index; NNH = number needed to harm; NNT = number needed to treat; RCT = randomized clinical trial; SF-36 = 36-Item Short Form Health Survey.

The main objective of this study was to review data related to CDA in comparison with fusion, revealing whether CDA has accomplished its objective of lowering the frequency of ALD.

Methods

Criteria for Selecting Studies for This Review

Types of Studies. Due to the potential importance of CDA for the treatment of cervical spine disorders, and due to the existence of RCTs comparing CDA with fusion, only randomized trials were evaluated (Table 1). All nonrandomized trials were excluded (Fig. 1). We excluded single-center studies that have been described as part of multicenter studies analyzed here to avoid repetition of data. Papers with fewer than 30 patients per group may not reveal a real difference in the distribution of outcomes, and thus were discarded.

Types of Participants. The study population included adult patients of both sexes with intractable radiculopathy, myelopathy, or both. Patients also exhibited nerve root or spinal cord compression (or both) by single-level cervical disc herniation.

Types of Intervention. We compared the results of surgical treatment of single-level cervical disc herniation or osteophyte formation with radiculopathy/myelopathy treated by ACDF or CDA.

Types of Outcomes Studied. The rationale for CDA is the prevention of acceleration of ALD. The objective of this manuscript is to determine if CDA lowers ALD, so the primary end point to be studied would be the presence of ALD. End points related to self-rated symptoms and signs and those related to questionnaires, such as quality-of-life questionnaires, were considered as secondary (soft) outcomes and, although described, were not studied. Because ALD occurs over time, and to avoid confusion with reoperation rates for other conditions (for example, as single-level surgeries when a greater number of levels would be appropriate), only studies with at least 2 years of follow-up were analyzed.

Critical Evaluation and Selection of Studies

Papers were classified from 1 to 5, according to the Jadad score.[9] On the Jadad scale, description of randomization, description of blinding in treatment and evaluation, and description of withdrawals and dropouts receives one point. In addition, another point is added or removed if there is or there is not adequate randomization and blinding. The total can range between 0 and 5 (Table 2). A score greater than 3 indicates that a study was performed with sound methodology. A trial with loss of patient follow-up greater than 20% of the initial sample has been considered a poor-quality trial.

The works selected for analysis were classified according to the Jadad method for evaluation of RCTs, but all randomized trials evaluating the effects of CDA on ALD were included for critical appraisal. As recommended, a standardized protocol to limit bias in selecting studies was followed by a predetermined checklist (the 2001 CONSORT checklist,[13] Table 3) evaluating the methodological quality and internal validity of the study, considering only RCTs. Only studies comparing patients with radiculopathy or myelopathy caused by single-level nerve root or spinal cord compression were included. Studies that evaluated different outcomes associated with degeneration adjacent to fusion or adjacent to arthro-

TABLE 1: Randomized controlled trials studying cervical arthroplasty in comparison with fusion*

Authors & Year	Device	Randomization	No. of Pts†	Study Characteristics	Blinding	Overall Loss (%)‡
Heller et al., 2009	Bryan	1:1 ratio, blocks of 4§	424	582 pts enrolled, 30 ctrs, 65 investigators, 24 mos FU	none	28.8
Wang et al., 2008	Bryan	1:1 ratio	59	single ctr, clinical & radiographic eval, 24 mos FU	none	26
Sasso et al., 2008	Bryan			part of major trial		
Coric et al., 2006	Bryan			part of major trial		
Sasso et al., 2007	Bryan			part of major trial		
Hacker, 2005	Bryan			part of major trial		
Riina et al., 2008	Prestige		16	single ctr, FDA approved		
Mummaneni et al., 2007	Prestige	1:1 ratio	421	32 ctrs, 24 mos, 541 pts enrolled FU	none	23
Porchet & Metcalf, 2004	Prestige		9	55 pts enrolled, 24 mos FU		
Murrey et al., 2009	ProDisc C	blocks of 4	209	13 ctrs, 24 mos FU	pts blinded to randomization until postop	3.5
Nabhan et al., 2007[17]	ProDisc C			only 13 mos FU		
Nabhan et al., 2007[16]	ProDisc C			only 24 wks FU		

* Entries with gray shading are the final multicenter studies evaluated. Abbreviations: ctr = center; FU = follow-up; eval = evaluation; Pts = patients.
† Number of patients evaluated at final outcome.
‡ The percentage of patients lost to follow-up.
§ Generated by sponsor.

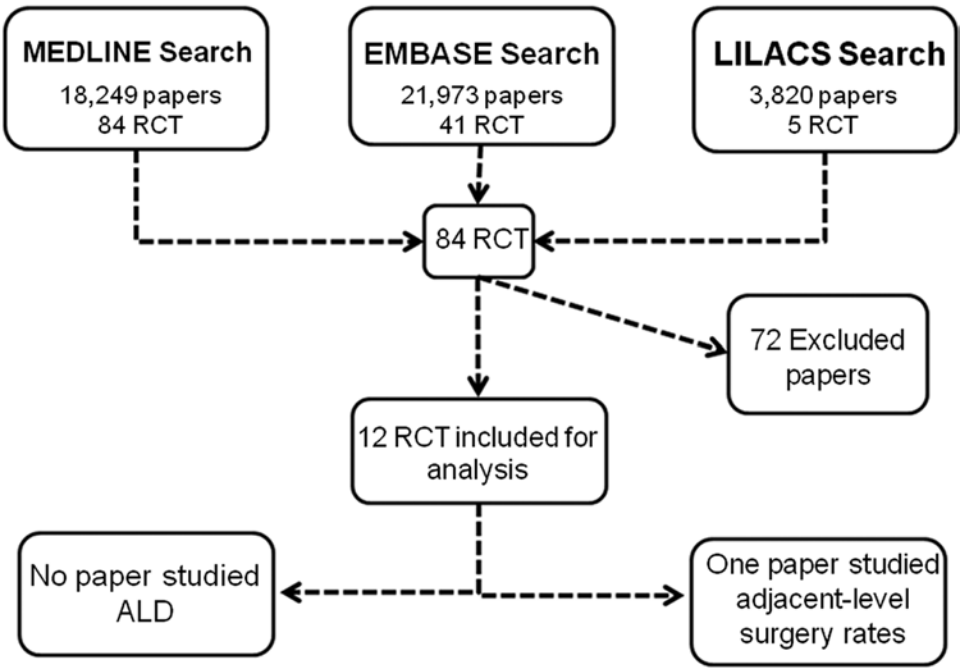

Fig. 1. Flowchart of recorded papers related to CDA and ALD.

plasty, such as neurological outcomes or complications, or any other secondary outcomes were excluded. Studies evaluating the effect of prostheses in cervical myelopathy and studies involving multilevel cervical disc disease were also excluded.

Search Strategy

The study period was between January 2002 and August 2009. This time period was based on the publication of the first paper that described a commercially available CDA device.[5] The search for papers was performed by 2 independent reviewers.

Databases Consulted. We searched MEDLINE, EMBASE, LILACS, and the Cochrane collection of randomized trials.

The MEDLINE search strategy involved a systematic review using the electronic search tool in the PubMed database (http://www.ncbi.nlm.nih.gov/pubmed/). An evidence-based systematic method was used to generate a structured question. This method is called "PICO"[11] (P for population of interest, I for intervention, C for comparison intervention, and O for outcome of interest). The PICO method guided the construction of a focused question according to the descriptors below ("Mesh database"): Search ((((("Cervical Vertebrae"[Mesh] AND "Radiculopathy"[Mesh]) OR "Spinal Cord Diseases"[Mesh]) AND "Arthroplasty, Replacement"[Mesh]) OR "Spinal Fusion"[Mesh]) OR "Arthrodesis"[Mesh]))). A search with these terms recovered 18,249 papers.

The LILACS search strategy used the Mesh terms (in Portuguese) (Coluna vertebral OR Vértebras Cervicais OR Disco intervertebral) AND (Compressão da Medula Espinal OR Síndrome do Cone Medular OR Mielopatia Compressiva OR Radiculopatia OR Compressão da raiz nervosa OR Transtorno da raiz nervosa) AND (Artroplastia OR artroplastia de substituição OR Artrodese OR Artrodese Vertebral, espinal ou da coluna OR Espondilodese OR Espondilossindese OR Fusão Espinal OR Fusão Espinhal) AND (Terapêutica OR Procedimentos Cirúrgicos Operatórios OR Procedimentos Ortopédicos OR Artrodese OR Artroplastia). A search using these terms recovered 3820 papers.

TABLE 2: The Jadad scoring system*

Initial Points		Additional Points		Deductions	
Was the study described as randomized?	1	appropriate randomization	1	randomization was described, but was inappropriate	−1
Was the study described as double blind?	1	appropriate blinding	1	blinding was described, but was inappropriate	−1
Was there a description of withdrawals & dropouts?†	1				
total	3		2		−2

* Based on Jadad et al. Each question must be answered with Yes (1 point) or No (0 points). Additional points are awarded for appropriateness of randomization or blinding. Points are deducted if the method of randomization or blinding is described but inappropriate. A score > 3 indicates that a study was performed with sound methodology.

† To receive the corresponding point, an article should describe the number of withdrawals and dropouts in each study group and provide the underlying reasons.

TABLE 3: Checklist from the 2001 CONSORT statement: items to include when reporting a randomized trial*

	Item No.	Descriptor
Title and abstract	1	How participants were allocated to interventions (eg, "random allocation", "randomised", or "randomly assigned").
Introduction		
Background	2	Scientific background and explanation of rationale.
Methods		
Participants	3	Eligibility criteria for participants and the settings and locations where the data were collected.
Interventions	4	Precise details of the interventions intended for each group and how and when they were actually administered.
Objectives	5	Specific objectives and hypotheses.
Outcomes	6	Clearly defined primary and secondary outcome measures and, when applicable, any methods used to enhance the quality of measurements (eg, multiple observations, training of assessors).
Sample size	7	How sample size was determined and, when applicable, explanation of interim analyses and stopping rules.
Randomisation		
Sequence generation	8	Method used to generate the random allocation sequence, including details of any restriction (eg, blocking, stratification).
Allocation concealment	9	Method used to implement the random allocation sequence (eg, numbered containers or central telephone), clarifying whether the sequence was concealed until interventions were assigned.
Implementation	10	Who generated the allocation sequence, who enrolled participants, and who assigned participants to their groups.
Blinding (masking)	11	Whether or not participants, those administering the interventions, and those assessing the outcomes were aware of group assignment. If not, how the success of masking was assessed.
Statistical methods	12	Statistical methods used to compare groups for primary outcome(s); methods for additional analyses, such as subgroup analyses and adjusted analyses.
Results		
Participant flow	13	Flow of participants through each stage (a diagram is strongly recommended). Specifically, for each group, report the numbers of participants randomly assigned, receiving intended treatment, completing the study protocol, and analysed for the primary outcome. Describe protocol deviations from study as planned, together with reasons.
Recruitment	14	Dates defining the periods of recruitment and follow-up.
Baseline data	15	Baseline demographic and clinical characteristics of each group.
Numbers analysed	16	Number of participants (denominator) in each group included in each analysis and whether the analysis was by "intention to treat." State the results in absolute numbers when feasible (eg, 10/20, not 50%).
Outcomes and estimation	17	For each primary and secondary outcome, a summary of results for each group, and the estimated effect size and its precision (eg, 95% CI).
Ancillary analyses	18	Address multiplicity by reporting any other analyses performed, including subgroup analyses and adjusted analyses, indicating those prespecified and those exploratory.
Adverse events	19	All important adverse events or side-effects in each intervention group.
Discussion		
Interpretation	20	Interpretation of the results, taking into account study hypotheses, sources of potential bias or imprecision and the dangers associated with multiplicity of analyses and outcomes.
Generalisability	21	Generalisability (external validity) of the trial findings.
Overall evidence	22	General interpretation of the results in the context of current evidence.

* Reprinted from Moher D, Schulz KF, Altman DG: The CONSORT statement: revised recommendations for improving the quality of reports of parallel-group randomised trials. **Lancet 357:**1191–1194, 2001. The last column (supplied in the original for indicating the reported page number) has been removed.

The EMBASE search strategy used the terms cervical vertebrae/exp AND radiculopathy/exp OR myelopathy/exp AND spinal fusion/exp OR arthrodesis/exp. A search using these terms recovered 21,973 papers.

The search strategy for the Cochrane collection of randomized trials used the terms cervical spine OR cervical spine arthroplasty OR cervical spine AND artificial disc OR cervical spine arthrodesis OR cervical spine fusion. The search recovered a total of 230 papers.

Statistical Analysis

The results were described as risk, risk difference (increasing or decreasing absolute risk), and the number of patients who must be treated to obtain benefit (NNT) or to cause harm (NNH).

The significance of the results was expressed as a confidence interval or as the probability of a Type I error (p).

The software used in meta-analysis was Comprehensive Meta-Analysis (Biostat, Inc.).

Results

The PubMed Search

The PubMed search revealed a total of 18,249 papers. Of these papers, 184 were described as clinical, randomized trials in humans.

Based on the analysis of titles, the following papers were also excluded: 13 works related to fractures, 2 papers related to the use of bone morphogenic protein (Rh-BMP-2), 100 papers describing conditions in the lumbar spine, 1 study related to absorbable devices, 2 papers related to dynamic systems, 6 papers studying the treatment of multilevel disease, 10 papers exclusively evaluating motion analysis, 1 paper describing the design of a trial, and 3 papers studying conditions associated with low-back pain.

Forty-six papers were reevaluated on the basis of their abstracts. Papers studying other outcomes were excluded.[1–3] The excluded papers are described in Appendix 1.

The bibliographic search revealed 12 randomized studies (Table 1).

The arthroplasty devices studied in RCTs were limited to Bryan, Prestige, and ProDisc C.

The EMBASE Search

The EMBASE search revealed 21,973 papers. Forty-one were described as RCTs but none of them were added to the PubMed search results.

The LILACS Search

Although the LILACS search revealed 3820 papers, only 5 were described as RCTs, and none of them related to the objective of this search.

The Cochrane Search

The search of the Cochrane collection of randomized trials revealed papers that already had been identified previously by the other searches.

Analysis by Type of Device

As there is evidence that the described arthroplasty devices have different mechanical properties, we individually analyzed the results for the different types of devices.[12] For each device, we performed a preliminary evaluation of the recorded evidence (evaluation of all papers initially described as randomized trials) and then performed our primary analysis and data extraction using the papers that satisfied our inclusion criteria.

The Bryan Device

Preliminary Evaluation. The search for RCTs related to the Bryan device recovered 13 papers.[2–4,6,7,10,12,21–24,26,27] One of these papers[2] described adverse events. Another paper[3] focused on 2-level disease. Four papers[10,12,21,22] studied sagittal angulation, stress analyses, cervical kinematics and biomechanical details. One paper[24] was an MR imaging clarity comparison between several arthroplasty devices. Another paper[27] studied the effect of a modified technique. Three papers[4,6,23] were reports by authors who were part of a major study encompassing 30 centers with a longer follow-up.[7] To avoid repetition of data, only the major multicenter study, the 2009 paper by Heller et al.[7] (referred to in the present paper as "The Bryan Study") and the paper by Wang et al.[26] were included for further analysis.

Analysis of the Recorded Evidence. The Bryan Study[7] was published in 2009 and was based on results from 30 primary centers, involving 65 investigators. Five hundred eighty-two patients were randomized initially, and final outcome was evaluated in 424 (91.57% of surgically treated patients were evaluated). Patients were randomly assigned into blocks of 4. There was an initial imbalance of samples regarding the mental component of the SF-36 quality-of-life questionnaire, range of motion, and body mass index. The primary end points studied were the following: a sum improvement greater than or equal to a 15-point improvement in the neck disability index (NDI) (a composite measure termed "overall success"), maintenance or improvement of neurological status, no serious adverse events related to device or surgical procedure, and no subsequent intervention. The outcomes studied were the responses to the questionnaires for the NDI, SF-36, numerical rating scales for neck and arm pain; angular range of motion; and the adverse occurrences in both techniques. The rates of fusion and secondary surgical procedures were also studied. The ALD rates were not specifically studied.

The paper by Wang et al.[26] described 59 patients randomized to treatment with the Bryan device or traditional ACDF. The objective was to study differences in clinical outcomes. The NDI and neck pain (visual analog scale) were evaluated as well as operation time and blood loss. The authors also evaluated the range of motion in the sagittal plane. The ALD rate was not specifically studied.

The Prestige Device

Preliminary Evaluation. The search for articles related to the Prestige device uncovered 4 RCTs.[14,18–20] One paper[19] was a secondary analysis of neurological outcome in patients with myelopathy. Another paper[20] was a single-center study, beginning with 55 patients but reporting final follow-up results in only 9. As final follow-up data from only 16% of the study group was evaluated, this paper was excluded from the analysis.

The 2 remaining papers—the 2007 article by Mummaneni et al.[14] and the 2004 article by Porchet and Metcalf[18]—were RCTs primarily comparing CDA and fusion.

Analysis of the Recorded Evidence. Porchet and Metcalf[18] enrolled 55 patients, 27 of whom received the Prestige device. At the time of the authors' report, 9 had a 24-month follow-up. The outcomes studied were neck and arm pain, NDI scores, SF-36 scores, neurological status, the foraminal compression test (positive or negative results), success of fusion in the Fusion Group and range of motion in the CDA Group, spinal functional success rate, and patient satisfaction. Adjacent-level disease was not studied.

The study reported by Mummaneni et al.[14] was a 32-center RCT with 24 months of follow-up and 541 patients. Beyond other outcomes studied in this paper, the rates for surgeries performed on adjacent levels in both study groups were described and were separated for further analysis.

The ProDisc C Device

Preliminary Evaluation. The search for ProDisc C revealed 3 RCTs.[15–17] Two papers by Nabhan and colleagues[16,17] were based on radiostereometric analysis performed at 24 weeks[16] and at 13 months.[17] In neither paper is there any mention of ALD.

The third paper was a multicenter study by Murrey et al.,[15] involving 13 investigational sites across the US, with 13 primary investigators evaluating 209 randomized patients who had single-level radiculopathy. A noninferiority study design was used.

Analysis of the Recorded Evidence. The study of Murrey et al.[15] was an FDA investigational device exemption study involving 209 patients who underwent surgery between August 2003 and October 2004. Using a fixed-randomization blocking method of 4 assignments per block, a contract research organization generated random allocations in a 1:1 ratio. This paper used the same noninferiority design as was used in the other multicenter RCTs, with the same design and variables but with the addition of a question about satisfaction with the type of treatment provided. The authors described a global rate of secondary surgeries with both experimental and fusion devices, but ALD was not specifically studied.

Critical Evaluation of Qualifying Paper

The study by Mummaneni et al.[14] was the only selected paper describing the rates for surgery adjacent to fusion, the described outcome similar to ALD.

Evaluation According to Checklist Protocol. This study used a noninferiority study design, which, although randomized, is very different from a typical (superiority) RCT. The level of significance determined according to this noninferiority study was $p < 0.10$, whereas $p < 0.05$ is standard in typical RCTs. Randomization was performed using the Plan Procedure in Statistical Analysis System (version 6.12 or higher, SAS). Treatment was 1:1 on a site basis. There was no attempt to conceal allocation of intervention assignment, and neither were there attempts to perform a blinded analysis of results. There was no attempt to perform clinical evaluations in a blinded manner, but the radiological evaluations were performed by 2 independent radiologists. Follow-up evaluations were completed in 80% of the investigational group (223 of 276 patients) and only 75% of the control group (198 of 265 patients). In the control group, measurable flexion-extension radiographs obtained at 24-month follow-up were available in only 125 patients, 56.8% of the 220 for whom comparable preoperative studies were available. These 125 patients represented only 47.2% of the total of 265 initially enrolled.

The interim analysis was performed for the first 250 patients in whom there were successful outcomes at 24 months. The presence of migration between groups was not described. Sample size and estimated differences between groups were calculated according to the noninferiority study design.

Evaluation According to the Jadad Scale. Evaluation based on the scoring system of Jadad et al.[9] yielded a score of < 3. The study was not double blind, and it did not include a precise description of the number of withdrawals and dropouts in each of the study groups and the underlying reasons. Additionally, the loss to follow-up was greater than 20% in the fusion group (56.8%) (Fig. 2) and the CI related to the studied outcome is large. The results of this study are thus considered Level 2b evidence (http://www.cebm.net/index.aspx?o=1025).

Additional Potential Sources of Bias. There was a statistically significant intergroup difference in frequency of alcohol consumption. Radiographic evidence of adjacent-segment degeneration, such as the formation of radial osteophytes or the narrowing of disc space, was not assessed in this study. Adjacent-segment degeneration was assessed only on the basis of an additional surgical intervention at an adjacent level. Rates for surgeries on adjacent levels are not equivalent to ALD rates. The selection of a single level to treat surgically is made on the basis of a surgeon's subjective impression that the source of compression is limited to that specific level. For example, in Mummaneni's work, 5 patients in the arthroplasty group are described as undergoing revision surgery (removal of the implant and revision to ACDF, in Table 4), with 2 out of these 5 undergoing a 3-level fusion, 12 months postoperatively in one case and 24 months postoperatively in the other. The change from one initially selected level on which to operate to a 3-level operation at revision after 12 or 24 months of follow-up may reveal other reasons besides ALD for additional surgery (for example, the initial selection of the disc levels for surgical treatment may have been too limited). It should be noted that the available data regarding reoperation in Tables 3 and 4 in the article by Mummaneni et al. are somewhat discordant. In Table 3, the authors reported that there was no revision or supplemental fixation for arthroplasty patients. In Table 4, 5 arthroplasty patients are described as undergoing revision fusion procedures; in 2 of them, 3-level fusions were performed.

The outcome measures used included the SF-36 questionnaire, the NDI and neck and arm pain numeric rating scales, and neurological and work status.

For technical reasons, radiological results were provided for 64% of patients in the arthroplasty group and 47% of patients in the fusion group. Only angular motion was assessed.

Adjacent-segment degeneration, such as the formation of radial osteophytes or the narrowing of the disc space, was not assessed in this study. Adjacent-segment degeneration was assessed only on the basis of additional surgical intervention at an adjacent level.

In the CDA and fusion groups, 3 of 223 and 9 of 198 patients, respectively, had undergone surgery for ALD at the final follow-up.

The authors disclosed their relationship with the industry and products studied in their work.

Synthesis of Benefit and Harm. Analysis of the results reported by Mummaneni et al.[14] shows an absolute risk reduction for surgery for adjacent-level surgery of 3.2%, and the NNT required to reveal this difference is 31 (Tables 4 and 5). The 95% CI is not statistically significant (–15 to 1000, Fig. 3).

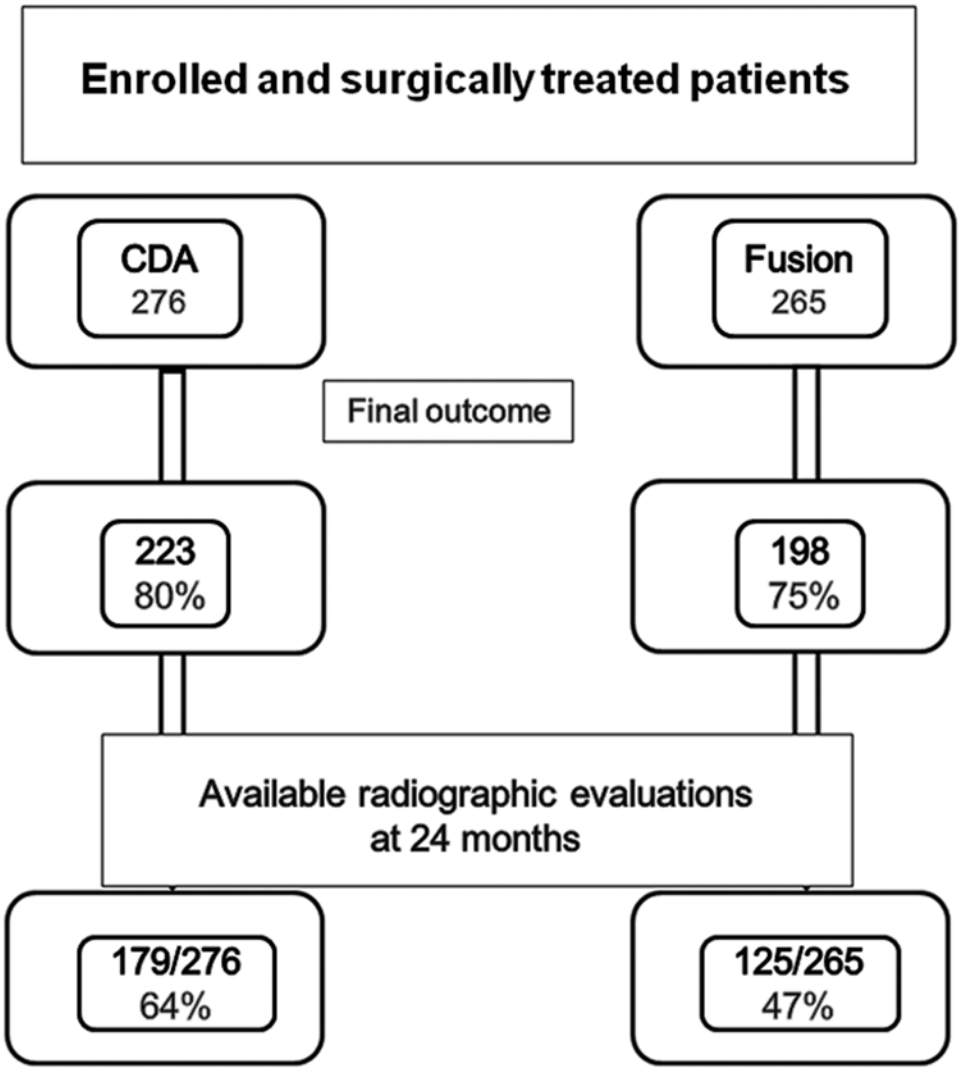

Fig. 2. Clinical (final outcome) and radiographic follow-up reported by Mummaneni et al.

