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Biomechanical comparison of expandable cages for vertebral body replacement in the cervical spine

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Object. Recently, expandable cages for vertebral body replacement in the cervical spine have been developed. The purpose of this study was to compare the biomechanical properties of expandable cages with those of a tricortical iliac crest graft and a nonexpandable cage.

Methods. Forty human cervical spines (C3–5) were tested in flexion, extension, axial rotation, and lateral bending. First all motion segments were evaluated intact. After corpectomy of C-4 the spines were divided into five groups of eight and the following stabilization techniques were used: 1) autologous iliac crest bone graft; 2) mesh titanium cage, 3) anterior distraction device; 4) Synex-C titanium; and 5) Synex-C PEEK. Additionally, anterior plating and anterior plating plus posterior screw/rod fixation were applied. Stiffness, range of motion, and neutral and elastic zones were determined.

In comparison with the intact motion segment all implants significantly increased stiffness in flexion and bending, but decreased stiffness in extension. There were no biomechanical differences between the nonexpandable and expandable cages. Furthermore, there were no biomechanical differences between the tricortical iliac crest graft and the cages, except for Synex-C in rotation. Additional anterior plating significantly increased biomechanical stiffness in all test modes; particularly in rotation mode, combined anterior–posterior stabilization increased stiffness by up to 102% compared with anterior plating alone.

Conclusions. In comparison to a tricortical iliac crest bone graft and a nonexpandable cage, expandable cages have no biomechanical advantages. Due to the low extension and rotational stiffness, none of the implants can be recommended as a stand-alone device. Additional anterior plating increased biomechanical stability adequately. Therefore, additional posterior stabilization should only be considered in cases of severe rotational instability of the cervical spine.

KEY WORDS • cervical spine • biomechanics • bone graft • cage • expandable cage • plate • screw/rod system

COMMON causes for the destruction of the cervical spine are fractures, tumors, and infections.[9,14,15,18,29] When cervical spine surgery is necessary because of spine instability, neurological deterioration, intractable pain, and failure of conservative treatment, allogenous or autogenous bone grafts such as rib,[41] fibula,[9,26,32] tibia,[1,23] and iliac crest [4,5] have been used to reconstruct the anterior column. These commonly performed bone grafting techniques may produce a number of well-known problems related to donor-site morbidity,[3,31] nonunion,[9,28,38] or fatigue failure.[41] Biomechanical problems, such as the low compression stiffness of the grafts[41] or the insufficient anchorage of the grafts to the vertebral endplates, sometimes have resulted in graft collapse and dislocation.[2,21,31] In attempts to solve these problems, cervical spine cages for VB replacement have been developed.

During the past few years several of these cages have been demonstrated to be effective;[14,23,35,39] however, after corpectomy the implantation of the currently available nonexpandable cages is often demanding. Adjusting the cages to the endplates and to the height of the defect is sometimes complicated because the cages are only commercially available in predefined endplate angles and heights, resulting in the need to trim the cage intraoperatively. If the cage must be trimmed, correct rotation of the cage must be ensured, otherwise tilting of the implant may occur. Furthermore, if intraoperative displacement of the implant occurs, removing the cage during the operation might compromise endplate integrity. Finally, direct internal repositioning of the anterior column is not possible with currently available cages.

In attempts to overcome the technical problems associated with nonexpandable cages, expandable cages for VB replacement in the cervical spine have been recently developed. Although these cages might be beneficial from the surgical point of view, their biomechanical properties have not been described until now.

The purpose of this study was to evaluate the biome-

Abbreviations used in this paper: ADD = Anterior Distraction Device, CSLP = Cervical Spine Locking Plate, EZ = elastic zone; NZ = neutral zone; PEEK = poly-ethyl-ether-keton; ROM = range of motion; VB = vertebral body.

chanical properties of expandable cages in comparison with a nonexpandable cage used with a tricortical iliac crest graft in the human cervical spine; anterior and posterior instrumentation procedures were also analyzed.

Materials and Methods

Spine Preparation

Forty intact adult cadaver cervical spine specimens (C3–5) and eight tricortical iliac crest bone grafts were harvested. En bloc specimens were stored at −20°C until they were thawed in a water bath at 25°C for biomechanical testing.