Discussion

Classically, ACDF has provided a high clinical success rate. In May 2002, the Bryan disc implant became the first cervical artificial disc replacement performed in the US. The promise of CDA was to lower the risk of ALD in segments above and below the devices.

All the authors of all the RCTs have emphasized this premise when introducing their papers. As the theoretical advantage of arthroplasty is a reduction in adjacent-level stresses and a decreased risk of ALD,[4] this should be the primary end point. All other related end points may be considered secondary or "soft" end points.[25]

TABLE 4: Numbers of patients undergoing surgical treatment for ALD after arthroplasty or fusion in the RCT of Mummaneni et al.*

Group	Pts w/ Adjacent-Level Op	Pts w/o Adjacent-Level Op
arthroplasty	3	220
fusion	9	189
total	12	409

* Table modified from Botelho RV: Disc arthroplasty. **J Neurosurg Spine 12:**580–581, 2010 (Letter). Based on analysis of reference 14.

The 3 multicenter randomized trials studied 1174 patients. All the RCTs used nearly identical FDA noninferiority study designs.

The outcomes evaluated were neck and arm pain, neurological success, adverse events with the prosthesis, or fusion and reoperation rates.

Only the article by Mummaneni et al.[14] described the number of second surgeries at adjacent levels. Although these authors have the merit of being the only ones to describe this end point, it must be remembered that surgery in adjacent levels is not synonymous with ALD. Most surgeons are aware of the relative subjectivity involved in choosing the level to be decompressed in the cervical spine, mainly in the presence of minor but real disease or degeneration in other motion segments. Many patients have multilevel disc degeneration. There is a great chance that a given patient's cervical spine has to be decompressed at more than one level by the first surgery, and this is particularly likely in patients with cervical spondylotic myelopathy. In the 5 CDA patients described by

TABLE 5: Statistics related to the difference in the number of patients undergoing adjacent-level surgery after arthroplasty or fusion in the RCT of Mummaneni et al.*

Statistic	Value
χ^2 (p value)†	2.808 (0.94)
relative risk (95% CI)‡	0.296 (0.081–1.078)
absolute risk reduction (95% CI)§	0.032 (−0.001 to 0.065)
NNT (95% CI)	32.248 (−15 [NNH] to 1000)

* Table modified from Botelho RV: Disc arthroplasty. **J Neurosurg Spine 12:**580–581, 2010 (Letter). Based on analysis of reference 14.
† Used to test statistical difference in the number of adjacent-level surgeries between the arthroplasty and fusion groups.
‡ Relative risk of reoperation for ALD between groups.
§ Reduction of reoperation risk with arthroplasty.

Mummaneni et al. as undergoing revision surgery, 2 required 3-level ACDF (1 year after the original surgery in 1 case and 2 years after the original surgery in the other). Because the number of secondary operations in adjacent levels was small, an inadequate choice of the single level to be decompressed in a few patients could enormously change the results.

Nevertheless, the analysis of final results, based on the difference between adjacent-level surgery rates and on the number needed to treat to reveal differences, did not exhibit statistical significance according to a large confidence interval.

As the name indicates, a noninferiority study design is intended to reveal similarities and not differences. To compare the effects on ALD of CDA and fusion, a study should reveal differences.

Noninferiority designs have generated vigorous debate in the literature. These designs have been described as not being in the best interests of patients and instead being dedicated to commercial interests.

The undesirable outcome that a physician would first like to avoid is the need to perform additional surgery in a patient who has undergone surgical treatment for radiculopathy or myelopathy.

The randomized trials used composite scales to reveal noninferiority effects based mainly on questionnaire responses.

Although the SF-36 questionnaire has become the main tool for quality-of-life studies, there remain doubts about studying secondary outcomes by using questionnaires when primary outcomes are not studied. There is a great chance of a Type I error when studies follow this design. All RCTs evaluated in this study used an "overall success rate" as the primary study end point.[25]

It is important that RCTs definitively clarify the effects of CDA in cervical spine surgery.

Adjacent-level degeneration was not studied as a main outcome in any RCT. In the only paper studying adjacent-level surgery rates, the results do not support a decrease in ALD.

Some noninferiority randomized studies comparing CDA and fusion have shown equivalence in several studied outcomes. This review is intended to specifically clarify the effect of arthroplasty on ALD, and other reviews probably will elucidate the global effect of CDA in surgery of the cervical spine.

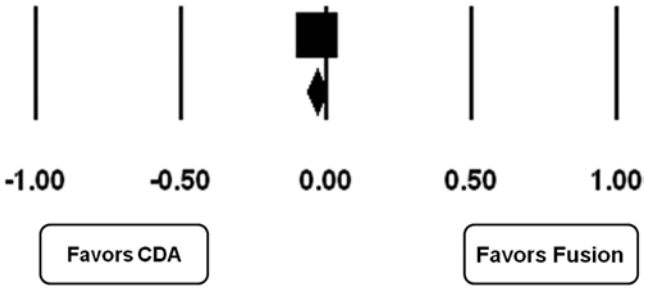

Fig. 3. Forest plot illustrating the difference between CDA and fusion with respect to risk for adjacent-level surgery in the study reported by Mummaneni et al. The 95% CI reveals nonsignificant results.

Conclusions

No study has specifically compared outcome with respect to ALD after CDA or fusion and there is no clinical evidence of reduction in ALD with the use of CDA.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: RV Botelho, OJS Moraes, WM Bernardo. Acquisition of data: all authors. Analysis and interpretation of data: RV Botelho, WM Bernardo. Drafting the article: RV Botelho, WM Bernardo. Critically revising the article: RV Botelho, WM Bernardo. Reviewed final version of the manuscript and approved it for submission: RV Botelho, WM Bernardo. Statistical analysis: RV Botelho. Study supervision: RV Botelho.

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APPENDIX 1: Excluded papers

Year	1st Author	Journal	Exclusion Reason
Papers related to the Bryan device			
2001	Kim SW	*Eur Spine J*	single- & 2-level cases
2009	Cheng L	*Int Orthop*	2-level cases
2009	XU JX	*Spine*	effect of modified technique
2009	Wenger M	*J Clin Neurosci*	not randomized
2008	Riew KD	*Bone Joint Surg Am*	subgroup analysis for treatment of myelopathy
2008	Anderson PA	*Spine*	comparison of adverse events
2008	Yang S	*Spine*	single & multilevel cases
2008	Sasso RC	*J Spinal Disord Tech*	kinematics
2007	Sasso RC	*J Spinal Disord Tech*	part of a major trial
2007	Rabin D	*Neurosurgery*	kinematics study
2007	Amit A	*Br J Neurosurg*	12-mo clinical outcome
2008	Kim SW	*Eur Spine J*	study of alignment

(continued)

APPENDIX 1: Excluded papers *(continued)*

Year	1st Author	Journal	Exclusion Reason
Papers related to the Bryan device			
2007	Lind B	*Spine*	not randomized
2007	Sears WR	*J Spinal Disord Tech*	not randomized
2007	Sekhon LH	*Spine*	MR imaging study
2006	Pickett GE	*J Neurosurg Spine*	complications study
2006	Coric D	*J Neurosurg Spine*	part of major trial
2005	Robertson JT	*J Neurosurg Spine*	not randomized
2005	Sekhon LH	*J Neurosurg Spine*	not randomized
2005	Leung C	*Neurosurgery*	not randomized
2004	Johnson JP	*Neurosurg Focus*	sagittal alignment study
2004	Anderson PA	*Spine J*	not randomized
2003	Sekhon LH	*J Spinal Disord Tech*	study of spondylotic myelopathy
2002	Bryan VE Jr	*Eur Spine J*	not randomized
2002	Goffin J	*Neurosurgery*	not randomized
Papers related to the Prestige device			
2009	Lin CY	*Spine*	stress analysis study
2007	Morrow T	*Manag Care*	discussion
2007	Chang UK	*J Neurosurg Spine*	range of motion study
2007	Chang UK	*J Neurosurg Spine*	cadaveric study
2007	Traynelis VC	*Expert Rev Med Devices*	descriptive paper
2007	Sekhon LH	*Spine*	MR imaging study
2005	Traynelis VC	*Neurosurg Clin N Am*	review
2004	Robertson JT	*Neurosurg Focus*	not randomized
Papers related to the ProDisc C device			
2009	Barbagallo GM	*J Spinal Disord Tech*	technical note
2009	Ahn PG	*J Neurosurg Spine*	range of motion & sagittal alignment study
2009	Bohlman HH	*J Bone Joint Surg Am*	not randomized
2009	Anakwenze OA	*Spine*	sagittal cervical alignment
2009	Lin CY	*Spine*	stress analysis
2009	Yang CW	*Chin Med J*	imaging study
2009	Peng CW	*Spine J*	not randomized
2009	Röhl K	*Spinal Cord*	not randomized
2008	Sukhomel P	*Zh Vopr Neirokhir Im N N Burdenko*	not randomized
2008	Stulik J	*Acta Chir Orthop Traumatol Cech*	not randomized
2008	Zhang X	*J Spinal Disord Tech*	mechanical study
2009	Rabin D	*Spine J*	sagittal balance study
2008	Rousseau MA	*Spine*	kinematic study
2008	Auerbach JD	*Spine J*	discussion
2007	Shim CS	*J Spinal Disord Tech*	case report
2007	Nabhan A	*Spine*	1 year FU
2007	Chang UK	*J Neurosurg Spine*	range of motion study
2007	Chang UK	*J Neurosurg Spine*	cadaveric study
2007	Panjabi M	*Spine*	mechanical study
2007	Sekhon LH	*Spine*	imaging study
2007	Pitzen T	*Eur Spine J*	12 wks FU

(continued)

APPENDIX 1: Excluded papers *(continued)*

Year	1st Author	Journal	Exclusion Reason
Papers related to the ProDisc C device			
2006	Mehren C	*Spine*	not randomized
2006	Laxer EB	*Stud Health Technol Inform*	cadaveric study
2005	Chi JH	*Neurosurg Clin N Am*	review
2005	Pracyk JB	*Spine*	review
2005	Bertagnoli R	*Orthop Clin North Am*	not randomized
2005	Bertagnoli R	*J Neurosurg Spine*	not randomized
2004	DiAngelo DJ	*Neurosurg Focus*	biomechanical study

Neurosurg Focus 28 (6):E6, 2010

Effect of arthroplasty design on cervical spine kinematics: analysis of the Bryan Disc, ProDisc-C, and Synergy Disc

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Object. Cervical total disc replacement has emerged as a surgical option to preserve motion and potentially avoid adjacent-segment disease after anterior cervical discectomy and fusion. Recently, much attention has been directed at the ability of a given device to maintain and/or restore normal segmental alignment. Nonphysiological disc and segmental angulation could result in increased stresses transmitted to the facet joints and posterior elements, conflicting with the essence of arthroplasty and potentially leading to adjacent-segment disease. The goal of this study was to contrast device alignment and segmental kinematics provided by 3 different cervical disc prostheses.

Methods. Sixty patients were retrospectively analyzed and divided into 3 groups receiving the Bryan, ProDisc-C, or Synergy disc. Only single-level arthroplasty cases were included in the study. Lateral dynamic radiographs of the cervical spine were analyzed using quantitative motion analysis software (Medical Metrics, Inc.) to analyze the kinematics at the index level both preoperatively and postoperatively. Several parameters were noted, including range of motion, disc angles, shell angles, anterior and posterior disc heights, translation, and center of rotation. Preoperative and postoperative data were compared using the Student t-test with a significance level of $p < 0.05$.

Results. Postoperatively, all 3 disc groups maintained adequate range of motion at the implanted level. With respect to the shell angles, the Synergy disc demonstrated the least variability, maintaining 6° lordotic configuration between the device endplates. In the Bryan disc group, significant shell kyphosis developed postoperatively ($p < 0.0001$). Both ProDisc-C and Synergy discs significantly increased anterior and posterior disc heights ($p < 0.0001$). The Bryan and Synergy discs maintained the natural center of rotation, whereas significant anterior shift occurred with ProDisc-C.

Conclusions. The goal for motion preservation at the implanted level was achieved using all 3 devices. The Synergy disc was unique in its ability to alter device angulation by 6°. The Bryan disc demonstrated device endplate kyphosis. Both the Synergy disc and ProDisc-C increased disc space height. *(DOI: 10.3171/2010.3.FOCUS1058)*

Key Words • cervical arthroplasty • cervical disc prosthesis • kinematics • lordosis • posture control • total disc replacement

Anterior cervical discectomy and fusion is considered the standard of care for treating radiculopathy and/or myelopathy due to DDD. The goals of this combined procedure are to decompress the neural structures, provide segmental stabilization, and restore or maintain lordotic alignment to optimize the chance of neurological recovery.[15,23,31,46] Cervical TDR has emerged as an option to preserve motion and avoid potential adjacent-segment disease.[4,8,11,13,18,21,28,48] To restore physiological biomechanics and reduce adjacent level forces, the goals of cervical arthroplasty must adhere to the same surgical principles, with the exception of motion preservation—that is, decompress neural structures, maintain intervertebral motion, and restore or maintain segmental lordosis. Although a number of currently available cervical TDRs provide evidence of in vivo ROMs, only isolated devices have specifically incorporated lordosis correction into the device design specifications.[29,31,32,35,36,41]

Cervical arthroplasty devices come in a variety of designs that provide different kinematic properties once implanted.[31] The ProDisc-C disc (Synthes Spine, Inc.) is a cobalt-chrome on polyethylene ball-in-socket single-articulating device that maintains a fixed COR.[12] With such devices, posterior placement is essential, whereas devices that allow a mobile COR have the theoretical advantage of providing normal kinematics over a range of device positions. In contrast, the Bryan disc (Medtronic Sofamor Danek) consists of a low-friction polyurethane core

Abbreviations used in this paper: ACD = anterior cervical discectomy; ADH = anterior disc height; COR = center of rotation; DA = disc angle; DDD = degenerative disc disease; PDH = posterior disc height; ROM = range of motion; SA = shell angle; TDR = total disc replacement.

situated between 2 titanium alloy shells and surrounded by a polyurethane sheath. It has double articulation surfaces and independent translation, allowing a mobile instantaneous axis of rotation. Pickett et al.[33] first demonstrated a mobile COR in an in vivo kinematic analysis of radiographs obtained in patients undergoing cervical TDR with the Bryan disc. The Synergy cervical disc (Synergy Disc Replacement, Inc.) incorporates a novel geometry allowing controlled deformity correction in the sagittal and coronal planes while restoring physiological biomechanics and ROM (Fig. 1). The Synergy disc has a titanium-on-polyethylene articulation with a mobile COR and varying degrees of lordotic correction incorporated into the polyethylene core to provide reliable, predictable correction of cervical alignment.

Despite initial positive clinical results, several reports have documented the occurrence of Bryan disc endplates kyphosis.[22,32,34,42,43] Several studies have demonstrated a correlation between cervical kyphosis, axial neck pain, new-onset neurological symptoms, segmental instability, and poor functional outcome.[16,23,25,32] Although authors of recent analyses have reported increased lordosis at the site implanted with the ProDisc-C,[2,3] Rabin et al.[35] showed that a lordotic configuration of ProDisc-C endplates was associated with a restricted segmental ROM and translation from neutral to extension. Given that segmental angulation can be influenced by a variety of technical factors—including the amount of endplate drilling, removal of the anterior lip of the superior vertebral body, intraoperative positioning, device angle insertion, and anterior-posterior depth of implantation[49]—the next generation of cervical TDR designs must incorporate strategies to provide reliable, predictable correction of cervical alignment along with the restoration of physiological biomechanics.[3,19,49]

In this in vivo retrospective study we analyzed device alignment and segmental kinematics to compare the quality of motion and device angulation provided by 3 differing cervical disc prostheses. A better understanding of the different device designs will ultimately lead to refined indications and device selection with a focus on improving the quality of motion.

Methods

The Health Sciences Research Ethics Board at the University of Western Ontario approved this study.

Patient Population

Prospective upright (standing) lateral flexion and extension cervical radiographs were obtained in consecutive patients undergoing a single-level ACD followed by cervical TDR. Patients with symptomatic cervical spondylosis demonstrating evidence of retained motion at the affected level on preoperative radiographs were offered cervical arthroplasty as an alternative to arthrodesis. Those with axial neck pain as the predominant or solitary symptom were not offered surgery.

Patients were selected for inclusion in this study based on the following criteria: 1) objective clinical evidence of single-level cervical disc disease causing cervical radiculopathy and/or myelopathy, 2) radiographic evidence of single-level cervical DDD, 3) no response to nonsurgical management for > 12 weeks, 4) a minimum of 6 months of postoperative radiographic follow-up, and 5) a preoperative ROM at the target level > 2°. Patients with traumatic or infectious pathology, clinically or radiographically demonstrated multilevel disc disease, radiographically demonstrated instability, severe facet disease, previous cervical spine surgery, and incomplete data at the last follow-up were excluded. To prevent postoperative pain from impacting the effort of postoperative dynamic cervical radiographs, a minimum of 6 months of follow-up was 1 of the criteria used for patient inclusion in the study. During the period of consecutive patient recruitment, no patient dropped out of treatment and no revision surgery was performed. No patient with a poor clinical outcome or poor disc placement was excluded from the study.

Fig. 1. Illustration of the Synergy disc showing its unique design, which allows the device endplates to maintain a 6° lordotic configuration in the neutral position.

Images from the first 60 consecutive patients undergoing single-level cervical arthroplasty using the ProDisc-C, Bryan, or Synergy discs were selected and retrospectively analyzed in this study; each disc type had been inserted in 20 patients. Standard presurgical assessments included clinical history, neurological examination, and MR imaging. Static and dynamic upright (standing) neutral and flexion and extension cervical radiographs were obtained preoperatively and at 6–12 months postoperatively to assess device kinematics and alignment. Our radiographic technique has been described elsewhere.[32]

Surgical Procedure

A standard right-sided cervical approach for ACD was performed in all patients. Selection of the arthroplasty device was dependent on availability. All devices were implanted as suggested in the product monographs.

Radiographic Analysis

Preoperative and the latest postoperative flexion and extension and neutral lateral cervical radiographs were analyzed for each of the disc groups. Independent quantitative motion analysis software (Medical Metrics, Inc.) was used to analyze the kinematics at the index levels. This validated radiographic software uses advanced pattern recognition algorithms to generate accurate measurements of ROM, DA, SA, ADH, PDH, sagittal plane translation, and COR.[39,40] The SA was defined as the angle between the superior and inferior endplates of the cervical TDR. The COR was obtained for the index and

TABLE 1: Summary of patient data

Measure	ProDisc-C	Bryan Disc	Synergy Disc
no. of patients	20	20	20
age (yrs)			
mean	46.5 ± 8.4	43 ± 6.6	45.8 ± 9.0
range	36–66	32–56	29–60
sex (% of group)			
M	6 (30)	12 (60)	9 (45)
F	14 (70)	8 (40)	11 (55)
levels (% of group)			
C3–4	0	1 (5)	0
C4–5	1 (5)	1 (5)	2 (10)
C5–6	11 (55)	9 (45)	14 (70)
C6–7	8 (40)	9 (45)	4 (20)

adjacent spinal levels and was reported as X and Y offset from the midline of the superior endplate of the caudal vertebral body.[32,33]

Statistical Analysis

The means ± SD were determined for ROM, DA, SA, ADH, PDH, translation, COR X, and COR Y. The ANOVA was used to compare results between the 3 disc groups. Further analysis was completed using the Student t-test. A p value < 0.05 was considered significant.

Results

Patient Population

All selected patients met the inclusion criteria. Sixty patients (27 men and 33 women) with a mean age of 45.1 years (range 29–66 years) were included in the study (Table 1). The mean follow-up was 12 months (range 6–24 months). No patients or data were lost at the follow-up. Each patient underwent a single-level disc arthroplasty, receiving 1 of the following disc types: ProDisc-C, Bryan, or Synergy disc. Cervical TDRs were performed from C-3/C-4 to C-6/C-7. There was immediate relief of radiculopathy and/or myelopathy in all cases, with no operative or device-related complications. No delayed complications were observed. All imaging studies had been prospectively collected during the latest follow-up visit and were compared with preoperative radiographs.

Range of Motion

Preoperatively, the patients in the ProDisc-C group had the least ROM. Postoperatively, this group demonstrated a significant increase in the segmental ROM from extension to flexion (preoperative mean 8.0 ± 4.0° vs postoperative mean 10.7 ± 5.5°, p = 0.0003). In cases in which hyperlordosis of the endplates was found in the neutral position, the component ROM demonstrated unequal ROM from neutral to flexion and neutral to extension (Fig. 2). Bryan disc insertion maintained segmental ROM (preoperative 9.5 ± 4.9° to postoperative 8.1 ± 4.3°, p = 0.23). The Synergy group had the largest preoperative ROM (11.1 ± 5.2°). Following surgery, there was no change in the ROM from extension to flexion (8.9 ± 4.4°, p = 0.06). There was no difference in ROM among the 3 devices.

Disc Angle and SA

The mean preoperative DA for the entire cohort of 60 patients was 2.9 ± 4.3°. The DA represents the angle of the diseased disc space prior to surgery.

The ProDisc-C preoperative DA at the surgical level was almost parallel at 1.2 ± 3.3°. Following surgery, the mean device SA was 1.1 ± 3.6° (p = 0.64). The postoperative SA was variable, with 3 patients (15%) demonstrating a > 2° worsening of kyphosis at the latest follow-up and 3 patients (15%) exhibiting postoperative hyperlordosis (SA > 5°; Fig. 2).

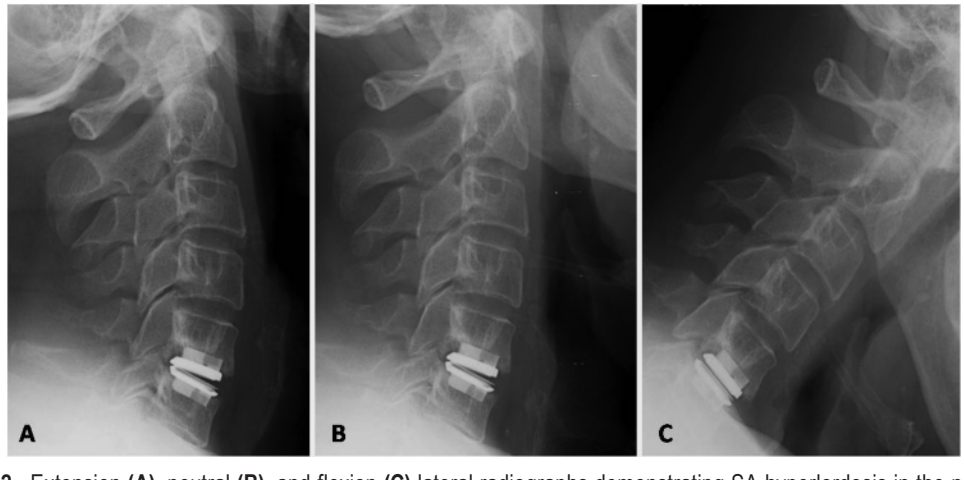

Fig. 2. Extension **(A)**, neutral **(B),** and flexion **(C)** lateral radiographs demonstrating SA hyperlordosis in the neutral posture following ProDisc-C insertion. Placement of this disc results in unequal motion, with the neutral to flexion ROM of 8° **(B–C)** but a limited ROM from neutral to extension of 1.2° **(A–B)**.

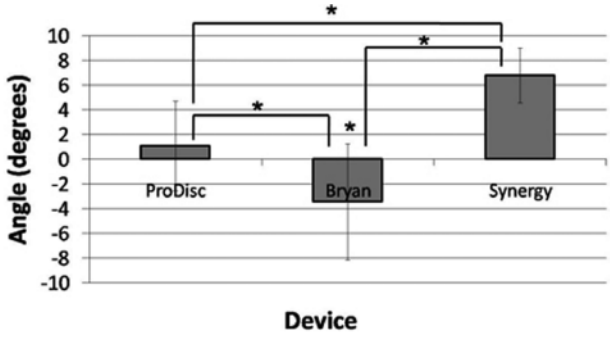

Fig. 3. Bar graph demonstrating the late follow-up SA following insertion of a cervical TDR. *Bars* represent SDs. *Asterisk* represents a significance level of $p < 0.05$.

In the Bryan disc group, the preoperative lordotic DA was 3.0 ± 3.1°. Following insertion of the Bryan disc, significant SA kyphosis was found at the late follow-up (–3.4 ± 4.7°, $p < 0.0001$; Fig. 3). An increase in kyphosis (> 4°) at the index level in the neutral position was found in 60% of patients (Fig. 4).

The Synergy disc demonstrated the least variability with respect to SA. The Synergy disc has a number of lordotic core offerings; the core used in this study had a 6° configuration. The preoperative DA for the Synergy group was 4.6 ± 5.9°. Following insertion of the 6° Synergy disc, the SA maintained a mean of 6.8 ± 2.2° ($p = 0.08$).

A comparison of the SA between the ProDisc-C and Synergy disc groups revealed a statistically significant increase in lordosis with the Synergy device ($p < 0.0001$; Fig. 3). Both the ProDisc-C and Synergy discs showed a lordotic SA configuration when compared with the Bryan disc ($p = 0.002$ and < 0.0001, respectively).