All superficial musculature was removed from C-3 to C-5. Care was taken to preserve all ligaments. The average age of the cadaveric donors (22 men and 18 women) was 56.9 ± 6.3 years (range 41–65 years). The medical history of each donor was reviewed to exclude trauma, malignancy, or metabolic disease that might compromise the mechanical properties of the cervical spine. Each specimen was radiographically screened to exclude osteolysis, fractures, or other abnormalities. Additionally, quantitative computerized tomography scanning was performed using a Somatom plus 4 scanner (Siemens, Inc., Erlangen, Germany) to determine the bone mineral density of C3–5.

Implants for VB Replacement

Figure 1 depicts the cages used. The height, width, and depth of the cages and the tricortical iliac crest grafts used in this study are shown in Table 1. To allow comparison between the different cage designs and the tricortical iliac crest grafts, implants of comparable endplate sizes were used, as far as possible. Additionally, no endplate angulation of the implants was done and all defects of the anterior column were filled with implants of comparable heights (Table 1). The average heights of the implants after insertion were measured on standardized lateral x-ray films.

Mesh Titanium Cage (Nonexpandable; DePuy Acromed). The mesh titanium cage according to Harms is a nonexpandable titanium cage. This type of cage has already been used for several years.[21] In this study the mesh titanium cage was used with a 14-mm round cross-section and flat endplates.

Synex-C Cage (Expandable; Mathys). The Synex-C is an experimental expandable cage with an oval conic endplate. Synex-C is made of titanium or PEEK. It is currently available with an endplate diameter of 13 × 15 mm and a distractible height ranging between 20 and 30 mm. The cage offers no option for endplate angulation. In this study we used a Synex-C titanium and Synex-C PEEK cage with the above mentioned features.

The ADD Cage (Expandable; Ulrich). The ADD is a commercially available expandable titanium cage with a round flat endplate. The ADD is available in three different endplate diameters—12, 14, and 16 mm—with a distractible height ranging between 10 and 65 mm. Endplate angulation is currently not possible. In this study we used an ADD cage with an endplate diameter of 14 mm and a distractible height ranging between 24 and 40 mm.

Test Setup

The testing was performed using a nondestructive flexibility method with a nonconstrained testing apparatus described in detail elsewhere.[18-21] Pure bending moments were applied using a system of cables and pulleys to induce flexion, extension, left and right lateral bending, and left and right axial rotation. Tension was applied to the cables with a material testing machine (Zwick 1456; Zwick GmbH, Ulm, Germany). Applied forces were measured with an axial load cell (Z 12; HBM, Darmstadt, Germany) mounted on the testing frame. Moments were calculated by multiplying the applied force by the radius of the pulley on the spine testing fixture.

Three-dimensional displacement of each motion segment was measured using an optical measurement system (Qualysis, Inc., Sävebalden, Sweden). Nonlinear diodes (Qualysis Inc.) were attached to the corpora of C-3 and C-5. Marker positions were detected with two cameras and recorded with a computerized motion analysis system (PC-Reflex; Qualysis, Inc.). Angular displacement of C-3 in relation to C-5 was calculated from the marker position by using a custom-made computer software based on Euler angles. The experimental error associated with this method was ± 0.12°.[23]

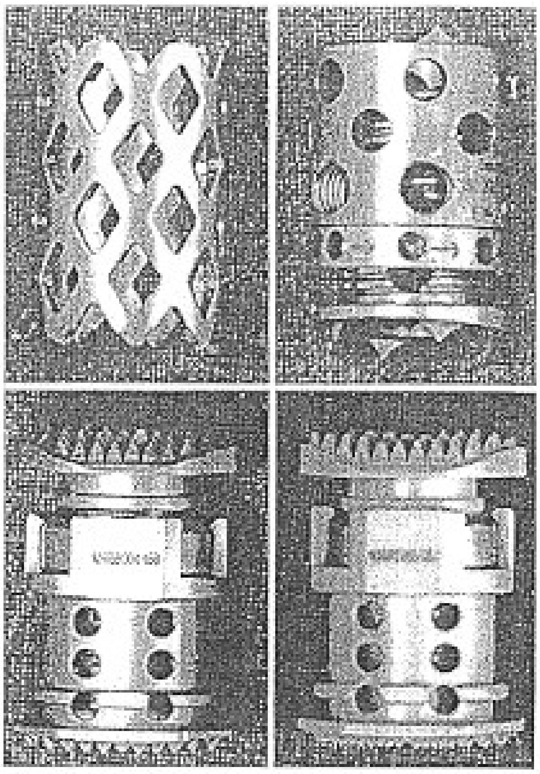

FIG. 1. Photographs showing the different cages tested in this study, from the *left* to the *right*: Harms (mesh titanium cage, nonexpandable cage), ADD (expandable cage), Synex-C Titanium (expandable cage), and Synex-C PEEK (expandable cage).

Study Protocol

Initially, all 40 specimens were tested while intact. Thereafter, a complete corpectomy of C-4 with resection of the anterior longitudinal ligament was performed and the specimens (eight per group) were randomly assigned to the following test groups: 1) autologous iliac crest bone graft; 2) mesh titanium cage; 3) ADD; 4) Synex-C titanium; or 5) Synex-C PEEK. All cages were implanted according to the manufacturer's instructions. Distraction of the cages was determined by clinical means. The preoperative x-ray films were used as a reference. Distraction was achieved with the aid of fluoroscopic control, the goal being an exact reconstruction of the preoperative height. After insertion of the implants a standardized lateral x-ray film view was used to determine the height of the implants after expansion. Each implant was then tested in the following sequence: implant (alone); implant plus anterior stabilization (CSLP); and implant plus anteroposterior stabilization (CSLP plus Cervifix).

The CSLP (Synthes)[8] is an angle-stable plate system, which was fixed in C-3 and C-5 by using four monocortical 4-mm screws (14 mm in length). The Cervifix (Synthes)[12,17] is a nonangle-stable screw/rod system, which was fixed at the lateral masses of C-3 and C-5 with 3.5-mm screws.

Specimens were kept moist during tests. The upper endplate of C-3 and the lower endplate of C-5 were mounted in pots using PMMA (Technovit 3040; Heraeus Kulzer GmbH, Wehrheim/Ts, Germany). The lower pot was rigidly attached to the base of the testing apparatus as previously described.[18-21] This test setup resulted in

TABLE 1

*The height, width, and depth of the expandable cages used in this study**

Implant	Type	Manufacturer	Material	Distraction Height (mm)	Average Height (mm)	Width (mm)	Depth (mm)
Bone graft	NA	NA	iliac crest	NA	26.3	13.3	14.4
Harms	nonexpandable	DePuy AcroMed	titanium	NA	25.9	14	14
ADD	expandable	Ulrich	titanium	24–40	26.2	14	14
Synex-C	expandable	Mathys	titanium	20–30	26.0	15	13
Synex-C	expandable	Mathys	PEEK	20–30	25.9	15	13

* NA = not applicable.

a compressive preload of 50 N due to the weight of the upper fixation pot. Moments were applied in a quasistatic manner in increments of 1 Nm to a maximum of 6 Nm. At each step, the specimen was allowed to relax for 60 seconds to minimize the viscoelastic response before data were recorded. Test modes were flexion, extension, left and right axial rotation, and left and right lateral bending. Specimens were preconditioned with three cycles of a 6-Nm load with a velocity of 1.2 mm/second of the traverse bar. The fourth cycle was measured. The ROM, NZ, and EZ, and the mean apparent stiffness values in the EZ were calculated from the corresponding load displacement curves. The NZ was defined as the difference in angulation at zero load between the two phases of motion. The EZ was defined from the end of the NZ to the point of maximum loading. The stiffness was only calculated in the EZ and was defined as the quotient of the loading to the deformation in the EZ.

Statistical Analysis

Comparison of data was performed using the one-way analysis of variance for independent samples followed by a Tukey post-hoc analysis for multiple comparison procedures. Statistically significant differences were defined at a 95% confidence level. The values are given as mean ± standard deviation. Commercially available SPSS (release 10.0; SPSS Inc., Chicago, IL) software supported statistical evaluation.

Results

After randomization there was no significant difference among all groups in the average bone mineral density of C-3 and C-5. Figure 2 shows the stiffness of the different fixation techniques during flexion, extension, rotation, and bending normalized with respect to the intact motion segment. Figure 3 summarizes the results of ROM, NZ, and EZ for all groups.

Comparison Between Stabilization Procedures and Intact Motion Segment

In comparison with the intact motion segment all stand-alone implants showed a significantly lower ($p < 0.01$) ROM, NZ, and EZ (Fig. 3) and a significantly higher ($p < 0.01$) stiffness in the test modes flexion and bending (Fig. 2 *upper left* and *lower right*). There was no significant difference between any implant and the intact motion segment in rotation, except for Synex-C, which demonstrated lower ($p < 0.05$) ROM, NZ, and EZ (Fig. 3) and higher ($p < 0.05$) stiffness (Fig. 2 *upper right*) than the intact motion segment. In extension, all implants showed a significantly higher ($p < 0.05$) ROM, NZ, and EZ and a significantly lower ($p < 0.05$) stiffness than the intact motion segment (Fig. 2 *lower left*).