Disc Height

Preoperatively, for the entire cohort of 60 patients, the mean ADH was 4.0 ± 1.1 mm, whereas the mean PDH was 3.1 ± 0.9 mm. At the surgical level the ADH increased by 80% (3.4 ± 1.0 mm preoperatively vs 6.1 ± 1.0 mm postoperatively, $p < 0.0001$) following insertion of the ProDisc-C, whereas the PDH increased by 52% (3.1 ± 0.9 mm preoperatively vs 4.7 ± 0.7 mm postoperatively, $p < 0.0001$). In contrast, following insertion of the Bryan disc, the ADH decreased by 32% (4.4 ± 1.0 mm preoperatively vs 3.0 ± 1.1 mm postoperatively, $p < 0.0001$), whereas the PDH decreased by 14% (3.5 ± 0.9 mm preoperatively vs 3.0 ± 1.0 mm postoperatively, $p = 0.0005$). With the Synergy disc there was a 48% increase in the ADH (4.0 ± 1.0 mm preoperatively vs 6.0 ± 1.3 mm postoperatively, $p < 0.0001$) and a 32% increase in the PDH (2.8 ± 0.9 mm preoperatively vs 3.8 ± 1.1 mm postoperatively, $p = 0.0003$).

In comparing the 3 devices, there was no significant difference in ADH between the ProDisc-C and Synergy disc. Both of these disc types presented a significant increase in the ADH and PDH when compared with the heights for the Bryan disc ($p < 0.0001$). All 3 devices differed from each other with respect to the PDH ($p < 0.05$ for all).

Sagittal Plane Translation

The ProDisc-C disc demonstrated translation of 1.5 mm (0.7 ± 0.5 mm preoperatively vs 1.5 ± 0.6 mm postoperatively, $p < 0.0001$). Changes in segmental translation induced by the Bryan disc were negligible ($p = 0.98$). The Bryan disc had 1.0 mm of translation preoperatively and 1.0 mm postoperatively. The Synergy disc had the largest amount of preoperative translation at 1.4 mm, almost double the preoperative translation seen in the ProDisc-C patients preoperatively. After Synergy disc insertion, there was no significant change in translation at 1.2 mm.

There was no difference in translation between the Synergy disc and the other 2 devices. Compared with the Bryan disc, there was increased translation in the ProDisc-C ($p = 0.03$).

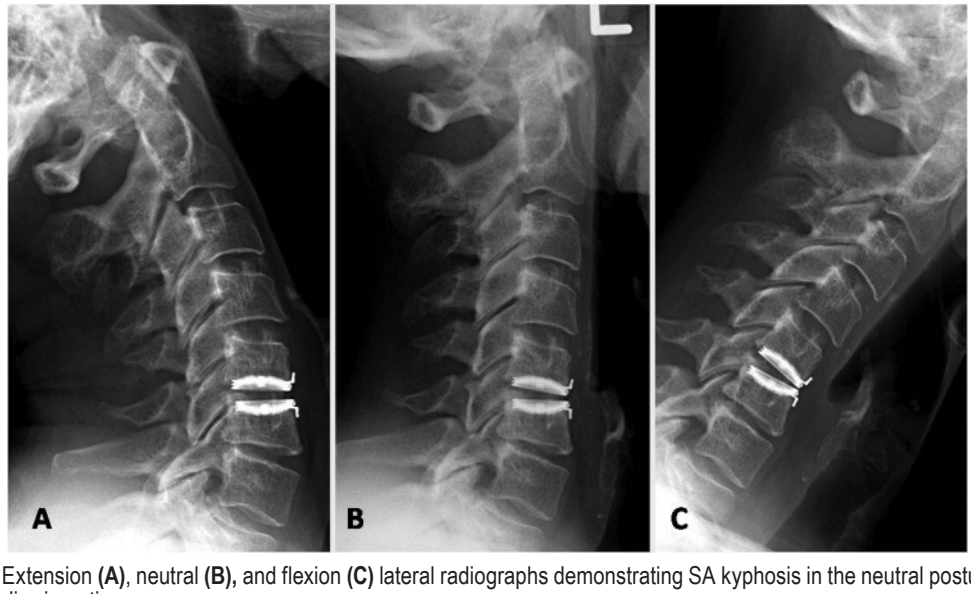

Fig. 4. Extension **(A)**, neutral **(B),** and flexion **(C)** lateral radiographs demonstrating SA kyphosis in the neutral posture following Bryan disc insertion.

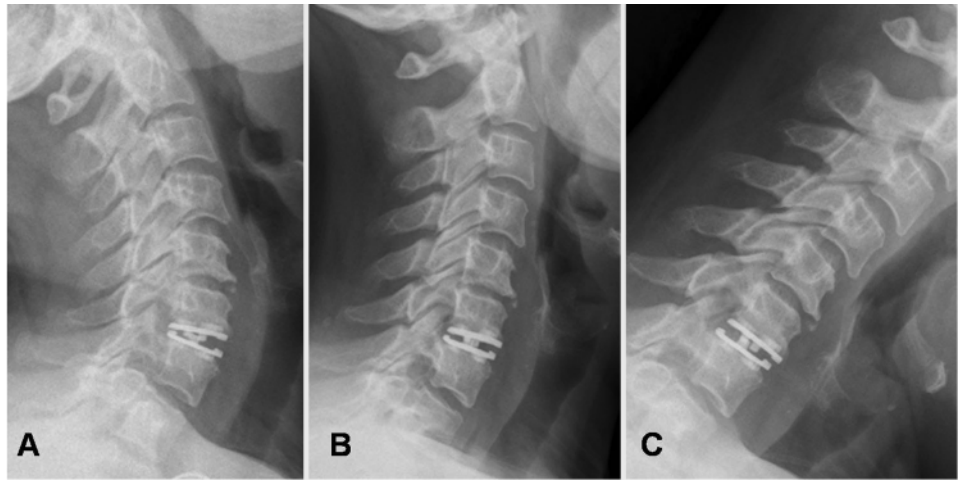

Fig. 5. Extension **(A)**, neutral **(B)**, and flexion **(C)** lateral radiographs obtained after Synergy disc insertion, demonstrating 14.2° ROM from extension to flexion **(A–C)**. The SA in the upright (standing) neutral radiograph **(B)** demonstrates 6.2° of lordosis.

Center of Rotation

At the surgical level, the COR X underwent a statistically significant anterior shift of 0.9 mm after the introduction of the ProDisc-C disc (–0.8 ± 1.2 vs 0.2 ± 0.8 mm, p = 0.002); there were no significant changes in the COR Y values (p = 0.99). The Bryan disc did not significantly change either the COR X or COR Y values (p = 0.16 and 0.27, respectively). Following insertion of the Synergy disc, the COR X underwent an anterior shift (–0.9 ± 0.9 vs –0.1 ± 0.8 mm, p = 0.002). There were significant changes in the COR Y values (3.9 ± 2.2 vs 2.7 ± 2.5 mm, p = 0.006).

When comparing the 3 devices for the COR X and Y, the only difference found was between the Bryan and Synergy disc for the COR X parameter (p = 0.0006).

Discussion

Three cervical disc replacements with different concepts in design and biomechanics were retrospectively compared in this study. Range of motion, the fundamental parameter, was preserved at the implanted site in all devices. The greatest difference between the 3 devices was in the SA measurements. The ProDisc-C disc had a slightly lordotic SA of 1.1 ± 3.6°, with 15% of patients demonstrating worsening kyphosis and 15% showing hyperlordosis (Fig. 2). In contrast, the Bryan disc demonstrated –3.4 ± 4.7° of SA kyphosis, with 60% of patients exhibiting postoperative device endplate kyphosis (Fig. 4). According to the product monographs, to optimize ROM, both the ProDisc-C and the Bryan disc should be inserted into the disc space with the goal of keeping the device endplates in a parallel orientation. The Synergy disc has a unique design, allowing the device endplates to maintain a 6° lordotic configuration in the neutral position while providing a full ROM (Fig. 5). The Synergy disc demonstrated the least variability in SA, with a mean of 6.8 ± 2.2°.

The initial objective of cervical disc replacement was the maintenance of motion at the implanted level, therefore reducing the incidence of adjacent-level disease. Despite favorable short-term clinical results, insertion of the Bryan disc has prompted concerns regarding postoperative kyphosis and cervical alignment.[27,32,43,49] Design limitations and technical nuances can contribute to the poor results in segmental alignment found with the Bryan disc.[42,43] Factors such as lordotic neck positioning, overdrilling and asymmetry of the vertebral endplates, angle of disc insertion, preexisting kyphosis, and the structural absence of lordosis in the device have been implicated in the development of postoperative kyphosis with the Bryan disc.[17,27,50] Studies involving long-term results in patients with cervical fusion have reported the new onset of axial symptoms and accelerated adjacent-segment disease related to focal and segmental kyphosis at the fused level.[24,26] As stated by Kim et al.,[27] "the Bryan artificial disc prosthesis has a passive nature in its design, and is not designed to correct kyphosis; hence, one would expect that it would be unable to restore lordosis to [the] spine." In contrast, Rabin et al.[35] showed that a lordotic configuration of ProDisc-C endplates at the surgical level was associated with restricted segmental ROM and translation from neutral to extension. Like the Bryan disc, the ProDisc-C was not designed to actively correct sagittal alignment. An emerging contraindication for cervical TDR is the presence of preoperative straightening or focal kyphosis at the index level. The Synergy disc is differentiated by its 6° preferred lordotic orientation, designed specifically for its unique ability to correct preoperative deformity and/or maintain cervical lordosis (Fig. 6). Our results demonstrated that the Synergy disc maintained a 6.8° lordotic SA alignment.

The preoperative DA for the entire patient cohort (60 patients) demonstrated a relative loss of lordosis due to the degenerative process (2.9 ± 4.3°). Harrison et al.[20] studied 252 asymptomatic volunteers and found that the average lordosis between cervical vertebrae was between 6 and 7°. It is important to note that only healthy volunteers without clinical or radiographic signs of DDD were

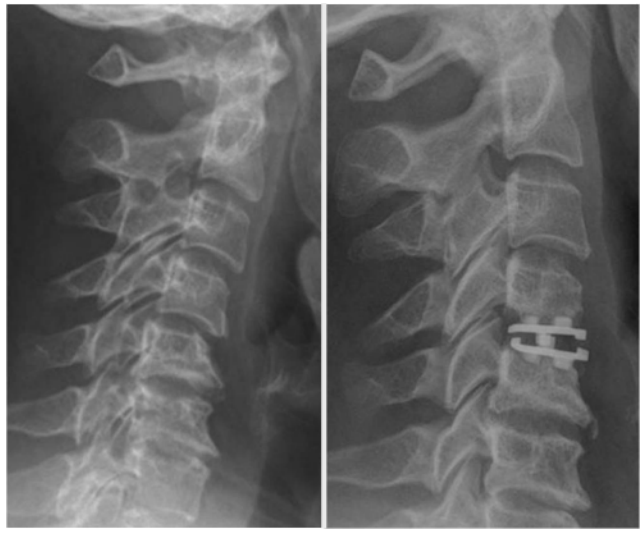

Fig. 6. Preoperative **(left)** and postoperative **(right)** lateral neutral radiographs demonstrating correction for preoperative focal kyphosis following insertion of the 6° Synergy disc.

considered.[20] Degenerative disc disease is characterized by deterioration and collapse of the intervertebral disc[1,7,47] accompanied by alterations in the spinal curvature.[14,30] Shim et al.[44] reported a preoperative DA (at index level) of −0.7° (47 patients). Fong et al.[17] studied 10 patients undergoing Bryan cervical disc arthroplasty and found that 40% had angles between 1 and 2° lordosis and 30% were straight (parallel with 0°). Johnson et al.[22] studied 13 patients with a mean preoperative angle of 1° and noted that the symptomatic segment was kyphotic because of a loss of ADH. Changes in disc height can contribute to the loss of the normal cervical lordosis seen in patients with DDD.[6,9,38] Traditional fusion strategies have incorporated techniques for the restoration of appropriate lordotic curvature.[24,37,45]

Our results lend further evidence to previous studies whose data suggest that a loss of disc space height accompanies DDD. In the ProDisc-C group, the preoperative mean ADH and PDH were 3.4 and 3.1 mm, respectively. For the Bryan and Synergy groups, larger differences were seen between the preoperative ADH and PDH values. Following arthroplasty, both the ProDisc-C and Synergy devices increased the ADH to approximately 6 mm, whereas the Bryan disc decreased the ADH following surgery. Increasing the disc height is important in restoring adequate foraminal height and preventing recurrent nerve root compression. Overdistraction of the disc space, however, can be associated with "overstuffing" and may be associated with both diminished motion of the TDR and facet distraction causing neck pain. The Bryan disc ADH and PDH values were equal at 3.0 mm. Despite the device size, the milling of the endplates required for device insertion may prevent the Bryan disc from restoring adequate disc height. Both the Synergy and ProDisc-C devices in this study had a device height of 5 mm. By virtue of its design, the Synergy disc has unequal values for ADH and PDH, as it has a configuration of a wedge with 6° of lordosis designed into the polyethylene core (Fig. 1).

Range of motion, a fundamental kinematic parameter, was preserved at the index level for all discs: ProDisc-C 10.7 ± 5.4°, Bryan 8.1 ± 4.3°, and Synergy 8.9 ± 4.4°. A comparison between the 3 devices demonstrated no significant difference in the ROM. The ProDisc-C added ROM to the preoperative level, increasing segmental motion by 34%. However, the preoperative ROM for the ProDisc-C group was only 8.0 ± 4.0°, whereas the preoperative ROM for the Bryan and Synergy groups was > 9.0°. Previous studies have already documented significant increases in in vivo and in vitro sagittal motion following insertion of the ProDisc-C.[5,10,35] Bertagnoli et al.[5] reported a significant in vivo increase in sagittal ROM (4° preoperatively vs 12° postoperatively) following insertion of the ProDisc-C. DiAngelo et al.[10] described in vitro biomechanical results in cadaveric cervical spines implanted with a single-level ProDisc-C and compared this strategy with single-level ACD and fusion. Following insertion of the ProDisc-C, the surgical level demonstrated a ROM of 13.1°.[10] It is unclear whether there is any clinical benefit to increasing the ROM at the diseased level. In theory, increased ROM may place increased strain on facet joints and uncovertebral joints at the surgical level, potentially causing a negative effect on the index and adjacent-level facets and discs. Alternatively, increased ROM may reduce the potential for autofusion across the arthroplasty level. Longer follow-ups will be required to evaluate the impact of significantly increasing ROM at a functional spinal unit already diseased by the degenerative cascade.

In contrast to the ProDisc-C, both the Bryan and Synergy discs did not change ROM at the index levels. This result may be related to device design with "constraints" incorporated into both devices. With the Bryan disc, a central post and outer membrane sheath limit both translation and ROM. With the Synergy disc, unique soft stops control and prevent excessive sagittal rotation, axial rotation, translation, and lateral bending. For example, in a patient who received a Synergy disc (Case 7; Fig. 6), the preoperative ROM was 19.3°. Following cervical TDR with Synergy, the ROM decreased to 10.6°. In addition to device design, the surgical technique can influence postoperative ROM for the device. Resection of the uncus and division of the posterior longitudinal ligament has been suggested to impact device ROM.

The ProDisc-C incorporates a ball-in-socket joint mechanism with a fixed axis of rotation. Hence, the quality of motion is strictly dependent on the anterior-posterior placement depth and alignment of the device endplates. The COR shifted anteriorly by 1.0 mm (COR X, $p = 0.002$). As expected, the Bryan disc preserved the physiological location of the COR. The Synergy disc also provided changes in the COR from the preoperative values. Caution must be applied while determining the importance of preserved CORs following cervical arthroplasty. The preoperative parameters observed in our studies cannot be taken as "normal" because all patients had symptomatic single-level disc disease. As such, the lack of significant change in biomechanical parameters in the Bryan disc between pre- and postoperative radiographs implies that the disc was able to maintain the existing preoperative biomechanical properties of the cervical spine. The

prosthesis, being passive, adapted itself into the local biomechanical profile provided by adjacent vertebral bodies, ligaments, and facet joints. However, Synergy disc implantation resulted in increased disc height and a lordotic SA, changes that would impact COR coordinates when compared with preoperative values. These changes in the COR may represent further deviations from "normal" parameters or, alternatively, a closer approximation of the properties of a healthy native disc.

Study Limitations

Interpreting in vivo x-ray–based kinematic analysis of spinal biomechanics should be approached with caution, especially in a small group of patients. Although kinematics software has demonstrated good reliability and accuracy, the analysis may be limited by patient factors. Out-of-plane motion, pain, and patient effort may introduce variability over sequential films. Patient body habits may obscure anatomical detail in the caudal cervical spine and contribute to error within all kinematic measures.[33] This study addresses only flexion and extension ROM and does not characterize the biomechanical behavior of any of the devices in axial rotation or lateral bending. Analyzing patients after the first 6 months theoretically decreases the influence of postoperative pain and patient discomfort on overall sagittal motion, allowing the cervical prosthesis to settle and the muscles and facet joints to adapt. Also within the first 6 months postoperatively, device endplates are expected to incorporate with the vertebral endplates. Nonetheless, the short-term follow-up in this study, averaging only 12 months, does not address the durability of the devices nor the long-term quality of motion. Long-term evaluation of cervical arthroplasty will require merging of clinical, radiographic, and kinematic information to determine optimal device design.

Conclusions

While limited by a small sample size and a short postsurgical follow-up period, this in vivo study demonstrated that ProDisc-C, Bryan, and Synergy discs adequately maintain ROM at the implanted level. The greatest difference between the 3 devices was in the SA measurements; the Synergy disc provided a 6° lordotic correction following insertion. In addition, there was an increase in the ADH and PDH after implantation of the ProDisc-C and Synergy discs. In contrast, the Bryan disc did not restore disc height and instead produced significant SA kyphosis at the implanted level. Preoperative COR values were fairly preserved among all devices. Longer follow-up is required to assess the durability of kinematic changes at the implanted levels following cervical TDR.

Disclosure

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Author contributions to the study and manuscript preparation include the following. Conception and design: N Duggal, D Rabin. Acquisition of data: N Duggal, K Yucesoy, KZ Yuksel, I Kowalczyk, D Rabin, M Fink. Analysis and interpretation of data: all authors. Drafting the article: N Duggal, BCR Lazaro, I Kowalczyk, D Rabin, M Fink. Critically revising the article: N Duggal, BCR Lazaro, I Kowalczyk. Reviewed final version of the manuscript and approved it for submission: N Duggal. Statistical analysis: K Yucesoy, KZ Yuksel, I Kowalczyk. Study supervision: N Duggal.

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The predictive value of the baseline Oswestry Disability Index in lumbar disc arthroplasty

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Object. The goal of the study was to determine patient factors predictive of good outcome after lumbar disc arthroplasty. Specifically, the paper examines the relationship of the preoperative Oswestry Disability Index (ODI) to patient outcome at 1 year.

Methods. The study is a retrospective review of 20 patients undergoing a 1-level lumbar disc arthroplasty at the author's institution between 2004 and 2008. All data were collected prospectively. Data included the ODI, visual analog scale scores, and patient demographics.

Results. All patients underwent a 1-level disc arthroplasty at L4–5 or L5–S1. The patients were divided into 2 groups based on their baseline ODI. Patients with an ODI between 38 and 59 demonstrated better outcomes with lumbar disc arthroplasty. Only 1 (20%) of 5 patients with a baseline ODI higher than 60 reported a good outcome. In contrast, 13 (87%) of 15 patients with an ODI between 38 and 59 showed a good outcome ($p = 0.03$). The negative predictive value of using ODI > 60 is 60% in patients who are determined to be candidates for lumbar arthroplasty.

Conclusions. Lumbar arthroplasty is very effective in some patients. Other patients do not improve after surgery. The baseline ODI results are predictive of outcome in patients selected for lumbar disc arthroplasty. A baseline ODI > 60 is predictive of poor outcome. A high ODI may be indicative of psychosocial overlay.
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Key Words • **lumbar arthroplasty** • **outcome** • **back pain** • **Oswestry Disability Index** • **artificial disc**

Numerous randomized trials have shown significant improvement with surgical intervention for lower-back pain. Unfortunately, a significant number of patients do not respond to surgical intervention. Multiple excellent FDA IDE randomized studies for arthroplasty have shown fairly consistent improvement with arthroplasty. The ProDisc-L (Synthes) IDE study demonstrated that 53.4% of patients who underwent arthroplasty improved based on the FDA's definition of success. Only 40.8% of patients in the control 360° lumbar fusion group improved.[11] Five-year results from the Charité prospective randomized study were similar with 57.8% of arthroplasty procedures defined as successful versus 51.2% of control anterior lumbar fusion procedures.[7] The multicenter trials focus on mean ODI changes. Our analysis shows that patients do not have a graded improvement in outcome measures. A patient either responds to the surgery and has a dramatic improvement in the ODI or there is no change in outcome measures. Better patient selection for arthroplasty surgery will decrease the number of patients undergoing surgery with minimal improvement. The purpose of this study is to determine if the baseline ODI significantly predicts outcomes after lumbar arthroplasty.

Abbreviations used in this paper: IDE = investigational device exemption; ODI = Oswestry Disability Index; VAS = visual analog scale.

Methods

In this retrospective study, between 2004 and 2008 all patients underwent a single-level lumbar disc arthroplasty at L4–5 or L5–S1. All surgeries were done by one surgeon at a single institution. Devices used include the DePuy Charité artificial disc and the Aesculap Activ-L artificial lumbar disc. Twenty-four patients were identified, but 1-year follow-up was only available for 20 patients. Data including the ODI, VAS scores, and patient demographics were collected prospectively. Patients were selected for lumbar arthroplasty based on MR imaging findings including loss of disc height, low T2 signal intensity on MR images, endplate changes, and bulging disc (Fig. 1). Patients with spondylolisthesis, severe facet arthropathy, or multilevel degenerative changes were excluded from lumbar arthroplasty. All patients had symptoms lasting longer than 1 year, and all had undergone nonoperative treatment for more than 6 months. Baseline plain radiographs with flexion/extension views were obtained in all patients. Discography results were available for 4 of 20 patients.

Statistical Analysis

Patients were categorized as having a baseline ODI of either greater or less than 60. An ODI of 60 was selected as an approximately one standard deviation above the mean ODI of 52. Patients' conditions were considered

TABLE 1: Patient demographics

Variable	No. of Patients*
no. of patients	20
mean age (yrs)	41
male/female	9:11
level	
L4–5	7
L5–S1	13
hospital stay (days)	1.8
baseline VAS score	
back pain	75.7
rt leg pain	28.5
lt leg pain	24.8
mean baseline ODI	52.7

* Unless indicated otherwise.

improved based on a reduction of 20 points in their ODI score at 1 year. The Fisher exact test was used to assess the significance of the 2 × 2 contingency table.

Results

Demographics for the 20 patients are given in Table 1. Good outcome as defined by improvement of 20 points on the ODI score was noted in 14 patients (70%). The mean VAS outcome scores are shown in Table 2. Improvement was noted in back pain VAS score as well as right and left leg pain. The mean ODI score improved from 52.7 to 26 ($p < 0.01$). Individual ODI changes for all 20 patients are plotted in Fig. 1. Fifteen patients were categorized as having an ODI between 38 and 59. Of these 15 patients, 13 (87%) had a good outcome while only 1 (20%) of 5 patients with an ODI 60 and above demonstrated a good outcome (Fig. 2). Outcomes were statistically different between these groups ($p = 0.03$) (Fig. 3 and Table 3).

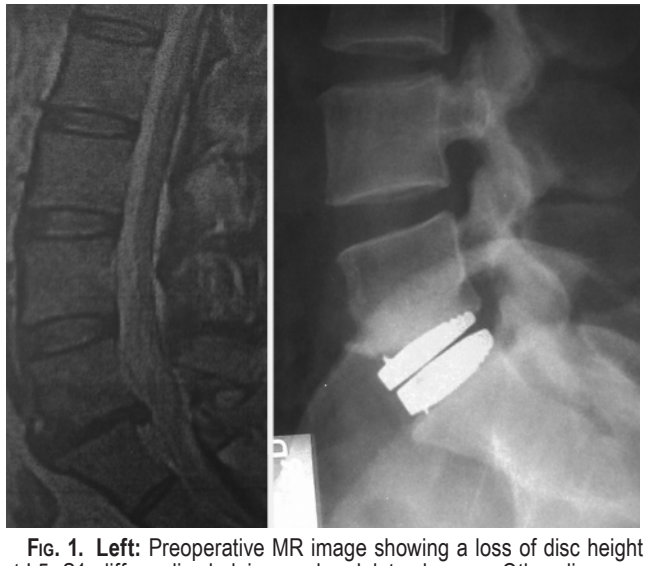

Fig. 1. Left: Preoperative MR image showing a loss of disc height at L5–S1, diffuse disc bulging, and endplate changes. Other discs are unremarkable. **Right:** Postoperative radiograph showing an artificial lumbar disc in place at L5–S1.

TABLE 2: Patient outcomes

Variable	Value	
	Baseline	1 Yr
ODI	52.7	26.6
VAS score		
back pain	75.7	28.5
rt leg pain	28.5	17.2
lt leg pain	24.8	7.5

The mean operative time was 122 minutes. The mean length of hospital stay was 1.8 days. No serious complications related to surgery were noted. Transient lower-extremity paresthesias were noted in 3 (15%) of the 20 patients. One patient who did not improve following surgery underwent posterolateral arthrodesis 8 months after lumbar disc arthroplasty. Her condition failed to improve with the subsequent surgery.

Discussion

Several FDA IDE studies provide Class I data showing that lumbar arthroplasty is effective in decreasing lower-back pain. The ProDisc-L IDE study demonstrated that 53.4% of patients undergoing arthroplasty improved based on the FDA's definition of success.[11] Only 40.8% of patients in the control lumbar fusion group improved.[7] Five-year results from the Charité prospective randomized study were similar. Successful outcomes were seen in 57.8% of patients who underwent arthroplasty and 51.2% of the control patients who underwent anterior lumbar fusion. In the ProDisc study, 67.8% of patients demonstrated a greater than 15-point improvement in their ODI compared with 54.9% of control patients showing a similar improvement. The ODI improvement in the Charité and the ProDisc-L studies is comparable to ODI improvement noted in lumbar fusion surgeries for spondylolithesis.[4,6]

The ProDisc study reported the FDA and ProDisc ODI definitions of success. The FDA defined success as an ODI improvement of 15 points, and the ProDisc spon-

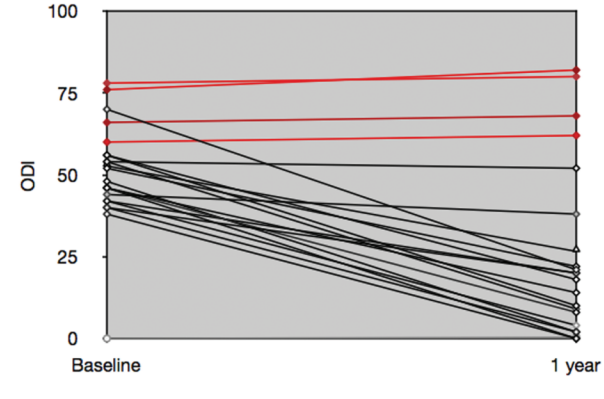

Fig. 2. Plot of the ODI change from baseline to 1 year.

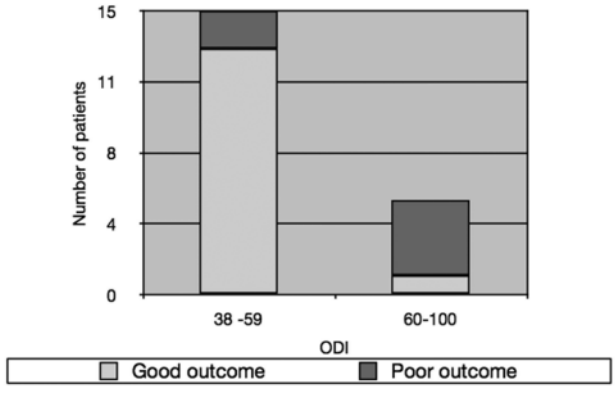

Fig. 3. Bar graph of outcome divided by ODI categories.

sor defined success as an improvement in ODI of 15%. The 15-point ODI improvement was more rigorous than the 15% criteria (67.8% of patients improved vs 77.2% of patients). The overall success reported in the FDA study was lower (53.4% of patients) because it included additional success criteria such as radiographic measures and 36-Item Short Form Health Survey results.[11] In this study, because other outcome measures were not assessed, a higher (20-point) ODI improvement was selected as a measure of success. Additionally, improvement in all patients was not ambiguous; patients showed either a dramatic improvement or minimal change. Analysis of the mean ODI change often fails to appreciate the bimodal results distribution. In many patients, lumbar arthroplasty is highly effective. In our experience, some patients have a dramatic clinical improvement with surgery while other patients have no improvement. This fact is verified visually by reviewing Fig. 2 where individual patient ODI changes are plotted.

The results after lumbar disc arthroplasty are good, but approximately one-third of patients do not respond to surgical intervention. Patient selection in the ProDisc-L study was based on radiographic findings, symptoms lasting longer than 6 months, and an ODI greater than 40. Unfortunately, no better selection criteria exist. Tests such as discograms or newer functional discograms have failed to demonstrate a significant increased specificity in selecting patients for surgical intervention.[3,6]

The failure of one-third of patients to respond to surgery could be viewed as a limitation of surgery and disc arthroplasty. The fact that surgery fails in about one-third of patients undergoing fusion and in one-third of patients undergoing various disc implants argues against the failure being device related. Geisler et al.[5] reported on patients who underwent fusion after they had unsuccessfully undergone arthroplasty. In the Charité IDE study, 7.1% of patients undergoing arthroplasty also underwent supplemental instrumentation for fusion because of poor clinical outcome with arthroplasty. The patients all had poor outcome. Geisler and colleagues concluded that failure to respond to surgery was not a limitation of the surgery but indicated an underlying problem in patients who were not amenable to surgical correction. These authors characterized the failure as an "imprecision in preoperative evaluation."

TABLE 3: Patient outcome as a function of baseline ODI

Outcome	No. of Patients	
	ODI 38–59	ODI 60–100
good	13	1
poor	2	4

An explanation for the inconsistent results with lumbar arthroplasty is that the population of patients with lower-back pain is not homogeneous. While about two-thirds of patients with lower-back pain and appropriate radiographic findings have true discogenic pain, the remaining one-third have other pathological conditions that are not amenable to current surgical intervention. Significant psychosocial overlay is a possibility. Studies by Carragee et al.[1,2] in which the authors used discography extensively demonstrated the overlap between psychosocial variables and lower-back pain. These authors reported that about one-third of patients with chronic pain had a positive discography result without a history of significant lower-back problems.[1]

In the present study, worse outcomes were observed in patients with a very high ODI (> 60) after lumbar arthroplasty. A low ODI has been associated with better outcomes. Siepe et al.[8] also examined outcomes after lumbar arthroplasty, and they observed that patient improvement was predicted by a lower baseline ODI. The relationship of ODI to psychosocial issues has not been well documented, although Slover et al.[9] noted that psychosocial issues affect ODI. The information that a high ODI is associated with poor outcome will allow for better informed decisions and expectations by surgeons and patients regarding the appropriateness of surgical intervention for chronic lower-back pain.[10] A high ODI by itself does not exclude a patient from consideration for lumbar arthroplasty.

Conclusions

Lumbar disc arthroplasty is highly successful in reducing lower-back pain in about two-thirds of patients. A significant one-third of patients do not respond to surgery. The ability to adequately exclude patients who respond poorly to surgery can improve arthroplasty surgery outcome. This paper shows that patients with very high ODI scores have relatively poor outcomes with lumbar disc arthroplasty.

Disclosure

The author reports no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Dynamic interspinous process stabilization: review of complications associated with the X-Stop device

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Object. The X-Stop interspinous device is designed for the treatment of patients with neurogenic intermittent claudication due to lumbar spinal stenosis. It distracts the posterior elements of adjacent vertebral bodies, unloading the intervertebral disc, limiting spinal extension, and improving central canal and neuroforaminal stenosis. In this paper, the authors reviewed the complications and failure/reoperation rates in a small series of patients and compared their results with other reported complication and failure/reoperation rates.

Methods. The medical records of all patients who underwent placement of the X-Stop device for the treatment of NIC at the authors' institution were retrospectively evaluated, and demographic information, diagnosis, and preoperative pain levels were recorded. Postoperatively, patients subjectively graded the percentage (0–100%) of improvement in pain as well as the amount of residual pain and underwent imaging at 1-, 3-, and 6-month intervals. Approximately 4 years after X-Stop placement, information on long-term outcomes was obtained from patient medical records or additional follow-up.

Results. Thirteen patients (8 men and 5 women) underwent placement of the X-Stop device. Central canal stenosis with bilateral foraminal stenosis was diagnosed in all patients: 9 (69%) of 13 had severe stenosis and 4 (31%) of 13 had moderate stenosis. Five patients (38%) also had associated Grade I spondylolisthesis. Nine patients underwent placement of the X-Stop device at the L4–5 interspinous space and 4 at both the L3–4 and L4–5 levels. The average duration of follow-up was 42.9 months (range 3–48 months). Initially, pain improved an average of 72% (range 50–100%) in these patients; however, preoperative pain returned in 77% of the patients (10 of 13). The overall complication rate was 38%, including 3 spinous process fractures (23%) and 2 instances of new-onset radiculopathy (15%). The ultimate failure rate requiring additional spinal surgery was 85% (11 of 13 patients). These complication and failure rates are much higher than those previously reported.

Conclusions. Overdistraction, poor bone density, poor patient selection, and preexistent adjacent foraminal stenosis may all be factors in the development of the aforementioned complications. Thus, careful attention should be paid preoperatively to adjacent-level disease, bone density, appropriate implant size, and optimal patient selection.
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Key Words • **interspinous spacer** • **X-Stop device** • **complication** • **neurogenic claudication**

Spinal fusion has been the standard of treatment for spinal instabilities due to degenerative changes in the disc with subsequent spondylolisthesis, ankylosis, and central canal and neuroforaminal stenosis. Although fusion devices have been shown to offer improved outcomes, some long-term clinical data fail to show a correlation between the high rate of fusion and pain improvement.[9,11] Biomechanical alteration in the load-transferring and stress-shielding effect, causing higher morbidity at the adjacent levels, instrumentation-related osteopenia, and a higher rate of nonunion, has been a growing concern.[5,10–12,19,21] Recently, new concepts, such as soft stabilization, dynamic stabilization, and motion preservation, have been explored as alternative treatment options to lumbar fusion. Interspinous process spacers have been introduced as a possible alternative to spinal decompression and fusion for the treatment of NIC and discogenic lower back pain. The interspinous devices distract the neuroforamen, unload the intervertebral disc, and limit spinal extension, improving central canal and foraminal stenosis.

The first interspinous device, the Wallis system (Abbott Spine), was developed in 1986 and used in patients with recurrent disc herniation. It was found to improve outcome in patients who underwent a second discectomy incorporating the Wallis device.[17] The second generation of the Wallis implant, made with elastic polyetheretherketone (PEEK), has been shown to reduce pain severity in patients with mild to moderate disc degeneration, lateral recess, central spinal stenosis, and significant lower back pain when used in combination with other surgical interventions. Other interspinous spacers used in Europe but not approved for use in the US include the DIAM

Abbreviation used in this paper: NIC = neurogenic intermittent claudication.

Fig. 1. Photograph of the X-Stop device.

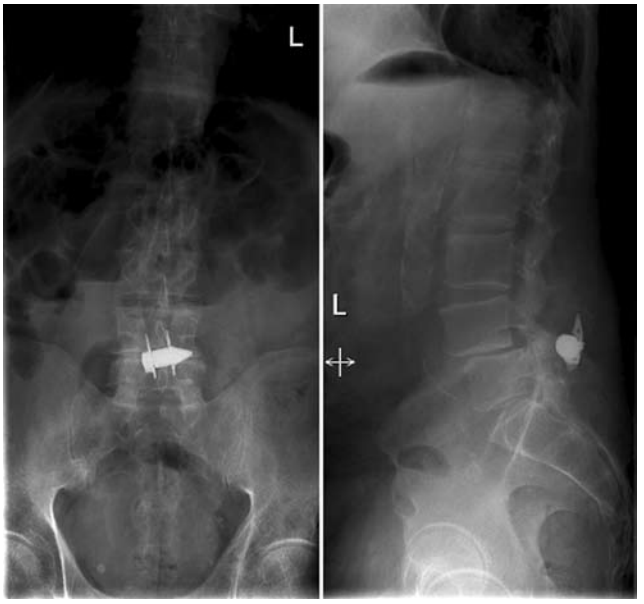

Fig. 2. Postoperative anteroposterior **(left)** and lateral **(right)** radiographs showing the X-Stop device in position.

(Medtronic Sofamor Danek) and the Coflex (Paradigm Spine).[17,20]

The X-Stop device (St. Francis Medical Technologies) was approved by the US FDA in November 2005 and has been shown to be superior to nonoperative therapy in patients with NIC.[27] Biomechanical and radiographic studies have shown that X-Stop increases spinal and neuroforaminal size, limits terminal extension, and reduces intradiscal and facet pressures. Although some large studies have shown very low complication and failure rates with the X-Stop,[14,26,27] more recent publications have suggested that these rates may be higher than those previously reported.[3,6,21] We used the X-Stop device (Fig. 1) at our institution for a brief period as an alternative to spinal decompression with or without fusion for patients with NIC due to lumbar spinal stenosis.

Methods

The medical records of all patients who underwent placement of the X-Stop device for the treatment of NIC were retrospectively evaluated under a protocol approved by the institutional review board. Demographic information, diagnosis, and preoperative pain levels were recorded. Postoperatively, patients were monitored at 1, 3, and 6 months after surgery, and anteroposterior/lateral lumbar spine radiographs (Fig. 2) were obtained to evaluate the position of the device. On follow-up examinations, patients subjectively graded the percentage (0–100%) of improvement in their pain and the amount of residual pain. These data were also collected from the medical records. Approximately 4 years after X-Stop placement, updated long-term clinical data were obtained to determine clinical outcome.

Patient Selection Criteria

All patients who underwent placement of the X-Stop device for the treatment of moderate to severe lumbar spinal stenosis and foraminal stenosis were included in this retrospective review. These patients all had symptoms of lower back pain, neurogenic claudication, and leg pain (unilateral or bilateral) that were evaluated by using MR imaging of the lumbar spine. Only patients with a history of neurogenic claudication with clear symptom amelioration by bending forward were offered treatment with the X-Stop system. After the diagnosis of NIC due to lumbar spinal stenosis, appropriately selected patients underwent placement of the X-Stop device by 1 of 2 different spinal surgeons.

Results

Thirteen patients (8 men and 5 women) underwent placement of the X-Stop interspinous spacers (Table 1): 9 at the L4–5 interspinous space and 4 at both the L3–4 and L4–5 interspinous spaces. Central canal stenosis with bilateral foraminal stenosis had been diagnosed in all of the patients. The degree of stenosis was severe in 9 (69%) of 13 and moderate in 4 (31%) of 13 patients. Five patients (38%) also had Grade I spondylolisthesis at the treated levels, and 1 patient (8%) had a mild degree of scoliosis as well. The average age at the time of surgery was 74.6 years (range 66–84 years).

Except for 1 patient who moved to a different state and was not contacted until the end of the study, all patients were regularly monitored. The average duration of follow-up in the remaining patients was 23.4 months (range 5–48 months), with an accumulative follow-up time of 281 months for all patients. Final follow-up data were obtained after a period ranging from 41 to 48 months postoperatively.

TABLE 1: Preoperative and postoperative data from 13 patients who underwent placement of the X-Stop device*

Case No.	Age (yrs), Sex	Affected Levels & Degree of Stenosis	Preop Diagnosis	Size of Implant (mm)	Initial & Final FU (mos)	% Initial & 2-Yr Pain Improvement	Complication	Second Surgery
1	74, M	L4–5, severe	CCS	12	38 & 46	80 & 0	L-4 spinous process fracture	L3–5, D&F
2	84, M	L4–5, moderate	CCS	10	7 & 43	60 & 60	none	none
3	74, M	L4–5, moderate	CCS	14	18 & 42	100 & 0	none	L4–5, D&F
4	74, F	L4–5, moderate	CCS	12	12 & 45	70 & 30	none	L4–5, D&F
5	82, F	L4–5, moderate	CCS	14	22 & 46	90 & 0	L-4 spinous process fracture	L4–5, D&F
6	67, F	L4–5, severe	CCS, GIS	14	5 & 48	70 & 70	none	none
7	70, F	L4–5, severe	CCS, GIS	12	37 & 47	90 & 0	none	L4–5, D&F
8	72, F	L4–5, severe	CCS, GIS	14	40 & 48	70 & RP	L-3 radiculopathy	L3–4, discectomy
9	80, M	L4–5, severe	CCS, GIS	12	26 & 41	80 & 0	none	L4–5, D&F recommended
10	66, M	L3–4 & L4–5, severe	CCS	12, 14	0 & 48	UN	none	L3–5, D&F
11	74, M	L3–4 & L4–5, severe	CCS	14, 14	25 & 48	80 & 0	none	L2–5, D&F
12	74, F	L3–4 & L4–5, severe	CCS, GIS	12, 14	46 & 48	100 & 0	L-4 spinous process fracture	L3–5, D&F
13	79, F	L3–4 & L4–5, severe	CCS, scoliosis	12, 12	5 & 47	70 & RP	L-3 radiculopathy	L3–5, D&F recommended

* CCS = central canal stenosis; D&F = decompression and fusion; FU = follow-up; GIS = Grade I spondylolisthesis; RP = radicular pain developed; UN = unavailable.

All patients (100%) reported improved symptoms in both lower back and radicular pain immediately after surgery. The average percentage of reported pain improvement was 72% (range 50–100%). However, only 3 patients (23%) did not experience a return of a significant portion of the preoperative pain. One (Case 8) of these 3 patients had adjacent-level radiculopathy due to a herniated disk that produced new back pain necessitating another operation.

Overall, our long-term complication rate was 38%. Three patients (23%) returned with a recurrence of their symptoms due to spinous process fractures of L-4, L-4, and L-5 at 19, 5, and 2 months, respectively (Table 1). These patients were treated using decompressive laminectomy with spinal fusion. Two patients (15%) presented with new L-3 radiculopathies: 1 (Case 13) was at the same level as the X-Stop device and 1 (Case 8) was at the adjacent level above the decompression system. Surgical treatment was recommended for both of these patients, but 1 patient (Case 13) declined because of a desire to avoid open surgery. An additional 6 patients (46%) underwent or were recommended to undergo a laminectomy and/or fusion because of recurrent pain. One of these patients (Case 10) had multiple medical comorbidities that precluded surgery. Another of these patients (Case 5) had only a decompressive laminectomy without subsequent spinal fusion. These additional surgeries occurred anywhere from 4 to 27 months after the initial X-Stop placement. Ultimately, 11 (85%) of 13 patients required additional spine surgery after X-Stop placement.

Discussion

Outcomes Following X-Stop Placement

The X-Stop implant has been designed with the knowledge that NIC symptoms are relieved by flexion of the lumbar spine. The device is placed between the spinous processes of stenotic levels, limiting extension and increasing the neuroforaminal space to decompress neural tissue (Figs. 3 and 4). Lindsey et al.[16] showed in 7 cadaveric lumbar spines (L2–5) that the interspinous X-Stop implant caused a loss in lumbar lordosis by shifting the neutral position 2° to the flexed position. They found that X-Stop decreased the degree of extension and flexion without affecting lateral bending and axial rotation. The adjacent levels remained unaffected by placement of the X-Stop device.[23] Preclinical data indicated that the X-Stop not only increases spinal canal and neuroforaminal sizes but also unloads the facets and the disk space.[13]

Earlier studies have supported these preclinical find-

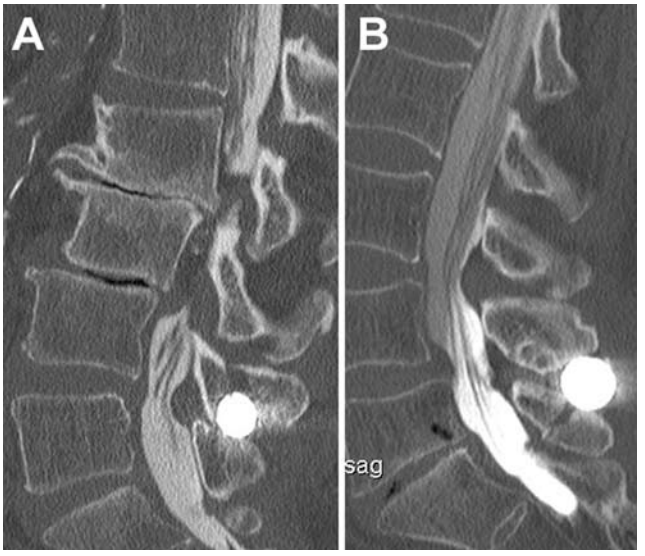

Fig. 3. Postoperative midsagittal CT myelograms demonstrating an L-4 **(A)** and L-5 **(B)** spinous process fracture.

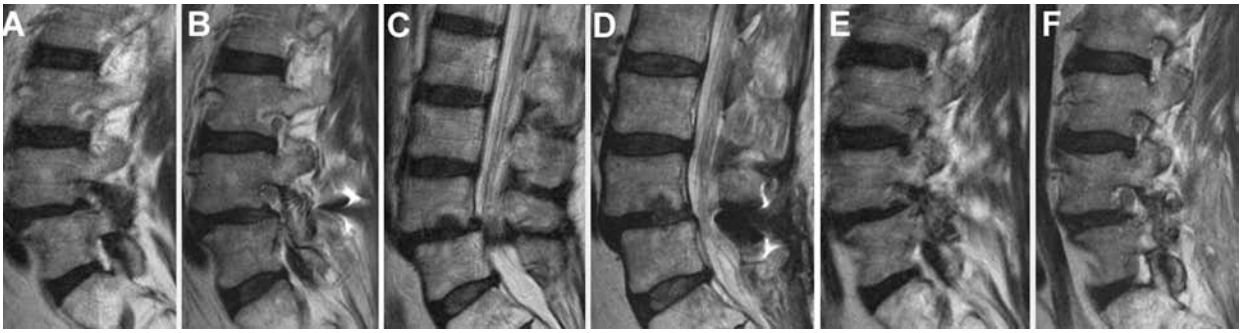

Fig. 4. Preoperative sagittal MR images demonstrating L4–5 left neuroforamina **(A)**, central canal **(C)**, and right neuroforamina **(E)** stenosis. Postoperative sagittal MR images obtained in the same patient after placement of an X-Stop device, showing the left neuroforamina **(B)**, central canal **(D)**, and right neuroforamina **(F)**. Note the extent of the opening of each of the neuroforamina and the central canal after placement of the X-Stop device.

ings. In a prospective randomized trial of 191 patients with pain arising from neurogenic claudication, Zucherman et al.[26,27] reported that patients who were treated with the X-Stop had significantly greater pain relief than those treated with epidural steroid injections (control group) after 1 and 2 years. However, these data could be misleading because the control group was treated with epidural steroid injection, which is not the therapy of choice for lumbar stenosis. Although these results are comparable with reported outcomes in patients treated with decompressive laminectomy, a better study would compare the outcome in patients following X-Stop placement with the outcome in patients following laminectomy.

Kondrashov et al.[13] described a study that included a 4-year follow-up in 18 patients with central canal stenosis who had received an X-Stop device and noted that 78% of the patients had a ≥ 15-point improvement from the baseline Oswestry Disability Index. Initially, 100% of the patients in our series reported improved symptoms, a rate better than the previously reported success rates of 70 and 73.1%.[15,26] The mean symptom severity improved by 72%, which compares favorably with the 45.4% reported previously.[26] However, after a 4-year follow-up, only 2 of our patients (15%) did not experience a return of the preoperative or the occurrence of new back symptoms requiring further surgery. One possible explanation for the wide discrepancy in long-term pain relief in our analysis compared with that in the Kondrashov et al.[11] study is that they may have had more patients with milder canal stenosis. Another plausible explanation is that there is a very steep learning curve associated with X-Stop use, and it takes a large number of cases to reach the high success rates often cited in the literature. In fact, most of the large randomized controlled trials demonstrating high success rates with X-Stop placement have been done in high-volume centers where the device is used with great frequency.[13,14,26,27]

Our results correspond with those in other recent series described in the literature (Table 2). The authors of a study based on patient responses to the Zurich Questionnaire, quantifying patient satisfaction after X-Stop placement, demonstrated a "good outcome" in only 31.3% of patients in a follow-up of < 24 months.[4] Furthermore, Siddiqui et al.[22] demonstrated that 7 (29.2%) of 24 patients with a 1-year follow-up after X-Stop placement had recurrent pain requiring caudal epidural steroid injections. Only 54% of these patients had significant improvement

TABLE 2: Recent publications on X-Stop device complications and failures*

Authors & Year	No. of Patients Treated	No. of Patients w/ Recurrent Pain (%)	FU (mos)	No. of Patients w/ Complication (%)	Patients w/ Additional Surgery Recommended/Performed (%)	No. of Patients w/ Good Outcome/Preop Goal Met (%)
current study	13	10 (77)	41–48	3 spinous process fracture (23); 2 radiculopathy (15)	11 (85)	2 (15)
Barbagallo et al., 2009	69	NA	23	4 spinous process fracture (6); 4 device dislocation (6)	(7)	NA
Brussee et al., 2008	65	1 (2)	12 ± 9	0	6 (9)	(31)
Verhoof et al., 2008	12	7 (58)	30.3	0	7 (58)	5 (42)
Siddiqui et al., 2007	39 (24 w/ full FU)	7 (29) (received caudal epidural steroid injection)	12	2 intraop spinous process fracture (5)	2 (8)	significant improvement in pain (54); physical function improvement (33)

* NA = not applicable.

in their pain, and only 33% had improvement in physical function after a 1-year follow-up.[22]

Reported Complications

Previously reported complications associated with the use of X-Stop primarily include device dislocation/malposition, spinous process fractures, erosion of the spinous process, infection, hematoma, and even neurological sequelae such as foot drop.[1,8,18] The randomized prospective trial conducted by Zucherman et al.[26] is one of the most oft-cited early papers documenting high effectiveness and low complication/failure rates of the X-Stop device, with a complication rate of only 4% and a failure/reoperation rate of 6% in 100 patients. Recently, however, there have been reports[3,4,22,24] of higher postoperative X-Stop complication rates than those demonstrated in many of the earlier publications (Table 2). There has also been a plea for the submission and publication of more X-Stop studies showing negative results.[7] Our complication and failure/reoperation rates were much higher than those reported by Zucherman et al.: 38 and 85%, respectively. We observed a higher rate of spinous process fractures (23%) than previously reported (Table 1). In addition, 2 patients (15%) presented with new-onset radicular pain, a complication that to our knowledge has not been reported in the literature. Perhaps most concerning was the relatively high rate of failure/reoperation (85%) in our own analysis. The authors of a recent study[24] describing the outcome of X-Stop placement in a small group of patients with Grade I spondylolisthesis also documented a high rate (58%) of failure/reoperation. This result led to the recommendation that X-Stop not be used in patients with spondylolisthesis, and spondylolisthesis is now a defined contraindication to X-Stop placement.[14,24] The data from our study support this recommendation since 80% of the patients (4 of 5) with Grade I spondylolisthesis required additional surgery.