Compared with the intact motion segment, all implants plus anterior stabilization and all implants plus anteroposterior stabilization significantly increased ($p < 0.001$) stiffness and decreased ($p < 0.001$) ROM, NZ, and EZ in all test modes (Figs. 2 and 3).

Comparison Between Bone Graft and Cages

In comparison with the bone graft, Synex-C demonstrated a significantly lower ($p < 0.05$) ROM, NZ, and EZ and a significantly higher ($p < 0.05$) stiffness in rotation (Fig. 2 *upper right*). There was no other significant difference in the ROM, NZ, EZ, and stiffness between the stand-alone bone graft and all stand-alone cages in all test modes. Furthermore, there was no biomechanical difference between the bone graft and any cage, if additional fixation techniques were applied.

Comparison Between Expandable and Nonexpandable Cages

There was no significant difference in the ROM, NZ, and EZ between the Harms nonexpandable cage and all other expandable cages regardless of the additional fixation techniques (Fig. 3). Additionally, there was no significant difference in stiffness between nonexpandable and expandable cages (Fig. 2).

Comparison Between Stand-Alone Implants and Implants Plus Anterior Stabilization

In comparison with the stand-alone implants, additional anterior plating significantly ($p < 0.01$) decreased ROM, NZ, and EZ and increased ($p < 0.01$) stiffness in all test modes (Fig. 3). In extension, stiffness increased up to 254% with an additional anterior plate (Fig. 2 *lower left*).

Comparison Between Stand-Alone Implants and Implants Plus Anteroposterior Stabilization

In comparison with the stand-alone implants, additional anteroposterior stabilization significantly ($p < 0.01$) decreased ROM, NZ, and EZ in flexion, extension, rotation, and bending (Fig. 3). All implants plus anteroposterior instrumentation provided significantly ($p < 0.001$) better stiffness than the stand-alone implants (Fig. 2).

Comparison Between Implants Plus Anterior Stabilization and Implants Plus Anteroposterior Stabilization

In comparison with implants plus anterior instrumentation, implants plus combined anteroposterior instrumentation significantly ($p < 0.05$) decreased ROM, NZ, and EZ