The 3 patients in our study with spinous process fractures had successful clinical outcomes up until their spinous process fractures, which occurred at 2, 4, and 19 months posttreatment. The patient with the delayed spinous process fracture at 19 months had what has recently been referred to as a "sandwich phenomenon" fracture of the middle spinous process in adjacent double-level X-Stop placement.[2] The onset of symptoms in these patients was immediate and similar to preoperative symptoms. The reasons for the spinous process fractures were unknown, although possible factors include each patient's degree of osteoporosis and possible overdilation/overdistraction of the interspinous space with a large X-Stop device. Hence, the bone density of each patient and the size of the implant should be carefully evaluated preoperatively. A moderately sized device and modest distraction may be needed to avoid spinous process fractures, especially in patients with poor bone quality and osteoporosis.

Overdistraction may also account for the new-onset radiculopathy at 1 level above the treated level. Wiseman et al.[25] showed that the X-Stop device unloads the facet joints of the affected levels; however, they also found that the adjacent facet peak pressure is increased up to 19%. A combination of increased pressure on the adjacent facet, a moderate level of adjacent foraminal stenosis, and larger than appropriate implant may induce severe adjacent-level foraminal stenosis causing adjacent-level radiculopathy. Thus, a lesser degree of distraction may be required in patients with mild to moderate adjacent-level foraminal stenosis.

In addition to the previously noted steep learning curve, the selection of patients less likely to suffer from complications or failure/reoperation due to X-Stop placement may explain the low complication/failure/reoperation rates seen in earlier studies. It has been suggested that higher success rates will be achieved by avoiding patients with Grade I spondylolisthesis and implanting the device in patients with only mild to moderate spinal stenosis instead of severe spinal stenosis.[6] Recent data show that the most important factor in selecting the proper patient for X-Stop placement may be the clinical demonstration of positional-dependent claudication relieved by flexion.[14] Although all of our patients met this criterion, other factors can affect success. For example, some believe that certain spinal anatomical variants predispose patients to X-Stop failure and suggest using this information as a guide to determine which patients receive X-Stop treatment.[3]

Conclusions

Although the X-Stop device has been shown in some studies to serve as a viable, minimally invasive treatment option for patients with NIC due to lumbar spinal stenosis, our small series demonstrated a high rate of complications and the need for further spinal surgery (85%). We found an increasing number of recent publications suggesting that the X-Stop device may not be as free of complications and failures/reoperations as has been traditionally reported. Additional areas of X-Stop investigation include appropriate in vitro assessments and a larger group of long-term clinical outcomes with several years of follow-up.[23] Further clinical studies are needed to evaluate the X-Stop system compared with our current standards of treatment—laminectomy or interlaminar decompression. Moreover, further randomized studies are needed to help identify the patient subset most likely to experience long-term benefit from X-Stop placement. Our data would seem to support the previously noted fact that patients with moderate to severe spinal stenosis are poorer candidates than those with mild to moderate stenosis. Furthermore, there may be a very steep initial learning curve for success with X-Stop placement. Careful preoperative evaluation of adjacent-level disease, bone density, appropriate implant size, and degree of spinal stenosis leading to optimal patient selection will provide the best chance of X-Stop placement success and avoid the aforementioned complications.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: MH Schmidt,

A Amini. Acquisition of data: C Bowers, A Amini. Analysis and interpretation of data: C Bowers, A Amini. Drafting the article: C Bowers, A Amini. Critically revising the article: MH Schmidt, AT Dailey. Reviewed final version of the manuscript and approved it for submission: MH Schmidt. Statistical analysis: C Bowers, A Amini. Study supervision: MH Schmidt, AT Dailey.

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Analysis of load sharing on uncovertebral and facet joints at the C5–6 level with implantation of the Bryan, Prestige LP, or ProDisc-C cervical disc prosthesis: an in vivo image-based finite element study

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Object. The goal of this study was to evaluate and compare load sharing of the facet and uncovertebral joints after total cervical disc arthroplasty using 3 different implant designs.

Methods. Three-dimensional voxel finite element models were built for the C5–6 spine unit based on CT images acquired from a candidate patient for cervical disc arthroplasty. Models of facet and uncovertebral joints were added and artificial discs were placed in the intervertebral disc space. Finite element analyses were conducted under normal physiological loads for flexion, extension, and lateral bending to evaluate von Mises stresses and strain energy density (SED) levels at the joints.

Results. The Bryan disc imposed the greatest average stress and SED levels at facet and uncovertebral joints with flexion-extension and lateral bending, while the ProDisc-C and Prestige LP discs transferred less load due to their rigid cores. However, all artificial discs showed increased loads at the joints in lateral bending, which may be attributed to direct impinging contact force.

Conclusions. In unconstrained/semiconstrained prostheses with different core rigidity, the shared loads at the joints differ, and greater flexibility may result in greater joint loads. With respect to the 3 artificial discs studied, load sharing of the Bryan disc was highest and was closest to normal load sharing with the facet and uncovertebral joints. The Prestige LP and ProDisc-C carried more load through their rigid core, resulting in decreased load transmission to the facet and uncovertebral joints. *(DOI: 10.3171/2010.3.FOCUS1046)*

Key Words • cervical disc arthroplasty • joint load sharing • facet joint • uncovertebral joint • cervical spine

Artificial cervical disc arthroplasty has been introduced to limit the development of ASD that can occur with ACDF. By direct decompression along with disc height and neuroforaminal restoration, ACDF has achieved a success rate of over 90%, with resolution of symptoms and return to normal daily activities after surgery.[3] However, immobility of the fused level has been associated with accelerated degeneration at levels adjacent to the fused site, which is a major long-term concern with ACDF surgery.[1,9,12,18,23] Evidence of ASD has been shown in many biomechanical studies in which removal of segmental motion increases stiffness at the fused segment, resulting in elevated stress at adjacent levels, where degeneration is potentially accelerated.[8] Therefore, artificial disc arthroplasty, by preserving segmental motion and alleviating the stress burden at adjacent levels, is believed to decrease the propensity for ASD. The concept has been supported by early clinical outcomes showing that artificial cervical discs were capable of preserving segmental motion[8,19] with improved pain and function scores.[2]

Despite its encouraging short-term outcomes with artificial cervical disc arthroplasty, however, there are concerns regarding complications related to device design as well as subsidence, dislocation, and instability due to misalignment.[1] In our previous work, we analyzed 3 different disc prostheses—Bryan (Medtronic, Inc.), Prestige LP (Medtronic, Inc.), and ProDisc-C (Synthes, Inc.)—using an image-based FE method to investigate the propensity

Abbreviations used in this paper: ACDF = anterior cervical discectomy and fusion; ASD = adjacent-segment disease; FE = finite element; ROM = range of motion; SED = strain energy density; STL = stereolithography.

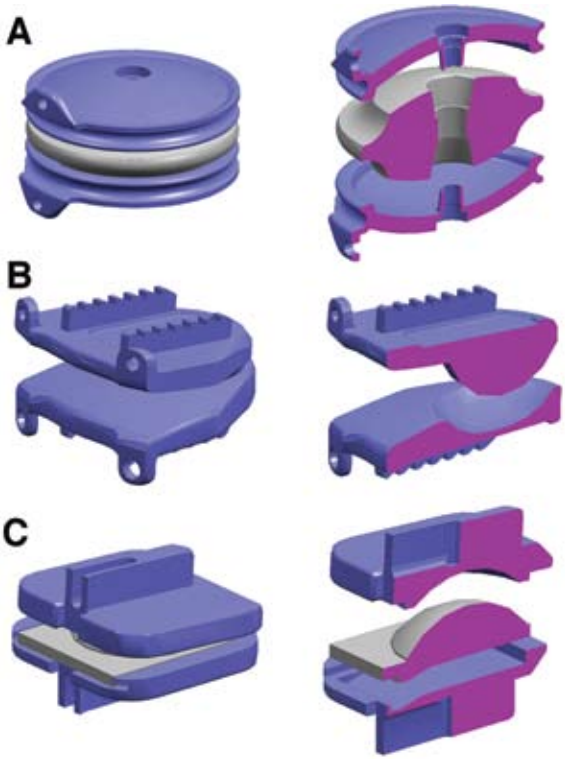

Fig. 1. Geometrical representations of Bryan **(A)**, Prestige LP **(B)**, and ProDisc-C **(C)** artificial cervical discs.

of subsidence caused by device design.[13] Based on the hypothesis that subsidence is related to high implant-interface stress, prostheses with a flexible core (nucleus) were shown to have less likelihood of subsidence, by absorbing high strain energy. However, this raised additional concerns regarding load sharing by facet and uncovertebral joints at the treated level, due to reduced loads transferred to the device's core causing greater shared load burdens for the facet and uncovertebral joints. Given that proper placement of implants in arthroplasty provides better restoration of the natural kinematics of the joint,[1] investigating how the underlying articular mechanism of an artificial disc impacts the biomechanical environment of the spinal segment should help achieve better performance of the prosthesis.

In this extended study, load sharing at the facet and uncovertebral joints was analyzed and compared among segments implanted with Bryan, Prestige LP, and ProDisc-C artificial discs. Using an in vivo image-based FE method, we computed von Mises stresses and the levels of strain energy density (SED). In addition, a spinal segment with an intact, healthy intervertebral disc was modeled and analyzed as a control reference. An underlying assumption in this study was that uncovertebral joints would be preserved at the time of implantation to avoid the possibility of segmental instability after total disc replacement with bilateral uncovertebral joint resection.[5,20] The goal of our study was to evaluate the potential consequences of load sharing on the joints after total cervical disc replacement using different implant designs.

Methods

Artificial Disc Models

Figure 1 illustrates STL models of the Bryan, Prestige LP, and ProDisc-C cervical disc prostheses used in this study (STL is a standard file format for solid freeform fabrication). The Bryan and ProDisc-C models consist of upper and lower endplates and a polymeric nucleus, whereas the Prestige LP disc is composed of upper and lower endplates, with a ball-trough–type metal-on-metal joint. The disc core of the Bryan disc is made of polyurethane, while the ProDisc-C core is polyethylene. The Bryan disc, unlike the ProDisc-C and Prestige LP, relies on a tight fit between its designed geometry and the concavity of the vertebral bodies rather than an explicit fixation mechanism. In general, artificial disc endplates have a porous coating to enhance bone-implant integration. In this study, it was assumed that the bony endplates and artificial disc endplates were fully integrated so that no relative motion was allowed between them.

In Vivo Image-Based FE Modeling

We built in vivo FE models, using an image-based FE modeling and analysis technique, based on a patient with left C-6 radiculopathy secondary to degenerative disc disease and spondylosis of the C5–6 segment. The advantage of an image-based FE modeling and analysis technique is that it can provide fast modeling with accuracy sufficient to capture actual anatomy in clinical settings. All inclusion criteria for enrollment in the FDA's Investigational Device Exemption trials for a possible total disc arthroplasty were met in this patient.[15] The protocols for image acquisition and processing were approved by the institutional review board of the treating institution.

Segmentation was conducted based on image densities using region-growing and masking tools in Simpleware ScanIP software (Simpleware Ltd.). Using these tools with properly chosen threshold values, vertebral bodies were segmented into masks for cortical shells and cancellous cores. Uncovertebral joints and facet joints were added as separate masks based on anatomical knowledge. All masks generated during segmentation could be automatically converted to 3D stereolithography (STL) models. Design models of Bryan, Prestige LP, and ProDisc-C prostheses were also prepared in STL format. In addition to the artificial disc model designs, an intact model of the intervertebral disc was also created. The intact disc model consisted of an outer replica of the annulus fibrosus and an inner core representing the nucleus pulposus.

To process the STL models of spine units with artificial discs, 3D voxel elements (8-node hexahedral elements) were created using Voxelcon (Quint Corp.), an image-based FE software application. Each STL model was imported in an orderly manner, such that vertebral bodies were imported first followed by disc endplates, as the latter imported components would replace any previous ones when creating voxels in Voxelcon. Using this method, we were able to conduct Boolean operations among components with geometrical overlap to further reduce modeling time. Voxel FE models for the C5–6

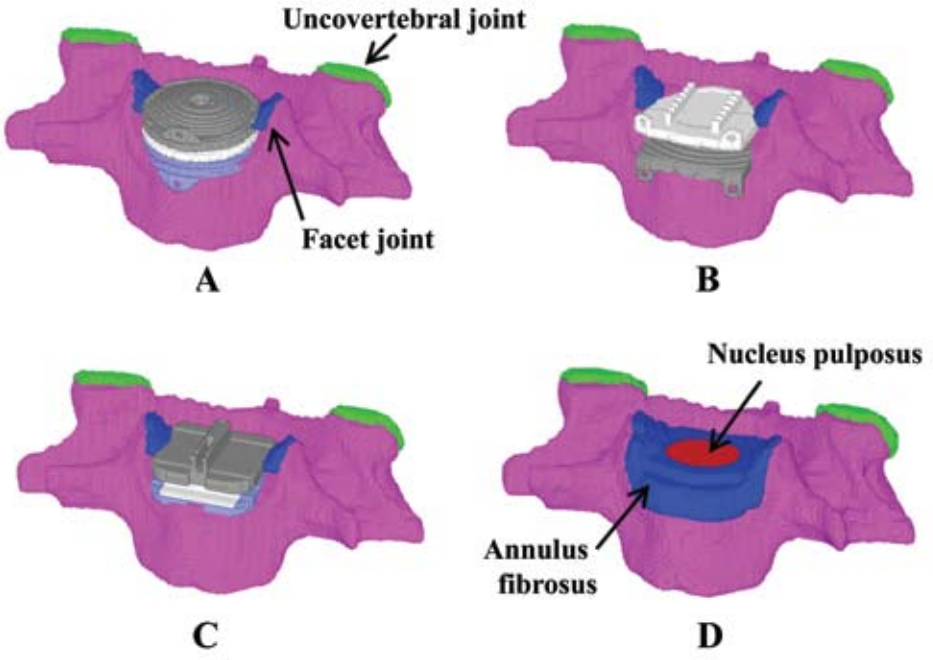

Fig. 2. Voxel FE models of C5–6 spinal units with Bryan **(A)**, Prestige LP **(B)**, and ProDisc-C **(C)** cervical disc prostheses, and intact intervertebral disc **(D)**. (The C-5 vertebral bodies are not shown.)

spinal segment with the 3 prostheses and the control are presented in Fig. 2. The size of the artificial discs was carefully chosen to fit the intervertebral disc height. The placement of each artificial disc was determined such that the resultant instantaneous axis of rotation was close to the region found in a previous FE study.[6] Furthermore, artificial disc endplates were placed parallel to the vertebral endplates with direct contact to cancellous bone. The unit voxel element size was 0.3 mm, and the total number of voxel elements was approximately 1,000,000 for all models so as to incorporate the full details of the complicated vertebral body geometries.

Table 1 presents material properties for spinal units, the 3 artificial disc components, and the natural intervertebral disc. The material properties in our study were determined based on those used in the previous FE studies of biomechanics including cervical spine FE models.[7,10,24] Linear isotropic material properties were assumed in the Voxelcon solver. Static analysis was conducted by imposing 1.5 Nm of flexion, extension, and lateral bending moments, with 73.6 N of axial precompression superior to

TABLE 1: Mechanical properties of components of the FE models

Components	Young Modulus (MPa)	Poisson Ratio
cortical bone	12,000	0.3
cancellous bone	100	0.3
facet joints	5	0.45
uncovertebral joints	5	0.45
intervertebral disc		
annulus fibrosus	3.4	0.4
nucleus pulposus	1	0.49
Bryan		
endplates (titanium)	110,000	0.3
nucleus (polyurethane)	25	0.45
Prestige LP		
endplates (titanium carbide)	110,000	0.3
ProDisc-C		
endplates (cobalt chromium)	210,000	0.3
core (polyethylene)	800	0.3

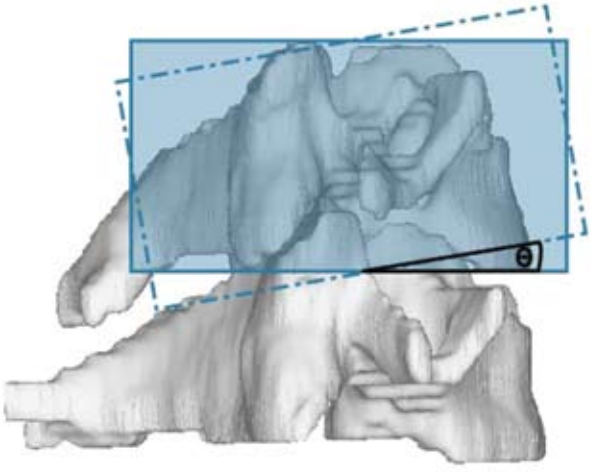

Fig. 3. The rotation angle (θ) was calculated as the difference between the Cobb angles measured before and after flexion-extension loading.

TABLE 2: Average von Mises stresses and SED levels for disc models evaluated by extension and lateral bending at facet joints

Variable	Bryan	Prestige LP	ProDisc-C	Intact
von Mises stress (MPa)				
extension	0.5535	0.03568	0.1015	0.4808
lateral bending	0.3145	0.07428	0.1530	0.2488
SED (10^{-6} J/mm^3)				
extension	32.43	0.155	1.172	24.72
lateral bending	12.52	0.758	3.101	7.326

C-5, with constraints on the inferior endplate of C-6. The axial precompression force and moments were implemented as equivalent load distribution and load couples, respectively.

Biomechanical Comparison

Static analyses were conducted on the C5–6 spine units with the 3 different artificial disc implants and the intact intervertebral disc to investigate load levels shared by the uncovertebral and facet joints. The von Mises stress and SED were calculated to measure loads shared by the uncovertebral and facet joints. Shared loads at the C5–6 segment with the 3 different artificial disc implants were compared with those of the intact intervertebral disc as the control. Shared loads at the facet joints were investigated only in extension and lateral bending moments because facet joints are not considered to carry tensile loads. The rotation angle was measured by the Cobb method (Fig. 3), which is frequently adapted for radiographic assessments.[16]

Results

Analyses of Load Sharing at the Facet Joints

Table 2 presents average von Mises stresses and SED levels at the facet joints of C5–6 for the Bryan, Prestige LP, ProDisc-C, and intact discs under either extension or lateral bending moment. Relative load and energy levels of the segmental unit with the artificial discs are illustrated in Figs. 4 and 5, which were normalized to the values of the intact spinal unit. Under extension moment, the von Mises stress at loaded facet joints in the spinal segment with the Bryan prosthesis reached 0.554 MPa, which was similar to that of the intact intervertebral disc (0.481 MPa). In contrast, when the Prestige LP and ProDisc-C discs were used, the facet joints of the spinal segments were found to have much lower levels of von Mises stresses (0.03568 MPa and 0.1015 MPa, respectively), which were 7.4% and 21.1% of the intact model. Under lateral bending moment, von Mises stresses also showed a similar distribution of higher values occurring with the Bryan and intact discs (0.314 MPa and 0.249 MPa, respectively), whereas values with the Prestige LP and ProDisc-C discs were much lower (0.0743 MPa and 0.153 MPa, respectively). However, the stress difference is smaller in lateral bending than in extension. When the energy absorbed by the joints was measured by SED, facet joints with the Bryan disc absorbed more strain energy (32.43×10^{-6} J/mm^3) than the Prestige LP (0.155×10^{-6} J/mm^3) and ProDisc-C (1.17×10^{-6} J/mm^3). The SED comparison clearly demonstrated that discs with rigid cores resulted in lower SED levels, since less motion and deformation at the joints was permitted (Fig. 5).

Analyses of Load Sharing at Uncovertebral Joints

Load sharing at the uncovertebral joints was evaluated and compared under flexion, extension, and lateral bending moments. The average von Mises stresses and SED levels indicate higher transferred loads and absorbed energy at uncovertebral joints with the Bryan

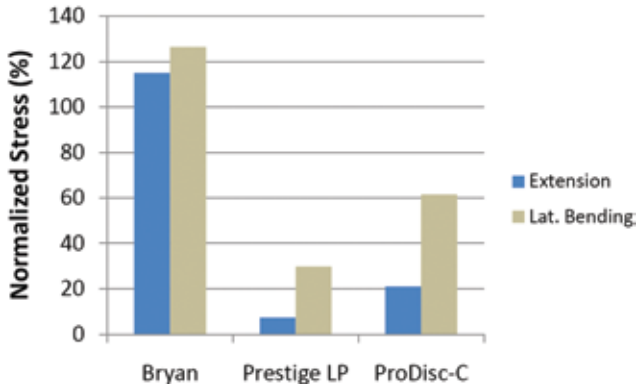

Fig. 4. Comparison of average von Mises stresses at facet joints of C5–6 spine segment with Bryan, Prestige LP, and ProDisc-C prostheses, normalized to the von Mises stress of intact intervertebral disc. Lat. = lateral.

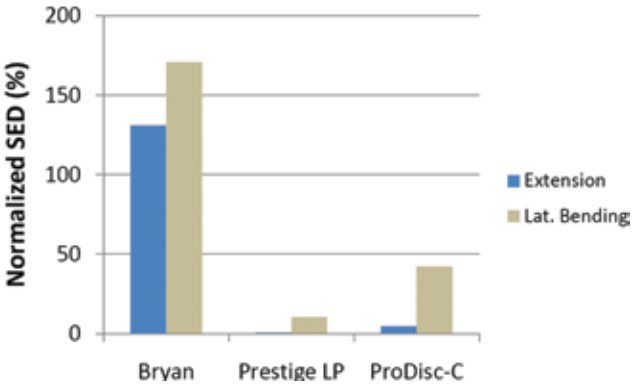

Fig. 5. Comparison of average SED at facet joints of C5–6 spine segment with Bryan, Prestige LP, and ProDisc-C prostheses, normalized to the SED of the intact intervertebral disc.

TABLE 3: Average von Mises stresses and SED levels for all disc models evaluated by flexion, extension, and lateral bending at uncovertebral joints

Variable	Bryan	Prestige LP	ProDisc-C	Intact
von Mises stress (MPa)				
flexion	0.5137	0.1056	0.1419	0.4095
extension	0.3999	0.1024	0.1513	0.3974
lateral bending	0.4696	0.2867	0.3302	0.3116
SED (10^{-6} J/mm^3)				
flexion	19.94	5.507	5.534	8.715
extension	16.56	2.503	5.363	10.64
lateral bending	30.93	20.25	20.14	6.435

prosthesis in flexion and extension moments, as opposed to the joints with Prestige LP or ProDisc-C disc (Figs. 6 and 7). As presented in Table 3, the average von Mises stresses of the Bryan model in flexion and extension moments (0.5137 and 0.3999 MPa, respectively) were 125% and 100% of those of the intact model (0.4095 and 0.3974 MPa), whereas stress levels of the Prestige LP (0.1056 and 0.1024 MPa) and ProDisc-C (0.1419 and 0.1513 MPa) models were 26% and 36% of those in the intact model. In lateral bending, the average von Mises stresses with the Prestige LP (0.2867 MPa) and ProDisc-C (0.3302 MPa) were similar to those of the control (0.3116 MPa), but were only slightly greater than half of the value measured with the Bryan disc. The SED levels of all loaded joints with the artificial discs (20.25, 20.14, and 30.93 × 10^{-6} J/mm^3, for the Prestige LP, ProDisc-C, and Bryan discs, respectively) were substantially greater than in the control (6.435 × 10^{-6} J/mm^3).

Load Displacement Responses

Due to the limited properties of the voxel element in the current modeling technique, facet joints were modeled as linear solid elements rather than contact elements that carry only compressive loads. This resulted in a stiff response in the ROM along flexion-extension, as presented in Table 4. The ROM in the C5–6 spinal unit of the control was 3.1° in 1.5 Nm flexion and extension moments. The Bryan disc spinal unit showed a similar ROM (2.9°) to that of the control. Spinal units with the Prestige LP and ProDisc-C discs presented stiff responses in ROM, presumably due to their rigid cores (0.43° and 0.64°, respectively).

Discussion

The study goal was to evaluate the effect of artificial disc designs on load sharing at the facet and uncovertebral joints. Although we did not conduct a kinematics study, the stability of unconstrained/semiconstrained artificial discs relies on the remaining joints and soft tissues to some extent.[6] In fact, the Bryan and Prestige LP discs are considered unconstrained or semiconstrained designs, and the ProDisc-C is semiconstrained with a fixed axis of rotation.[1,4,6] This suggests that the core material stiffness can play a major role in the comparison of the load sharing of the artificial discs. Therefore, our image-based FE analysis with static loading conditions can reflect possible complications related to the cervical disc arthroplasty.

Cervical disc arthroplasty has been purported to limit the potential long-term complication of ASD after spinal fusion. Although promising outcomes have been reported from short-term investigations, many concerns for the "artificial" preservation of segmental motion still remain with regard to subsidence or migration of the device, as well as degeneration of joints at the treated and adjacent

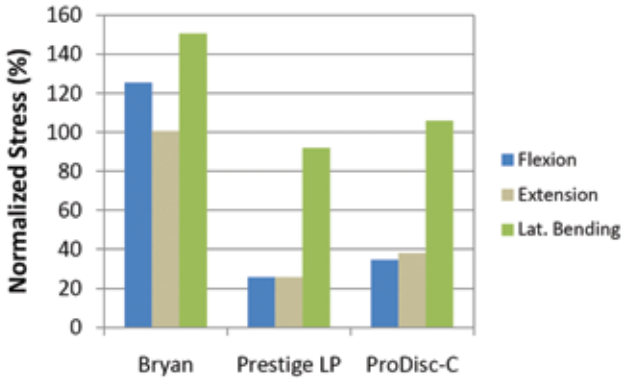

Fig. 6. Comparison of average von Mises stresses at uncovertebral joints of C5–6 spine segment with Bryan, Prestige LP, and ProDisc-C prostheses, normalized to the von Mises stress of the intact intervertebral disc.