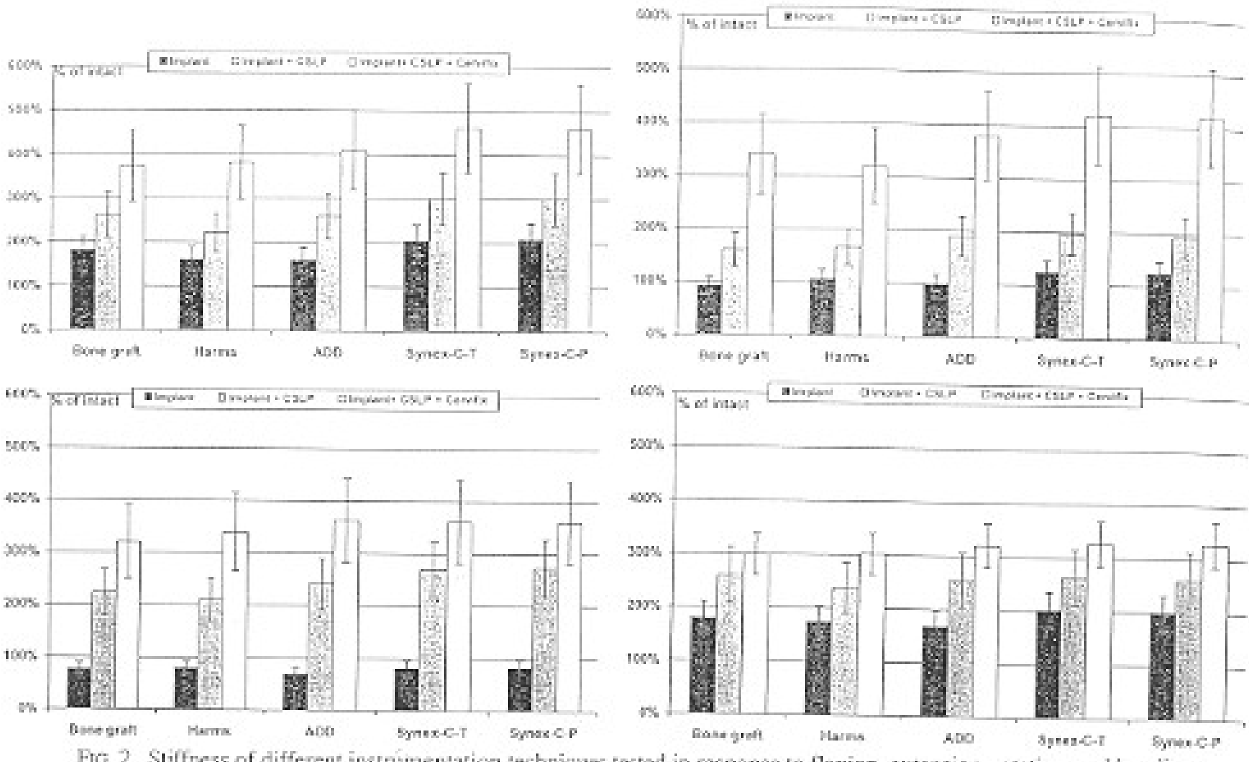

FIG. 2. Stiffness of different instrumentation techniques tested in response to flexion, extension, rotation, and bending normalized with respect to the intact motion segment (for statistical evaluation see text). *Upper Left:* Flexion. *Lower Left:* Extension. *Upper Right:* Rotation. *Lower Right:* Bending.

in all test modes (Fig. 3). Additionally, combined anteroposterior instrumentation led to a significant ($p < 0.05$) increase in stiffness compared with anterior instrumentation (Fig. 2). In rotation, stiffness increased up to 102% with an additional posterior stabilization (Fig. 2 *upper right*).

Discussion

Recently, there has been a rapid increase in the commercial availability and the clinical use of expandable cages for VB replacement in the cervical spine. Compared with nonexpandable cages these implants offer several technical advantages. Although one of the expandable cages evaluated in this study is already approved for the clinical use in Europe, no information about the biomechanical properties of these implants is available. Therefore, the purpose of this study was to compare, for the first time, the biomechanical properties of nonexpandable and expandable cages with a tricortical iliac crest bone graft in a human cervical spine corpectomy model. Additionally, different stabilization procedures (anterior and anteroposterior) were evaluated.

The limitations of this model should be mentioned. Application of distraction is a critical point in this study because distraction influences the biomechanical stability of the construct. The amount of distraction was applied based on clinical means. No sensor was used to determine the distraction force between the implants and the vertebra. An exact evaluation of the distraction force would only have been possible if a sensor had been implanted between the endplate of the vertebra and the implants; however, locating the sensor in this way would have affected the endplate–implant contact area and modified of the biomechanical properties of the implants. The study was also limited by the inability to include the stability provided by the cervical spine musculature. The muscle forces would most likely stabilize the construct; however, this might not influence the substance of findings, because this was a comparative study. A high preload of 50 N was necessary to ensure a safe fixation between the expandable implants and the vertebral endplate. Due to this high preload the ROM of the native motion segment was significantly lower in this test setup, as previously reported.[3,11,21,36] The preload used in this study is still significantly lower than the normal loads in vivo.[5] The testing order itself was not randomized and therefore could represent a bias in favor of the fixation method tested first. Additionally, one specimen was used for four experimental stages. Therefore, fatigue failure could occur. The first test was native, followed by the stand-alone implant, implant plus anterior stabilization and implant plus anteroposterior stabilization. The fact that the first fixation method tested provided the least stability provides a strong argument against such a bias and may also argue against fatigue failure. In conclusion, however, the limitations of a cadaver model appear, given the difficulties and limited accuracy of in vivo measurement, to be acceptable.

Although authors of several studies have investigated the biomechanical properties of interbody fusion cages[12,34,40] or anterior plate systems[6,8,34] in discectomy models of the human cervical spine, currently only a few biome-