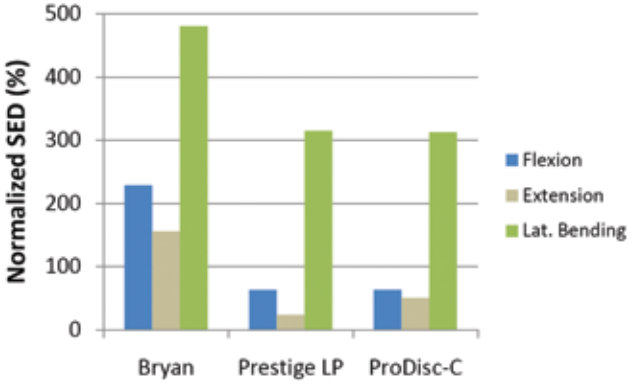

Fig. 7. Comparison of average SED at uncovertebral joints of C5–6 spine segment with the Bryan, Prestige LP, and ProDisc-C prostheses, normalized to the SED of the intact intervertebral disc.

TABLE 4: Measurement of Cobb angles in sagittal flexion-extension for all disc models

Disc Model	Cobb Angle (°)
Bryan artificial cervical disc	2.90
Prestige LP artificial cervical disc	0.43
ProDisc-C artificial cervical disc	0.63
intact model	3.10

levels. Van Ooij et al.[22] reported facet joint arthrosis due to abnormal segmental motion in 11 of 27 patients who had persistent symptoms after cervical disc arthroplasty. Abnormal segmental motion has been thought to create excessive load burden on the facet joints and therefore may induce early degeneration. A late complication that has been reported up to 18 years after artificial disc arthroplasty is facet joint degeneration, which has been hypothesized to result from instability caused by removal of anterior longitudinal ligaments.[17] According to these prior investigations and our previous findings, we hypothesized that arthroplasty with an unconstrained prosthesis may accentuate the instability and possibly result in facet degeneration over time. The instability can then induce an increased shared load at the remaining joints, which can cause deterioration of the joint.

For the Bryan disc, which has a flexible polyurethane core, there would be a higher propensity for the implant to transfer loads to the facet joints after disc replacement, since the implant is allowed greater ROM for a given constraint from the surrounding tissues. Our results indicate that with the Bryan disc, the facet joints bore greater loads compared with the other artificial discs. As a consequence, stress levels at the facet joints with the Bryan disc were 0.55 MPa in extension moment and 0.31 MPa in lateral bending moment, which were higher than those with the ProDisc-C disc (0.10 MPa in extension and 0.15 MPa in lateral bending) and orders of magnitude higher than those with the Prestige LP disc (0.036 MPa in extension and 0.074 MPa in lateral bending). However, the stress level at the facet joints with the Bryan disc was comparable to the intact model (0.48 MPa in extension and 0.25 MPa in lateral bending), suggesting that the biomechanics are similar to the inherent state.

Low load sharing at the facet joints with the Prestige LP and ProDisc-C discs, which have greater core rigidity, can also be problematic with respect to disuse osteopenia of the joints. Although these artificial discs can provide better stability to the treated spine segment, the low load sharing can result in further degeneration of the remaining joint tissue. Trouillier et al.[21] studied the effect of artificial disc implantation on facet loading at the operated and adjacent levels by observing subchondral bone density using CT osteoabsorptiometry. They concluded that decreased subchondral bone density of the facet joints may be related to joint load reduction associated with artificial disc arthroplasty, compared with preoperative abnormal facet loads. In the current study, our results agreed with their observations. The high degree of stiffness of the prosthetic disc nucleus results in greater load to the anterior of the implanted discs and therefore adversely alleviated the default loads originally shared by the facet joints. These findings may provide valuable insight when making decisions about the most appropriate artificial disc for a given condition.

Because the artificial discs in this study are unconstrained or semiconstrained designs, uncovertebral joints may be preserved with arthroplasty to increase the stability of the segmental motion. Uncovertebral joints, along with the facet joint and intervertebral disc, provide stability and guidance for cervical spine segmental motion.[11] It has been shown that the ROM increases at the cervical segment after the uncovertebral joints are resected, especially in extension and lateral bending modes.[5,11,20] Uncovertebral joint resection can be performed during implantation to facilitate insertion of the device or to resolve symptoms related to foraminal stenosis. A study of the effect of uncovertebral joint excision on stability after total disc replacement suggested that the unilateral resection of uncovertebral joints can be beneficial for decompression of intervertebral disc space as well as restoration of ROM.[20] However, total disc replacement after bilateral resection of uncovertebral joints may result in hypermobility, which in turn may cause accelerated degeneration of the joints and potentially, in the long term, growth of osteophytes. Thus, we assumed the preservation of the uncovertebral joints in our study to investigate possible effects of device design on joint degeneration.

Excessive loads on the uncovertebral joints after disc arthroplasty may also lead to joint degeneration. Our results show that the average von Mises stresses at the uncovertebral joints for flexion-extension moments with the Bryan discs were up to 25% greater than those of the intact disc model (Fig. 6). The SED at uncovertebral joints with the Bryan disc was dramatically increased to 230% of that in the intact model, suggesting that the joints were overstimulated (Fig. 7). Conversely, SEDs at the uncovertebral joints of the cervical units with ProDisc-C and Prestige LP discs were found to be much lower (Fig. 7), which might indicate offloading of the joints which, in turn, may interfere with normal kinematics of the segmental motion. The difference in SED is thought to be due to the greater rigidity of the 2 designs, thus shielding a significant amount of stress borne by the uncovertebral joints after implantation of the Bryan disc.

The proportion of increased SED in the uncovertebral joints was much greater with the Bryan disc when the loading mode was lateral bending (Fig. 7). Nearly 5–10 times greater SEDs normalized to the intact segmental unit were observed compared with the Prestige LP and ProDisc-C discs in flexion or extension, whereas the normalized SED in the uncovertebral joints with the Bryan disc was 2–3 times more when the loading was switched to lateral bending. These results could be explained by impingement of the edges of the artificial disc endplates into the uncovertebral joint space, thus elevating the contact stress. It should be emphasized that the design of the endplate of the artificial disc should be geometrically compatible with the uncinate process, which is known to be the densest region in the superior surface of cervical vertebrae,[14] to avoid undesired collision dur-

ing segmental motion. Moreover, as uncovertebral joints are pivotal to segmental motion in the cervical spine, the overhanging endplates of the artificial disc would create obstacles for the joints to articulate under certain motion modes, such as lateral bending. The Prestige LP and ProDisc-C discs may therefore have less tolerance for malpositioning within the disc space, since the instantaneous centers of rotation in both devices are fixed. Malaligned centers would magnify the excessive loads shared by the joints. Alternatively, Bryan discs are designed with a flexible core that allows an offset along the transverse plane, which may actually counter the iatrogenic impact of disc replacement, although it does appear to result in greater load sharing by the uncovertebral joints.

The purpose of the current study was to understand how the implant design of a particular artificial disc affects coordination of load sharing among the artificial and segmental joints at the treated level, which is of paramount importance for the modern spine surgeon as more devices become available for implantation. Learning the possible underlying mechanisms that alter load sharing after disc arthroplasty as well as how certain implant designs can predispose the implant to failure will help the surgeon navigate the increasing array of implant options available. Finite element analysis may serve as an important tool to help determine the differences between disc designs, as clearly shown in the 3 types of artificial discs analyzed in this study.

Study Limitations

Since our FE model involved a single motion segment, analysis of the adjacent segments could not be performed. Given that the potential benefit of arthroplasty is prevention of ASD, comparison of different artificial disc designs on the adjacent-segment facet and uncovertebral joints warrants further study. Another limitation of our study is that current image-based analysis only allows linear modeling and analysis. Nevertheless, the results of our study provide valuable information concerning probable changes in shared loads and stresses at the facet and uncovertebral joints after disc replacement using different implants. Furthermore, the image-based analysis used in our study allows reconstruction of in vivo models in a rapid and efficient fashion. Future studies will be extended to include a multilevel FE model of spine motion segments and nonlinear ligamentous elements to increase the accuracy of the simulation.

Conclusions

The device core/nucleus material stiffness as well as device endplate design appear to affect the load transmission to the remaining facet and uncovertebral joints. The load sharing of the Bryan disc was the highest of the 3 discs evaluated and was closest to normal load sharing with the facet and uncovertebral joints. The high degree of stiffness of the prosthetic disc nucleus in the Prestige LP and ProDisc-C resulted in decreased load sharing with the facet and uncovertebral joints.

Disclosure

Dr. Park is a consultant to Medtronic, but has no personal financial or institutional interest in any of the materials or devices described in this article.

Author contributions to the study and manuscript preparation include the following. Conception and design: F La Marca. Acquisition of data: H Kang. Analysis and interpretation of data: C Lin, H Kang, P Park. Critically revising the article: C Lin, P Park, F La Marca, S Hollister. Reviewed final version of the manuscript and approved it for submission: F La Marca. Study supervision: C Lin.

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Screw loosening in the Dynesys stabilization system: radiographic evidence and effect on outcomes

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Object. Dynamic stabilization systems are used to stabilize degenerative lumbar spondylosis. Loosening of the pedicle screws in such nonfusion implants is predictable. This retrospective study evaluated the incidence of screw loosening and its effect on clinical outcomes.

Methods. Charts, radiographic films, and medical records of 71 consecutive patients who underwent decompression using Dynesys dynamic stabilization for 1- or 2-level lumbar spondylosis were reviewed. Radiographic films were evaluated and compared to detect screw loosening. A visual analog scale (VAS) for back pain and the Oswestry Disability Index (ODI) were used for measuring clinical outcome. Statistical analysis was conducted using the chi-square test and Student t-test.

Results. The 71 patients in the study sample had a mean age of 59.2 ± 11.65 years (range 23–80 years), with slight female predominance (39 women, 32 men). The mean follow-up duration was 16.6 months (range 8–29 months). There were loose screws in 14 of 71 patients (19.7%), for a rate of 4.6% per screw (17 of 368 screws). Most screw loosening occurred in patients ≥ 55 years old (13 of 14 patients) although age and sex had no effect on screw loosening ($p = 0.233$ and 0.109, respectively). Both the loose screw and solid screw groups experienced significant improvement after the surgery in VAS and ODI scores. On the VAS, scores improved from 5.9 ± 2.99 to 2.1 ± 2.14 in the loose screw group ($p = 0.003$), and from 5.7 ± 3.45 to 2.9 ± 2.68 in the solid screw group ($p < 0.001$). For the ODI scale, scores improved from 43.5 ± 16.78% to 28.0 ± 18.18% ($p = 0.006$) in the loose screw group, and from 52.1 ± 20.92% to 24.6 ± 19.78% ($p < 0.001$) in the solid screw group. There were no significant differences between the 2 groups ($p = 0.334$ for VAS, $p = 0.567$ for ODI).

Conclusions. The preliminary study of this pedicle-based dynamic stabilization device for 1- and 2-level lumbar spondylosis shows radiographic evidence of screw loosening in 19.7% of patients and 4.6% of screws. Nonetheless, the loosening of screws has no adverse effect on clinical improvement. *(10.3171/2010.3.FOCUS1052)*

Key Words • dynamic stabilization • Dynesys • lumbar spondylosis • spondylolisthesis • screw loosening

Lumbar spine degeneration has been described by Kirkaldy-Willis and Farfan in 1982[10] using the concept of 3 phases: 1) temporal dysfunction, 2) unstable phase, and 3) restabilization. Phase 1 patients may respond to conservative treatment, while late Phase 2 and Phase 3 cases require surgery for stabilization, decompression, and correction of deformity. To stabilize the lumbar spine, internal fixation with bone graft fusion is acceptable, and various rigid fixation systems have been developed, including screws and rods.

Over the years, spinal fusion facilitated by instrumentation has been regarded as the standard treatment for severe degenerative lumbar spondylosis. However, a considerable amount of associated morbidity and complications have been reported,[3,8] and adjacent segment degeneration is one that has drawn the most attention. The transition syndrome theoretically occurs from an overloading of adjacent segments,[1,15] thereby challenging the long-accepted choice of fusion as standard surgical treatment. Numerous devices have since been developed to overcome the shortcomings of spinal fusion.

Dubois and colleagues first used the Dynesys system (Zimmer Spine) in 1994. Although several studies report that this system is a safe and promising alterna-

Abbreviations used in this paper: ODI = Oswestry Disability Index; VAS = visual analog scale.

tive to fusion in treating unstable lumbar spondylosis,[2,14,21] there has been no randomized controlled study addressing long-term outcome. To date, there is still a lack of strong evidence corroborating the concept of "dynamic stabilization."

The use of pedicle-based lumbar stabilization devices spares the need for graft incorporation and spinal fusion. However, demands for durability and mechanical strength of the implant are higher than those required for fusion. Few reports address the problem of screw loosening in the literature. The true incidence of screw loosening and its effect on clinical outcomes remain uncertain.

This retrospective study evaluated the rate of screw loosening in the Dynesys system and correlated image findings to clinical outcomes. This study cohort was the largest from a single center with a reasonable follow-up duration, although this duration was shorter than in studies for spinal fusion because no graft incorporation was involved.

Methods

Patient Enrollment

Eighty-two consecutive patients were enrolled based on operative indications of symptomatic lumbar spinal stenosis and/or Grade 1 degenerative spondylolisthesis presenting as low-back pain, radiculopathy, or neurogenic claudication that failed conservative treatment longer than 12 weeks. Surgical procedures included lumbar total laminectomy in addition to dynamic posterior stabilization using the Dynesys system. All patients were treated and followed-up at the Taipei Veterans General Hospital in Taipei, Taiwan. The patients provided informed consent for the retrospective analysis of their clinical data.

Seventy-one patients completed the clinical and radiological follow-up evaluations. Eleven patients were excluded from the study due to inadequate neurological or radiological evaluations, or were lost to follow-up. The mean patient age was 59.2 ± 11.65 years (range 23–80 years) and the mean follow-up duration was 16.6 months (range 8–29 months). There was slight female predominance (39 patients, 55%). The Dynesys system was implanted for 1 level in 29 patients and for 2 levels in 42 patients, with 368 total screws inserted (Table 1).

TABLE 1: Patient characteristics

Variable	Value (%)
no. of patients	71 (100)
M/F	32:39 (45:55)
mean age ± SD (yrs)	59.2 ± 11.65
op	
1 level	29 (41)
2 level	42 (59)
total no. of screws	368 (100)
L-2	2 (0.5)
L-3	64 (17.4)
L-4	134 (36.4)
L-5	130 (35.3)
S-1	38 (10.3)

Surgical Procedures

Patients were placed prone in natural lumbar lordosis with adequate cushions, and fluoroscopy was used routinely for confirmation of this positioning. Standard lumbar total laminectomies with foraminotomies were performed via midline incision for direct posterior decompression at indicated levels. The exiting and traversing nerve roots were probed to confirm the adequacy of decompression. Generous subdermal dissection through the same incision provided access to another 2 fascial incisions, one on each side, allowing a bilateral approach through the Wiltse plane. The Dynesys pedicle screws were then inserted and connected in the relatively avascular intermuscular plane.[24]

All pedicle screws used in the series were standard titanium alloy, closed-head (side-loading) screws, without hydroxylapatite coating. The trajectory, length, and diameter of the screws used were previously determined based on preoperative CT scans and correlated with intraoperative measurements and fluoroscopic images. The polycarbonate-urethane spacer was inserted following the standard insertion techniques, with independent measurement using the pedicle distance gauge to tailor the length for every spacer. We attempted to hold the spinal segment in a more neutral anatomical position, avoiding excessive distraction on the facets; pre- and intraoperative fluoroscopic images were compared for confirmation. The tension cord was then assembled accordingly. In the setting of 2-level constructs, the lower level was always assembled first. A drainage catheter was placed before wound closure. Three fascial incisions (1 midline and 1 on each side for the Wiltse plane) and the midline skin excision were closed by interrupted sutures.

Clinical Evaluations

Charts, radiological imaging, and medical records were reviewed. Neurological examination and functional assessment were recorded preoperatively, at 3 weeks, and at 3, 6, 12, and 24 months postoperatively. Two independent nurse specialists under supervision of the attending physicians conducted the evaluations. Short questionnaires were completed, including the VAS for back pain and the ODI for functional disability.[6]

Radiographic Evaluations

In every patient, the following preoperative images were obtained: standing anteroposterior and lateral radiographs, dynamic lateral radiographs (flexion-extension views), lumbar spine CT scans, and lumbar spine MR imaging. All patients underwent anteroposterior plain radiography and lumbar spine CT scans within 1 week postoperatively, or as soon as the drains were removed. The follow-up protocol included anteroposterior and dynamic (flexion-extension) radiographs at 3, 6, 12, and 24 months postoperatively. Lumbar CT scans confirmed questionable screw loosening.

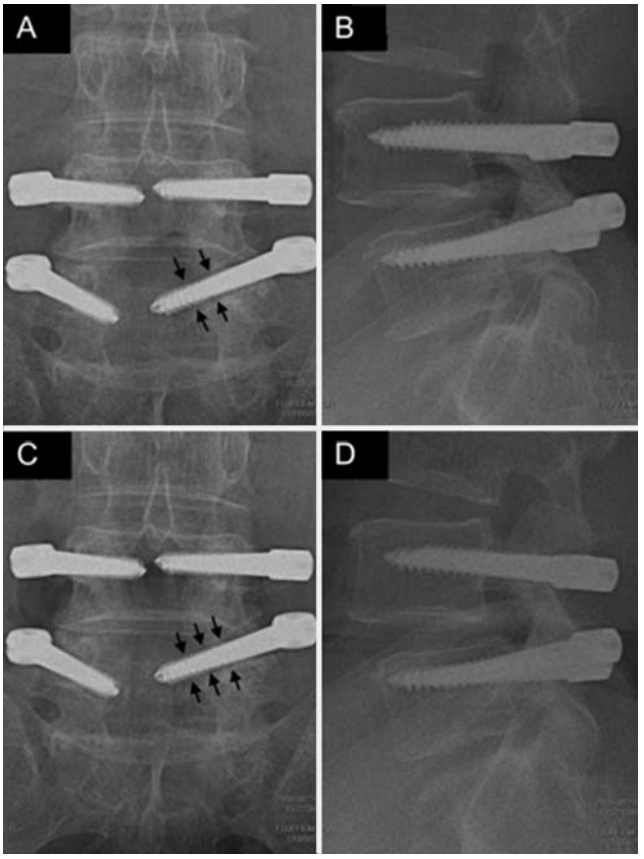

Fig. 1. Anteroposterior **(A and C)** and lateral **(B and D)** postoperative radiographs obtained in a 64-year-old man who underwent L4–5 laminectomy for decompression and L4–5 Dynesys stabilization. **A and B:** At 6 months after the operation, a halo zone sign *(arrows)* indicated loosening of the left L-5 pedicle screw. **C and D:** At 12 months after the operation, a double halo sign *(arrows)* further confirmed the loosening.

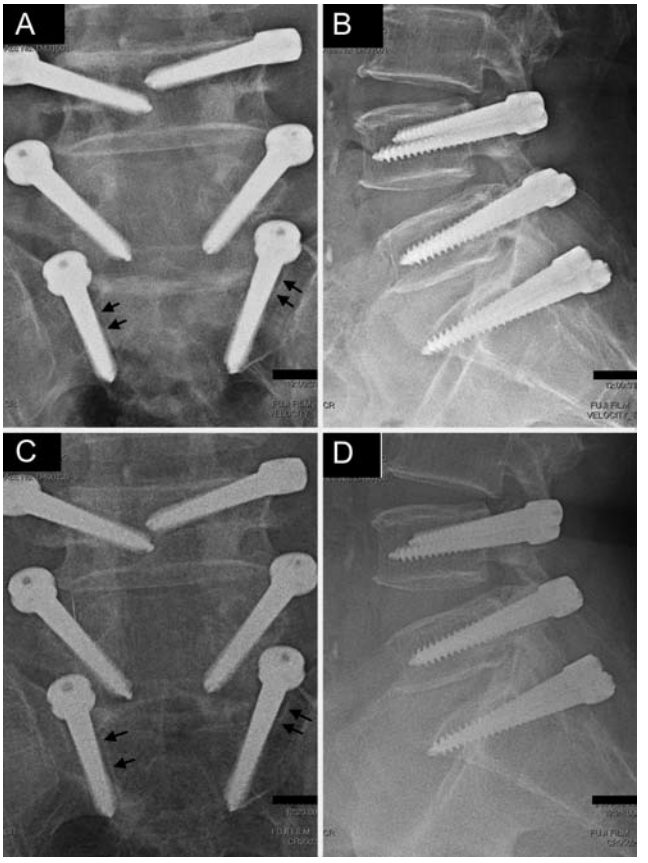

Fig. 2. Anteroposterior **(A and C)** and lateral **(B and D)** postoperative radiographs obtained in a 77-year-old man who underwent an L3–5 laminectomy for decompression and L4-S1 Dynesys stabilization. **A and B:** At 4 months after the operation, a halo zone sign *(arrows)* indicated loosening of the bilateral S-1 pedicle screw. **C and D:** At 6 months after the operation, a double halo sign *(arrows)* further confirmed the loosening.

Definition of Radiographic Loosening of Screws

On digital anteroposterior radiographs, a wide (> 1 mm) radiolucent zone surrounding the screws, regardless of length of lucency, was described as a "halo zone sign," and was defined as radiographic loosening (Figs. 1A and 2A).[4,16] Sometimes the films were difficult to read because of bowel gas, body mass, or osteoporotic changes. The "double halo" sign was used to confirm the diagnosis if later radiographs were available (Figs. 1C and 2C). The "double halo" was described as a radiolucent rim surrounding the screw that is framed by the rim of radiopaque dense bone trabiculae.[4] The radiologists and neurosurgeons resolved all ambiguities by consensus. The radiographic signs used for determination of screw loosening were usually better appreciated on anteroposterior than on lateral radiographs. (Figs. 1B, 1D, 2B, and 2D).

Statistical Analysis

The statistical program SPSS version 17 (SPSS Inc.) was used to perform all statistical analyses. Data were analyzed using the chi-square test and Student t-test, where appropriate. Statistical significance was accepted at a probability value < 0.05.

Results

Radiographic Follow-Up

Dynamic stabilization was applied to 1 disc level in 29 patients and to 2 disc levels in 42 patients. Of the 368 screws inserted and evaluated in this series, 17 screws (4.6%) in 14 patients (19.7%) were loose according to radiographic examinations. The distribution of screw loosening was: 5 screws in 5 patients from the 1-level stabilization group and 12 screws in 9 patients from the 2-level stabilization group (Table 2). Interestingly, none of the loose screws in the patients with 2-level stabilization were found at the middle segment.

One malpositioned screw was identified on a postoperative CT scan. This malpositioned screw was a breach without compromising the nerve roots. There was no screw breakage or other instrumentation failure in the patient series. There were no wound infections and no secondary surgery was required.

Of the 14 patients (19.7%) with screw loosening, 8 were first found to have screw loosening on radiographs obtained 3 months postoperatively, whereas the other 6 patients were found to have loose screws 3–6 months postop-

TABLE 2: Loose screws by instrumented segments

Op (no. of patients [%])	Level Distribution	No. of Patients (%)	No. of Loose Screws	No. of Patients w/Loose Screws
1 level (29 [40.8])	L3–4	5 (7)	1	1
	L4–5	20 (28.2)	4	4
	L5–S1	4 (5.6)	0	0
2 level (42 [59.2])	L2–4	1 (1.4)	0	0
	L3–5	25 (35.2)	7	5
	L4–S1	16 (22.5)	5	4
total (71 [100])		71 (100)	17	14

eratively. Regarding confirmation of screw loosening, the interval between the halo zone sign and the double halo sign was 0–3 months in 7 patients, 6–12 months in 6 patients, and 16 months in 1 patient.

The group with loose screws had 14 patients (5 women and 9 men) with a mean age of 62.3 ± 7.25 years (range 47–77 years), whereas the group with solid screws had an average age of 58.3 ± 12.40 years (range 23–80 years; $p = 0.223$; Table 3). Thus, age was not related to screw loosening. However, if the patients were placed into a subgroup < 55 years old or ≥ 55 years old, almost all loosening (except 1) happened within the group ≥ 55 years old ($p = 0.025$). Sex also had no significant effect on screw loosening ($p = 0.109$) (Table 3).

Neurological Evaluations

The overall mean preoperative VAS score was 5.8 ± 3.34 (range 3–10), consisting of 5.7 ± 3.45 (range 3–10) for the solid screw group and 5.9 ± 2.99 (range 3–10) for the loose screw group. The mean preoperative ODI score was 50.4 ± 20.34% (range 22–91%), including 52.1 ± 20.92% (range 22–91%) for the solid screw group and 43.5 ± 16.78% (range 32–91%) for the loose screw group (Tables 4 and 5).

The mean postoperative VAS score for low-back pain was 2.7 ± 2.59 (range 0–9), consisting of 2.9 ± 2.68 (range 0–9) for the solid screw group, and 2.1 ± 2.14 (range 0–7) for the loose screw group. The mean postoperative ODI score was 25.3 ± 19.4% (range 0–67%), including 24.6 ± 19.8% (range 0–67%) for the solid screw group and 28.0 ± 18.2% (range 4–51%) for the loose screw group (Table 3).

Comparing the latest VAS score with the preoperative VAS score, low-back pain improved significantly after surgery in both groups ($p = 0.003$ for the loose screw group and $p < 0.001$ for the solid screw group). Similarly, there was significant improvement in the ODI ($p = 0.006$ and $p < 0.001$, respectively; Tables 4 and 5; Figs. 3 and 4).

Discussion

Arthrodesis is a well-accepted strategy in the surgical treatment of degenerative lumbar spondylosis, with satisfactory outcomes.[7,22] Achieving fusion has therefore been the goal of every spine surgeon for decades. However, there are a few reports in the literature of patients with failed spinal fusion and pseudoarthrosis that have comparable clinical outcomes as solid fusion.[7] There is the hypothesis that the reduction, rather than the elimination, of lumbar segmental motion results in alleviated back pain.[9] Moreover, the issue of adjacent level disease

TABLE 3: Characteristics of the patients in each group

Characteristics	Total	Screw Loosening*		p Value
		Yes	No	
no. of patients	71	14 (19.7)	57 (80.3)	
mean age ± SD (yrs)	59.2 ± 11.65	62.3 ± 7.25	58.3 ± 12.40	0.233
age <55 yrs	23	1 (4.3)	22 (95.7)	0.025†
age ≥55 yrs	48	13 (27.1)	35 (72.9)	
M	32	9 (28.1)	23 (71.9)	0.109
F	39	5 (12.8)	34 (87.2)	
mean preop ODI score ± SD	50.4 ± 20.34	43.5 ± 16.78	52.1 ± 20.92	0.160
mean postop ODI score ± SD	25.3 ± 19.40	28.0 ± 18.18	24.6 ± 19.78	0.567
mean preop VAS score ± SD	5.8 ± 3.34	5.9 ± 2.99	5.7 ± 3.45	0.891
mean postop VAS score ± SD	2.7 ± 2.59	2.1 ± 2.14	2.9 ± 2.68	0.334
op				
1 level	29	5 (17.2)	24 (82.8)	0.665
2 level	42	9 (21.4)	33 (78.6)	

* Data given as number of patients (%) unless otherwise indicated.

† Statistically significant.

TABLE 4: Clinical outcome of 14 patients with loose screws*

Scale	Mean Preop Score	Mean Latest FU Score	p Value
VAS	5.9 ± 2.99	2.1 ± 2.14	0.003†
ODI	43.5 ± 16.78	28.0 ± 18.18	0.006†

* FU = follow-up.
† Statistically significant.

TABLE 5: Clinical outcome of 57 patients with solid screws

Scale	Mean Preop Score	Mean Latest FU Score	p Value
VAS	5.7 ± 3.45	2.9 ± 2.68	<0.001*
ODI	52.1 ± 20.92	24.6 ± 19.78	<0.001*

* Statistically significant.

resulting from spinal arthrodesis has drawn much attention in the past. Despite insufficient data, various dynamic stabilization systems have been developed to neutralize noxious forces as well as to restore the normal movement of the spinal segments.

The Dynesys neutralization system, as a pedicle screw-based system, is compatible with direct decompression procedures without requiring the presence of the posterior element, which interspinous stabilizers rely on.[21] The techniques basically decompress the neuroforamen while sparing the need for interbody arthrodesis or posterolateral fusion. Thus, it inherently avoids donor-side morbidity from fusion with autogenous iliac crest graft, decreases intraoperative blood loss, reduces muscle dissection, and shortens operative time. The Dynesys neutralization system reportedly maintains enough stability to prevent further progression of spondylolisthesis with shorter operation time, and less invasiveness.[17,19,21] However, scant data in the literature provides little information regarding long-term results of such lumbar dynamic stabilization.

One major argument against the dynamic stabilization system is the possibility of implant failure.[19] A broken Dynesys pedicle screw implanted in a multiple sclerosis patient with abnormal gait patterns is reported by Schnake et al.[19] and Schaeren et al.[17] Di Silvestre et al.[5] reported no implant-related complications (screw loosening or breakage) in another series of 29 patients. Despite the limited numbers reported, the Dynesys stabilization system appears to be superior to the rigid pedicle-screw fixation systems in terms of rate of screw breakage.[12,13] Such results lead to the assumption that the Dynesys stabilization system offers more biomechanical flexibility than the rigid fixation system, which minimizes the incidence of broken screws.[18] On the other hand, more flexibility may translate the shearing force onto the vertebral body, resulting in screw loosening.

The incidence of loosening per screw and percentage of patients with implants reported in the current study is similar to previously presented data. Stoll et al.[21] report 10 loose screws (in 7 patients) out of 280 total screws (3.6%). In 1 of the 7 patients, a radiologically suspected screw loosening correlated with clinical symptoms and necessitated a secondary intervention 14.5 months postoperatively. These investigators also noticed that most loose screws appeared in early postoperative radiographs (< 6 months) and none appeared later than 1 year postoperatively. In contrast, in the current report, all cases of screw loosening were discovered within 6 months postoperatively.

Schnake et al.,[19] in a series with a minimum 2-year follow-up, reported that 4 (17%) of 24 patients had potential implant failure. They noted 4 pedicle screws with radiolucent lines and 1 broken pedicle screw out of 96 screws. The same patient population was continually followed-up for another 2 years by Schaeren et al.,[17] who reported no new cases of screw loosening between the 2-year and the 4-year follow-up evaluations. The loosened screws in 3 patients remained radiologically unchanged, without evidence of progression of instability until the end of observation.

Di Silvestre et al.[5] reported a series of 29 elderly patients in which 4 cases (13.8%) had asymptomatic radiolucent lines around the screws of the S-1 level without screw loosening. This finding appeared to be questionable as to whether the screws were solid or moving. Moreover, these investigators claimed no other implant failures. Compared with these data, the percentage of screw loosening in the current study is slightly higher. One explanation is that the patients have been actively followed-up in a

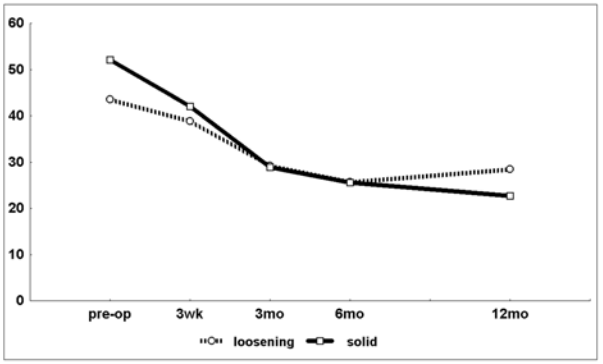

Fig. 3. Graph showing significant improvement on the ODI in both the solid screw group and the loosening group.

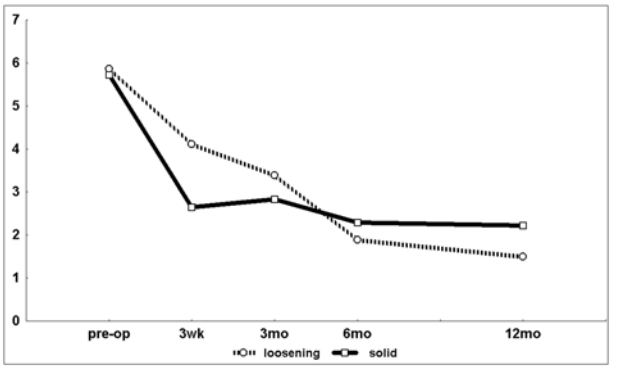

Fig. 4. Graph showing significant improvement on the VAS in both the solid screw group and the loosening group.

prospectively scheduled manner, whereas patients in previous reports have not.

It is interesting to note that radiologically loosened screws have never occurred in the middle segment of vertebral bodies (for the 2-level stabilization). It is an assumption that screws inserted into the marginal segments have greater strength loading than those in the middle segment. As a result, loosening of screws is more likely to occur at the marginal segments. However, current data does not support this hypothesis and further biomechanical studies are warranted.

The present study has been conducted in Taiwan, a region with a high prevalence of osteoporosis. It is reported that in the Taiwanese population, especially among those aged > 50 years, the average prevalence of osteoporosis is 11.4% in women and 1.6% in men.[23] Most patients with radiologically loose screws in this study were ≥ 55 years old (13 of 14 patients). Even though none of them had proven osteoporosis using dual-energy x-ray absorptiometry, the possibility of preexisting osteopenia cannot be completely ruled out. According to the experience of Schwarzenbach et al.,[20] pedicle-based dynamic stabilization devices such as Dynesys have limitations in elderly patients with osteoporosis. It is crucial to conduct the more demanding techniques during pedicle screw placement to avoid multiple tapping or the backing out and readvance of the screws. Meanwhile, the fact that this system does not require fusion may be considered an advantage over spinal fusion procedures in patients with a high risk of arthrodesis failure, such as cigarette smokers.

Loosening of screws implies more range of motion in the stabilized lumbar spine segments than expected, which can be problematic. In contrast, the data here reveal similar outcomes in patients with or without screw loosening. The clinical results of the VAS for low-back pain and the ODI for functional disability improved significantly, regardless of screw loosening (Figs. 3 and 4; Tables 4 and 5). These data further challenge most spine surgeons' concept that failure of arthrodesis correlates with symptomatic back pain. Schaeren et al.[17] also report that neither screw breakage nor loosening causes symptoms or back pain. It is possible that pedicle-based dynamic stabilization devices unload the posterior elements by transmitting the weight loading anteriorly. Thus, the degenerated spinal segment is unloaded with controlled motion, instead of complete immobilization by arthrodesis.[11] The hypothesis that the reduction (rather than the elimination) in segmental motion results in the alleviation of back pain is corroborated.[9]

Regarding the radiographic definition of screw loosening, the radiolucent line, or "halo" sign, noted on plain radiographs can be vague due to overlapping bowel gas, fecal material, body mass, osteoporotic changes, or even digital magnification. Dakhil-Jerew et al.[4] report using a "radiolucent zone sign" together with a "double halo sign" based on plain radiographs for detecting screw loosening in dynamic stabilization devices. The experience here of using their method shows that the duration between the occurrence of the halo zone sign and that of the double halo sign is 0–3 months in 7 patients, 6–12 months in 6 patients, and 16 months in 1 patient. Thus, if 1 screw is suspected of being loose, the double halo sign can be used to confirm the diagnosis in the next follow-up, with high concordance.

Conclusions

In this preliminary study of a pedicle-based dynamic stabilization device for 1- and 2-level lumbar spondylosis, radiographic loosening of pedicle screws occurred in 19.7% of patients and 4.6% of screws. Nonetheless, the loosening of screws had no adverse effect on clinical improvement.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: JC Wu, CC Ko. Acquisition of data: CC Ko. Analysis and interpretation of data: CC Ko, HW Tsai, HC Chen, CL Wu. Drafting the article: JC Wu, CC Ko. Critically revising the article: JC Wu. Reviewed final version of the manuscript and approved it for submission: JC Wu. Statistical analysis: HW Tsai, YC Chen. Administrative/technical/material support: WC Huang, H Cheng. Study supervision: WC Huang, H Cheng, YH Shih.

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Biomechanics of a posture-controlling cervical artificial disc: mechanical, in vitro, and finite-element analysis

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Different methods have been described by numerous investigators for experimentally assessing the kinematics of cervical artificial discs. However, in addition to understanding how artificial discs affect range of motion, it is also clinically relevant to understand how artificial discs affect segmental posture. The purpose of this paper is to describe novel considerations and methods for experimentally assessing cervical spine postural control in the laboratory. These methods, which include mechanical testing, cadaveric testing, and computer modeling studies, are applied in comparing postural biomechanics of a novel postural control arthroplasty (PCA) device versus standard ball-and-socket (BS) and ball-in-trough (BT) arthroplasty devices. The overall body of evidence from this group of tests supports the conclusion that the PCA device does control posture to a particular lordotic position, whereas BS and BT devices move freely through their ranges of motion. *(10.3171/2010.3.FOCUS1063)*

Key Words • cervical disc arthroplasty • artificial disc • postural control • segmental kyphosis • biomechanical testing

First-generation cervical arthroplasty devices were designed to maintain motion and simulate normal kinematics. One design consideration that has until recently been ignored is the ability of an arthroplasty device to maintain correct cervical posture. This issue is of concern because clinical evidence has shown that segmental kyphosis may occur weeks to months after cervical arthroplasty.[4,6,9] Although some have argued that kyphotic deformity after arthroplasty is due to surgeon error and not device design, it would still be desirable for an arthroplasty device to resist loss of lordosis even in the case of poor surgical technique.

A second-generation cervical PCA device (Synergy Disc [Fig. 1]; Synergy Disc Replacement, Inc.) has been developed that is intended to maintain cervical kinematics while also controlling segmental posture. Various methods have been described previously for experimentally assessing the kinematics of cervical artificial discs, including measurement of range of motion, axis of rotation, and other parameters.[1–3,8] The PCA device has been tested using such methods, and compares favorably kinematically to other arthroplasty devices; although they are pertinent, results of these tests are not described herein. The purpose of this paper is to describe the special considerations and methods for experimentally assessing postural control, thereby providing outcomes for the PCA versus standard BS and BT devices. These methods have not been described previously, and include mechanical testing, cadaveric testing, and computer modeling studies.

Mechanical Testing of Isolated Devices

The PCA device works to control posture through the design feature of "stability zones" that are adjacent to rounded regions on the top and bottom articulating surfaces. The stability zones are achieved by elongating a spherical surface to contain flattened regions. At angles where the flattened regions are nearly in contact, the PCA is naturally forced toward the equilibrium state of flattened surface against flattened surface. Once at the equilibrium position, less force is required for the device to stay in this position than to move off the stability zone. To evaluate the behavior as the device angulates through each phase of motion from extension through flexion, a simple apparatus was devised that would hold the halves of the PCA or standard arthroplasty device in apposition while applying a compressive load of 79 N (Fig. 2). Adjustment of the position of the mass on the overhanging

Abbreviations used in this paper: BS = ball-and-socket; BT = ball-in-trough; PCA = postural control arthroplasty.

Fig. 1. Postural control arthroplasty device (Synergy Disc; Synergy Disc Replacement, Inc.). The device is composed of titanium endplates and an ultra–high molecular weight polyethylene fiber core.

rail forces the arthroplasty device through a range of angular orientations.

One PCA device, one BT device (Prestige; Medtronic Spine and Biologics), and one BS device (ProDisc-C; Synthes Spine) were evaluated. Applied moment was approximated as the distance of offset multiplied by the constant compressive load, ignoring the restorative counter-moment induced by the springs.

It was found that the PCA but not the BS or BT devices demonstrated a plateau in the angle-versus-moment plot (Fig. 3), indicating that the PCA tended to stay at or near the angle dictated by the stability zone, whereas the standard arthroplasty devices moved freely through all phases of motion, limited only by the friction of the device articulations and the restorative counter-moment

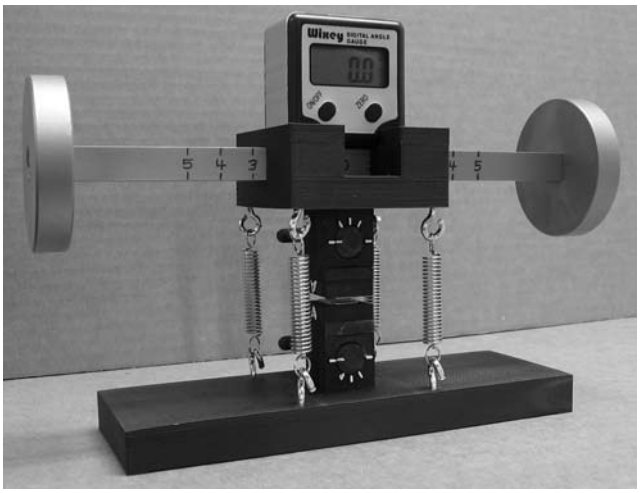

Fig. 2. Mechanical testing apparatus for evaluating postural control in isolated standard arthroplasty and PCA devices. A mass of fixed magnitude and adjustable position is applied by 2 cylindrical weights. The anteroposterior position of the center of gravity of the mass is adjusted by sliding the square bar horizontally through the housing. Springs help maintain equilibrium. Angular orientation is monitored by a digital angle gauge, with 0.1° accuracy (Barry Wixey Development).

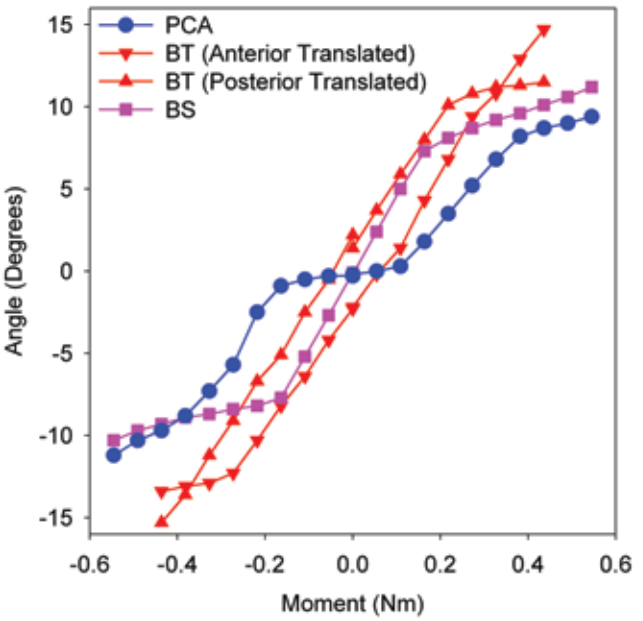

Fig. 3. Graph showing angle versus applied-moment curves for independent devices studied in the mechanical testing apparatus.

produced by the apparatus' stabilizing springs. The plateau in the curve for the PCA extended to approximately ± 0.2 Nm, indicating that within this range of applied moments, the device tended to stay near 0°, the angle at which the flattened articulations were designed to be in contact.

This evaluative mechanical test indicates that the PCA exerts postural control of approximately 0.2 Nm if conditions are ideal, meaning that the stability zones of the device are in contact.

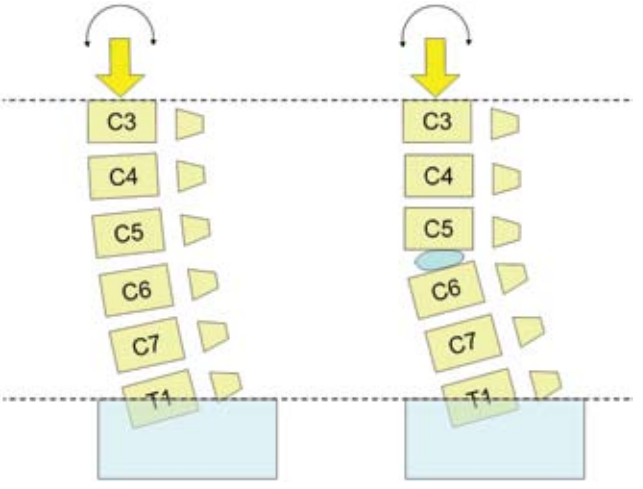

Fig. 4. Schematic of the conditions applied during the neutral upright posture testing protocol. This protocol is based on the assumption that the neutral gaze or global angle (here, C-3 relative to T-1) should remain constant, as indicated by the *dashed lines*. After device insertion, the same neutral gaze was restored by adjusting the uppermost vertebra relative to the base without applying intersegmental forces. The segmental angle change at the index level was studied to assess the ability of the device to control index-level posture.

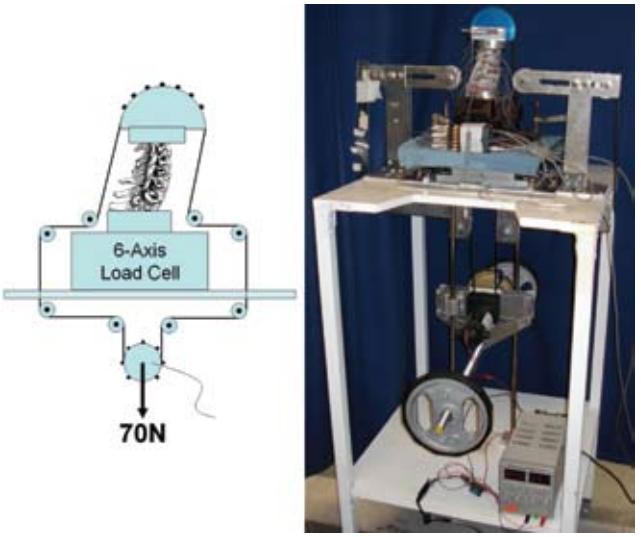

Fig. 5. Simple schematic and photo of the belt apparatus used in experiments for controlling the orientation of the rostralmost vertebra relative to the caudalmost vertebra tested, while simultaneously applying a compressive follower load of 70 N.

In Vitro Cadaveric Testing

To our knowledge, no test has previously been performed or devised specifically to address postural control in vitro in cadaveric specimens. For evaluating spinal postural control, 3 experimental methods were devised and applied.

Neutral Global Posture Method

The first experimental method for posture testing is based on the assumption that the global upright posture (the posture of the head relative to the shoulders, or of the rostralmost vertebra tested relative to the caudalmost vertebra tested) should remain constant in the normal condition and after disc replacement. In other words, it is assumed that, after placement of an artificial disc, a patient would restore his or her neutral gaze to the same orientation that he or she had used when the spine was healthy and normal. All individual motion segments would be expected to adjust via the path of least resistance to achieve this fixed global posture, meaning that the segmental angles needed to achieve the constant global posture would have various amounts of flexion and extension, depending on the properties of each level (Fig. 4). At the level with the PCA, the angular orientation would be expected to tend toward a flexed or extended position dictated by the device, compensated by extension or flexion at adjacent intact levels to achieve the fixed (0°) global posture.

For this testing protocol, a belt apparatus was used in which a notched belt dictates the position of the notched, semicircular upper fixture relative to the lower fixture that is mounted to the table (Fig. 5). With weights suspended below the table from the belt, the belt applies compression that remains aligned with the axis of the spine because of the positions of the pulleys near the base of the spine. A weight of 70 N (motor and weights combined) was used to represent the weight of the head plus slight muscular contraction.

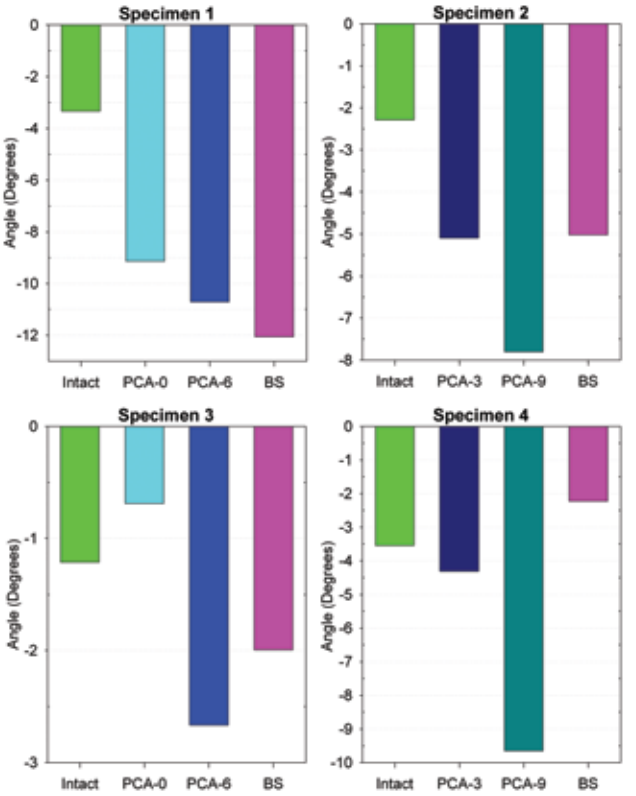

Fig. 6. Bar graphs showing the C5–6 (index level) angle under 70-N compression after restoring global C3–T1 posture to 0°.

The neutral upright (0°) posture, both segmentally and globally, was defined as the posture of the intact unloaded specimen when it was first set up on the test frame after thawing and attachment of optical markers. The positions of the optical markers in this posture were captured and stored for reference throughout the experiment, to enable the global posture to be restored and to study segmental posture changes. Specimens were tested in 4 conditions: 1) intact (4 spines); 2) after insertion of a PCA device with 0° lordosis (PCA-0, 2 spines) or a 3° lordotic PCA (PCA-3, 2 spines); 3) after insertion of a 6° lordotic PCA (PCA-6, 2 spines) or a 9° lordotic PCA (PCA-9, 2 spines); and 4) after insertion of a BS device (ProDisc-C, 4 spines). To allow continuous tracking of posture, arthroplasty devices were removed and inserted with the specimens upright and mounted to the test frame. For testing, 70 N was applied, and then the specimen was moved to a global posture of 0° by using the belt apparatus in each of these conditions, and the index-level segmental angle was evaluated. It was hypothesized that the index-level angle should rest at a position 6° more extended with the PCA-6 device than with the PCA-0 device, or 6° more extended with the PCA-9 device than with the PCA-3 device. It was also hypothesized that the index-level angle should be close to the lordotic angle specified by the device (0°, 3°, 6°, or 9°). Finally, it was hypothesized that the BS device would not tend toward any particular position, and instead, because it offers little postural control, would tend toward either extreme flexion or extreme extension.

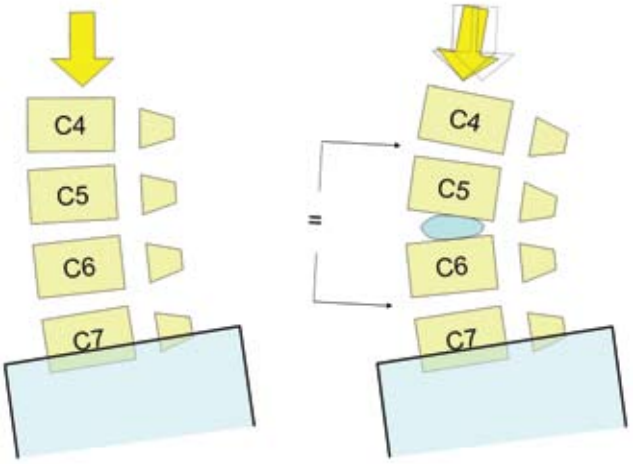

Fig. 7. Schematic of the conditions applied during the neutral balance testing protocol. This protocol is based on the assumption that the neck can be realigned and the forces redistributed so that balance can be obtained for a neutral upright neck posture requiring minimal muscular exertion. As indicated by the "=" and *arrows*, when completely balanced, the levels adjacent to the index level should be equal, both with a 0° angle (same angle as in the intact neutral upright posture).

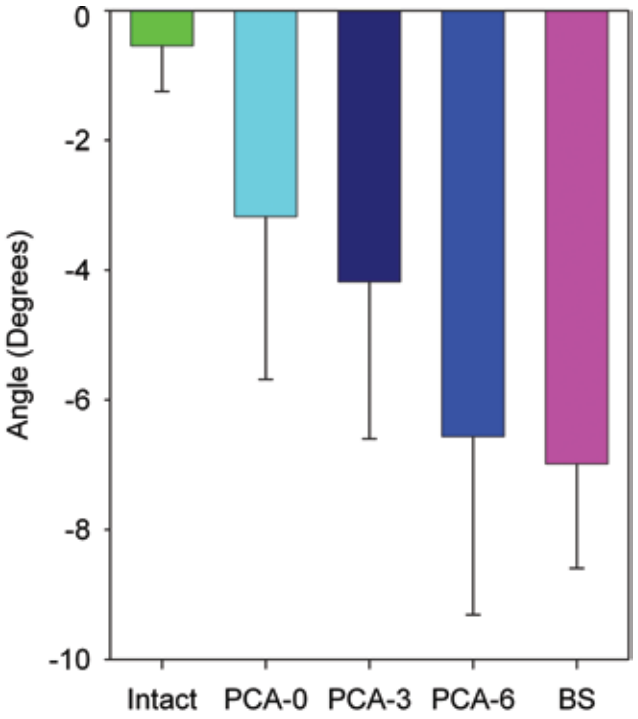

Fig. 8. Bar graph showing the mean postural change after rebalancing during each condition tested using the neutral balance method. *Error bars* show SDs.

In all 4 specimens studied, the PCA with a more lordotic design found a more lordotic posture than the PCA with a less lordotic design (Fig. 6). The difference in resting angles between low and high postural control devices (that is, between PCA-0 and PCA-6 or between PCA-3 and PCA-9) was 2.9 ± 1.7°. The magnitude (absolute value) of deviation of the resting angle from the target (designed) angle under a 70-N load averaged 2.9 ± 2.9° for PCA devices.

It was found that the PCA device caused a shift in the index-level posture, although the difference between devices intended for 6° separation was found to average 3°. Precise control to the posture dictated by the device was not observed, probably because it is more difficult to immobilize a dissected specimen to a fixed neutral posture during surgery than to immobilize an actual patient, especially with devices being inserted while specimens were upright. As predicted, the BS did not tend toward any particular position. In one case (Specimen 1), the BS condition was the most extremely extended; in another case (Specimen 4), it was the most extremely flexed. In this experimental method, long specimens (5 levels) were used so that the index level would have a better chance to find its "sweet spot." Theoretically, as long as the balance of the specimen is within a reasonable range, the index level should tend toward that spot.

Neutral Balance Method

The second experimental method for posture testing is based on the assumption that the loading of the spine should be consistently balanced regardless of the condition of the index level (Fig. 7). In other words, there should always be a way in which an individual can position the head and neck so that posture is naturally balanced with minimal muscular effort. Unlike the neutral global posture method, where balance refers to segmental angles summing to 0°, in the second method, "balanced" is defined to mean that all except the index level return to their neutral posture. Because in general, balancing a long stack of objects is more difficult than balancing a small stack, shorter specimens (C4–7) were used for this experimental method.

For this testing protocol, the belt apparatus (Fig. 5) was also used; by driving the belt in small increments with the motor, the angle of the rostral adjacent level was adjusted to be balanced (same angle as the neutral posture). The anteroposterior position of the upper notched pulley on the rostral potting fixture was then adjusted and the belt repositioned until the caudal adjacent level was simultaneously balanced (previously recorded segmental neutral posture). Four specimens were tested intact, with 0°, 3°, and 6° PCA, and with BS. Hypotheses were similar to those for the neutral global posture experimental method. It was hypothesized that the index level should balance at an angle that was more extended when using a more lordotic device. That is, the balance angle with a 6° device should be more extended than the balance angle with a 3° device, which in turn should be more extended than the balance angle with a 0° device. It was also hypothesized that the index-level angle should be close to the lordotic angle specified by the device (0°, 3°, or 6°). Finally, it was hypothesized that the BS would not tend toward any particular position, and instead, because it offers little postural control, would tend toward either extreme flexion or extreme extension.

In all 4 specimens, insertion of a more lordotic PCA device led to a more extended balance position (Fig. 8). The magnitude (absolute value) of the deviation from the

target lordotic angle with PCA devices was 3.2 ± 2.5° for the 0° device, 2.1 ± 2° for the 3° device, and 2.1 ± 1.8° for the 6° device (average overall deviation 2.5 ± 2°). The BS device tended toward the most extended position of the conditions tested.

It was found that the PCA device caused a shift in the index-level posture. However, the absolute resting angle did not precisely match the target designed for the device. As with the neutral global posture method, deviation from absolute target angle may have been related to inserting devices with specimens upright. Relative shifts in angle when switching between devices were less than the angular differences designed into the devices (Fig. 8): in going from a 0° to a 3° device, the angular shift averaged 2 ± 1.6°; in going from a 0° to a 6° device, the angular shift averaged 3.9 ± 2.1°. As predicted, the BS tended toward an extreme—in this case, the most extended posture of the conditions tested. From these findings it is unclear whether the neutral global posture or the neutral balance method is a superior technique. Both methods are fairly easily implemented, and both seem capable of detecting differences in postural control. The neutral global posture method should perform better with longer specimens, because additional motion segments provide an easier path for the index level to find a specific posture. Conversely, the neutral balance method should perform better with shorter specimens, because it becomes difficult to find a balanced position when attempting to balance more than just the segment immediately adjacent to the index. Length of specimens is also a consideration in the third experimental method, described next, which can be used in conjunction with either of the first 2 methods.

Dynamic Extension-to-Flexion Method

The third experimental method was based on the assumption that when the spine moves dynamically from extension through flexion, a PCA device would force the index level to snap in and out of a "sweet spot" at which posture is preferred. Clinically, such behavior would mean that even as the patient moves his or her neck through flexion and extension, the index level would prefer to stay at or near the angle dictated by the device. Conversely, a relatively low-friction arthroplasty would allow the index level to move even more rapidly than normal through the level's preferred angular orientation.

For this testing protocol, both the 6 short (C4–7) and the 4 long (C3–T1) specimens were dynamically moved with the belt apparatus (Fig. 5) by using a 70-N follower load. Specimens were moved through a range of global extension and flexion positions that represented the nondestructive physiological range as previously determined for that specimen by using pure moments or manual loading. Such testing was repeated in the normal condition, after PCA implantation (0° and 6° devices; 3° and 9° devices; or 0°, 3°, and 6° devices [2, 2, and 6 specimens, respectively]), and after BS implantation. The index-level angle was plotted versus the global angle. It was hypothesized that plateaus in the index- versus global-angle curves (that is, regions where the index level moves relatively little while the whole spine continues moving) would be more prominent than normal after PCA implantation and less prominent than normal after BS implantation. It was also hypothesized that plateaus would occur at more extended index-level angles after implanting more lordotic devices.

Plateaus that were indistinct after implantation of BS devices were apparent after implantation of the PCA device (Fig. 9). In all cases, plateaus occurred at an angle that was more extended after implantation of more lordotic devices. In normal and implanted conditions, plateaus were less distinct and steeper in short than in long specimens. Typically, the slope of the curve was steeper through regions of postural influence after BS implantation than in the normal condition or after PCA implantation, indicating the least resistance to motion in that region with the BS device (for example, see curves for Specimens 2 and 10). Through these regions, slopes for the normal condition were typically steeper than with PCA devices implanted.

Some index- versus global-angle curves for the dynamic extension-to-flexion method indicate that the PCA device provided postural control. Note, for example, the clear plateaus separated by approximately 6° for PCA devices, compared with the absence of a plateau for BS in Specimen 1. However, results were inconsistent among all the specimens, probably due to the varying size and fit of devices. One advantage of the dynamic extension-to-flexion method is that it is probably less sensitive to malpositioning of the upper fixture (as long as position remains consistent among conditions) than either the neutral upright method or the neutral balance method. An additional advantage is that this method is easily studied in conjunction with either or both of the other methods. A disadvantage is that it is difficult to define and extract parameters from the index- versus global-angle curves to allow a simplified comparison among specimens (hence the need to plot all 10 curves for comparison). In longer specimens it is sometimes possible to pick out the approximate plateau value from the curves (see Specimen 1). However, clear plateau values are not present in the short specimens (Specimens 5–10), and are not always apparent in long ones (see Specimen 4). It might also be desirable to extract the slope of the curve through the region of postural influence for comparison, but it is not always clear where the region of postural influence begins and ends, and in some cases there are ambiguous multiple slopes through this region.

Finite-Element Modeling

With finite-element modeling, it is possible to isolate effects that are due only to device differences from other competing effects (experimental artifact). An experimentally validated, ligamentous, intact C3–7 finite-element model[5] was used to study how the PCA differed from standard arthroplasty devices in its ability to maintain posture.

Model geometry was defined from digitized CT images of a cadaveric specimen, and consisted of 24,732 nodes and 21,895 elements (Fig. 10). A lordotic curve was simulated across C3–7 by assigning segmental angles as follows: C3–4, 7°; C4–5, 4°; C5–6, 5°; and C6–7, 6°. The

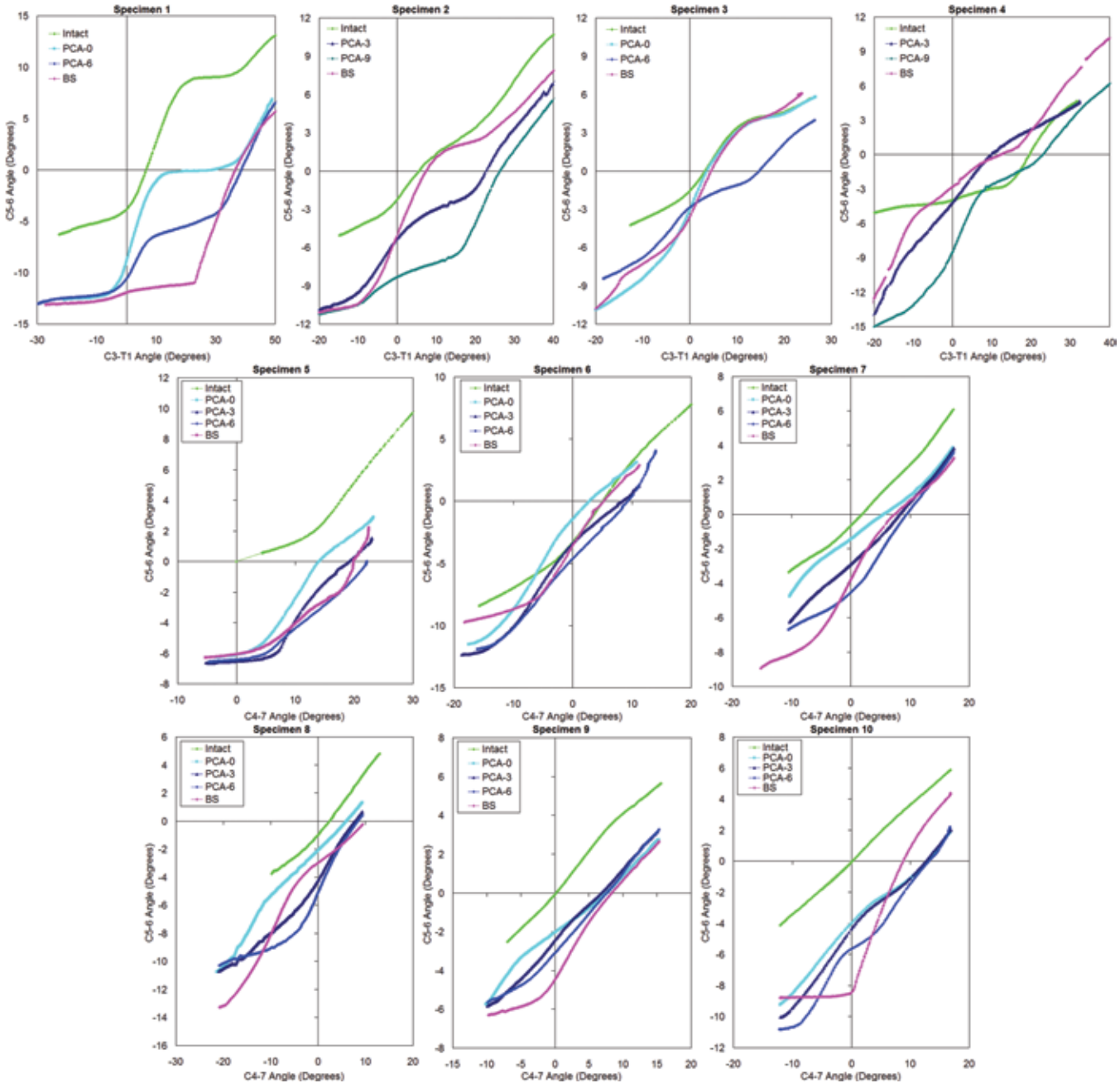

Fig. 9. Charts showing the index- versus global-angle curves for all specimens. Specimens 1–4 spanned 5 levels (C3–T1), whereas Specimens 5–10 spanned 3 levels (C4–7). The index level in all specimens was C5–6.

apophyseal (facet) joints were simulated with 3D gap contact elements. The facets were oriented at approximately 45° from the horizontal plane, with some variation in the sagittal plane alignment, according to CT geometry. The anulus fibrosus was modeled as a composite configuration wherein a series of fibers simulating the lamellae of the disc were embedded in a ground substance surrounding a more gelatinous nucleus region. Each layer of ground substance contained 2 alternating layers of 4 fibers arranged at ± 65° from the transverse plane, with an overall fiber content of 20% of the anular volume assumed; fiber elements were defined to be active only in tension. The Luschka joints were simulated by creating a space between the anulus horizontal layers around the uncinate processes and placing gap elements in the resulting fissures. The elements adjacent to the fissures were reinforced with fibers that were aligned approximately parallel to the fissure to simulate Luschka joints. All 7 major ligaments were represented in the intact spine model: anterior longitudinal, posterior longitudinal, intertransverse, ligamentum flavum, interspinous, supraspinous, and capsular. The ligaments were modeled as 3D, 2-node truss elements and assigned nonlinear material properties such that at low strains, the ligaments exhibited low stiff-

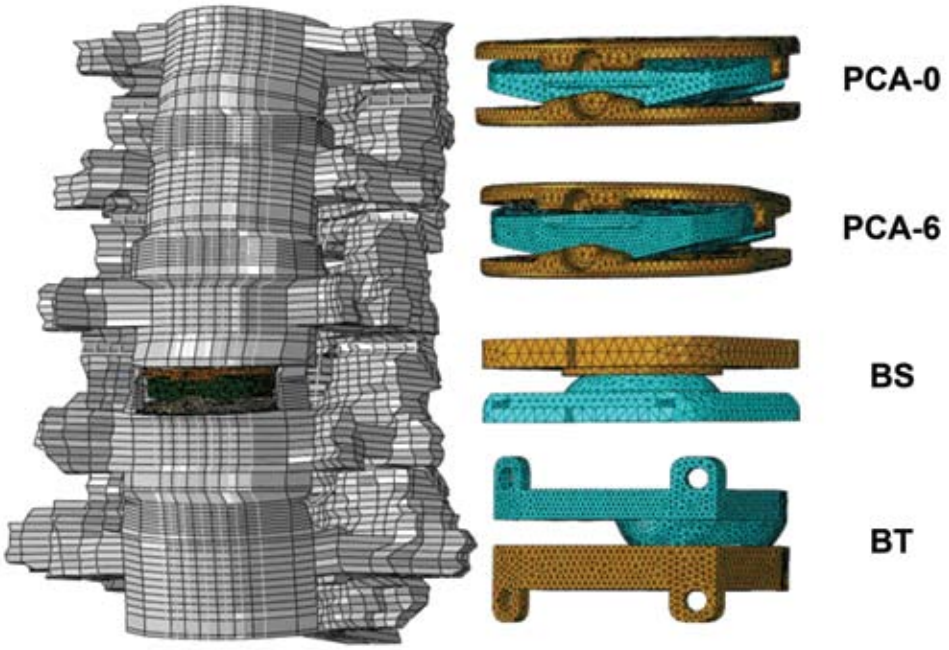

Fig. 10. Schematics showing the geometry of the C3–7 finite-element model with 4 different artificial disc designs applied at C5–6.

ness, but as the strains increased, the ligament stiffness also increased. Material properties were chosen from data published in the literature and were assumed to be homogeneous and isotropic.

Models were defined to simulate intact spines and those with 4 conditions of arthroplasty at C5–6: 1) PCA-0; 2) PCA-6; 3) BS; and 4) BT. The PCA-0 condition had parallel metal endplates, whereas PCA-6 had a 6° built-in lordosis between the endplates. Both PCA-0 and PCA-6 had a polymer core. The BS had an inferior polymeric ball and a superior metal socket, and the BT had a metal ball on a superior endplate, with an elongated inferior trough. All arthroplasty devices were positioned ("inserted") in models after making room for them by removing bone and disc elements without altering segmental lordosis; devices were oriented in their neutral (midrange) positions, and metal endplates were considered fused to bone.

Boundary conditions were set such that the C-7 vertebra was completely constrained in all 6 degrees of freedom at the inferior endplate, inferior facets, and inferior part of the spinous process while loads were applied to C-3 in 2 steps to simulate precompression and bending. A set of nonlinear springs that followed the curvature of the spine was used to apply a 73.6-N compressive load to simulate precompression. Springs were defined bilaterally through the estimated instantaneous center of rotation of each segment, mimicking the follower load method.[7] While under compression, a bending moment of 1.5 Nm was applied on the superior face of the C-3 vertebra to simulate physiological flexion/extension, lateral bending, and axial rotation. The follower load and boundary conditions were the same for all intact and implanted models. Simulations were run using Abaqus software (SIMULIA).

Compressive loading of 73.6 N applied to models that were initially at neutral posture at C5–6 (–5°) resulted in less than 1° of extension for intact, PCA-0, and PCA-6 conditions; 3° of extension for BS; and 1.2° of flexion for BT (Fig. 11). This finding indicates that the PCA devices provide better postural control at a set angle than intact, BS, or BT conditions. The BS appeared to have excessive and rapid motion compared with the intact condition near the neutral position; the PCA-0, PCA-6, and BT demonstrated index-level angle-versus-moment curves similar to the intact condition (Fig. 12). The PCA-0 and PCA-6 curves differed from each other during extension, with PCA-6 showing more extension than PCA-0 at positions slightly more extended than neutral. This behavior was milder than was observed in cadaveric specimens or in isolated device tests, because PCA devices were inserted in finite-element models in neutral orientations, whereas in cadaveric specimens and the benchtop testing apparatus, they were inserted with device endplates parallel to bony (or fixture) endplates. Inflections in the angle-versus-moment curves in the PCA finite-element model results therefore represent the motion segment shifting between the different flattened regions of the PCA devices, but well-separated plateaus would not be expected.

Discussion

The purpose of this paper was both to describe methods used to investigate postural control of an artificial disc, and to present postural results for the Synergy PCA device compared with standard BS and BT designs. Because of the novelty of the testing paradigm, test methods and device designs were both under development during this study, limiting the ability to collect large sets of data. For example, only 4 specimens were tested using the neu-

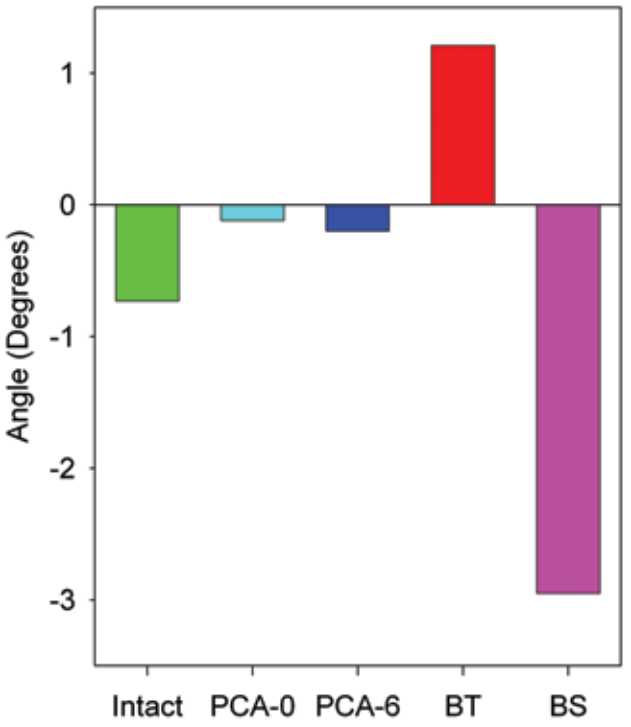

Fig. 11. Bar graph showing the change in neutral angle at C5–6 (initially –5°) after applying 73.6 N of compression and no moment.

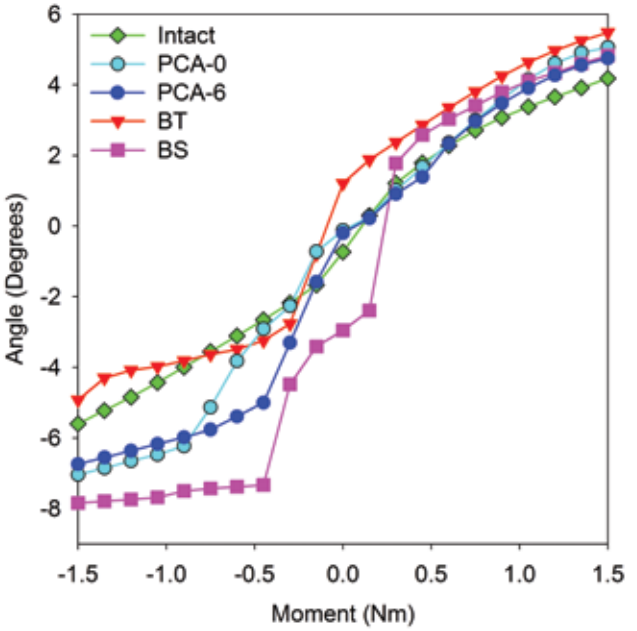

Fig. 12. Chart showing the C5–6 angle versus applied moment in each simulation. Negative angles correspond to extension and positive angles correspond to flexion.

tral global posture method, and within this group, certain specimens were only given 2 of 4 PCA device designs. However, it is still possible to identify trends that hold true consistently for the entire dataset.

One uniformly consistent trend is that when 2 or 3 different PCA devices were tested in a cadaveric specimen, the devices with more lordotic designs found static postures that were more lordotic. For example, the static posture with a PCA-0 device in place was at an angle less extended than the static posture of the same specimen with a PCA-6 device in place. This finding was true in all of the 4 specimens tested with the neutral global posture method (Fig. 6), and also in all of the 4 specimens tested with the neutral balance method (Fig. 8). In finite-element modeling, the static posture did not differ between devices (Fig. 11). However, in the finite-element analysis, devices were incorporated into spine models with the articulating stability zones already in apposition at the neutral posture.

Another consistent trend is that the index-level angle with the PCA in place tended to have a plateau or range through which the non–index-level angles changed more rapidly than the index-level angle. This plateau in all 10 cases in cadaveric tests was more extended with PCA devices of more lordotic design (Fig. 9). For example, the index- versus global-angle curves coincided in some regions for PCA-0, PCA-3, and PCA-6 devices, and then were disparate in other regions; these disparate regions always showed that PCA-6 was more extended than PCA-3, and that PCA-3 was more extended than PCA-0. The clearest plateau occurred in the mechanical test of the isolated device (Fig. 3), in which behavior was fully dictated by the device, without the influence of any surrounding tissues. Finite-element modeling showed only a slight separation between angle-versus-moment curves for PCA-0 and PCA-6 (Fig. 12). The reason for smaller differences is that the vertebral bodies were initially positioned with the PCA resting at its designed angle. Therefore, the finite-element output effectively modeled a 0° and a 6° patient, not a correction of 6° in a 0° patient.

Conclusions

No examples of laboratory posture testing exist in the spinal biomechanics literature. To study the ability of the PCA device to influence cervical posture, new methods were therefore devised, and were applied to isolated devices, cadaveric constructs, and finite-element models. The posture testing techniques each provide evidence that the PCA device provides a greater degree of postural control than the intact condition or BS. From this work, it is unclear whether there is a preferred method for future testing, because each method has certain advantages and disadvantages. Clearly, one method should be selected, and that method should be studied in a larger set of specimens to provide more definitive findings, with statistical support and better control of error sources.

Disclosure

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Author contributions to the study and manuscript preparation include the following. Conception and design: NR Crawford, JD Arnett, JA Butters, VK Goel, N Duggal. Acquisition of data: NR Crawford, JD Arnett, LA Ferrara, N Kulkarni, N Duggal. Analysis and interpretation of data: NR Crawford, JD Arnett, LA Ferrara, N Kulkarni, N Duggal. Drafting the article: NR Crawford. Critically revising the article: JD Arnett, JA Butters, LA Ferrara, N Duggal.

Reviewed final version of the manuscript and approved it for submission: VK Goel. Administrative/technical/material support: JA Butters, LA Ferrara, N Duggal. Study supervision: NR Crawford, VK Goel.

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