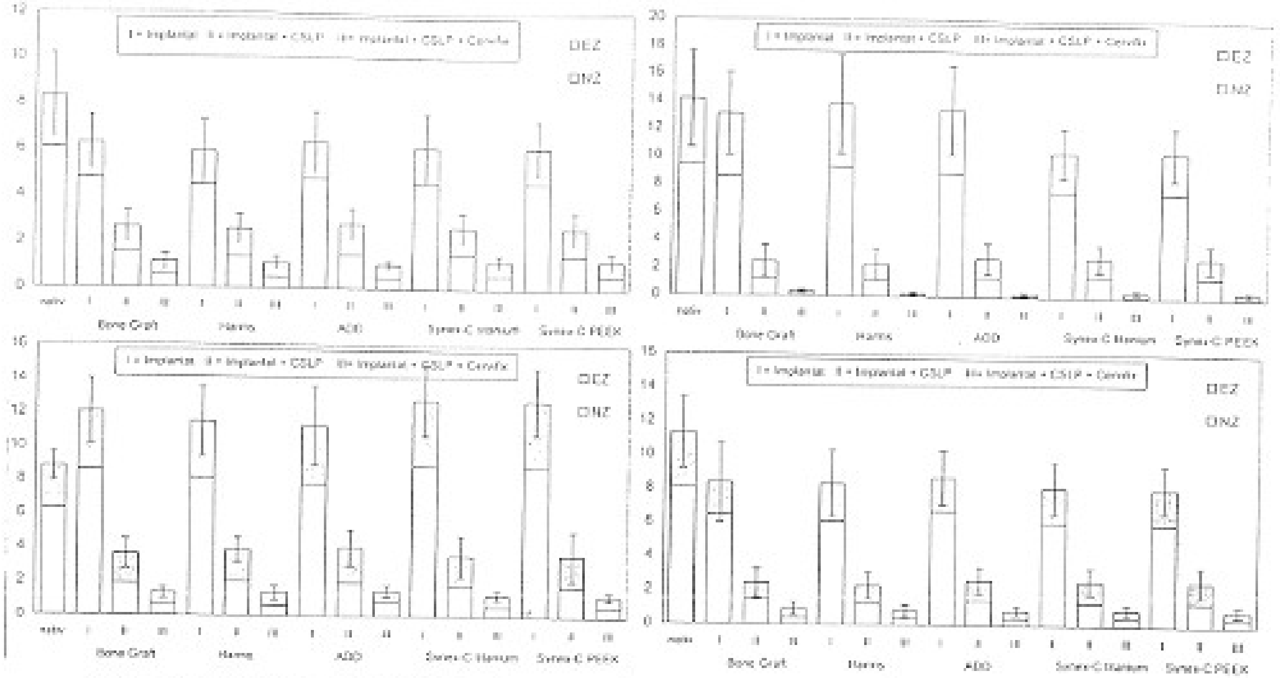

FIG. 3. The ROM, NZ, and EZ of different instrumentation techniques tested in response to flexion, extension, rotation, and bending (for statistical evaluation see text). *Error bars* represent standard deviation of ROM. *Upper Left:* Flexion. *Lower Left:* Extension. *Upper Right:* Rotation. *Lower Right:* Bending.

chanical studies are available in which a corpectomy model of the human cervical spine has been used.[8,10,16,24,36] Most of these studies have involved multilevel corpectomy.[7,10,24] To our knowledge, currently only three studies are available in which a single-level corpectomy model is used.[15,36] The focus of all of these studies was anterior or posterior plating and not intervertebral stabilization. Isomi, et al.,[16] used a one- and three-level corporectomy model to determine the stabilizing potential of an anterior plate system. In contrast to our study, Isomi and coworkers applied significantly lower moments (1 Nm) and used plastic blocks instead of strut bone grafts as VB replacements. Spivak and colleagues[36] used a C-5 corpectomy model with additional dissection of the posterior ligaments or the facet joints. After the insertion of a synthetic bone graft they sequentially placed anterior and posterior plating alone and in combination. Although the comparability of these studies with our study is significantly reduced because of the different study designs, authors of both studies demonstrated a significant increase in the biomechanical stability after anterior or posterior plating. Spivak, et al., also emphasized that combined plating should be considered in the severely unstable cervical spine. Grubb, et al.,[15] also used a C-5 corpectomy model in human and porcine cervical spines to determine the stabilizing effect of different anterior plate systems including the CSLP. Although they used lower moments (2 Nm) for biomechanical testing, they demonstrated comparable results for the stabilization potential of the CSLP in all test modes.

The results of our study showed no significant difference in stiffness, ROM, NZ, and EZ between the mesh titanium nonexpandable cage and all other expandable cages, regardless of the additional fixation procedures. Furthermore, there was no biomechanical difference in any test mode comparing the tricortical iliac crest bone graft and the cages. An exception is the Synex-C, which demonstrated a significantly higher rotational stiffness than the tricortical iliac crest bone graft regardless of the cage material (titanium or PEEK). In contrast to all other cages and the tricortical iliac crest bone graft, which have flat implant surfaces and therefore punctiform contact areas between the vertebral endplates and the implant, Synex-C has a curved surface configuration mimicking normal vertebral endplate anatomy. The higher endplate–implant contact area of Synex-C resulted in an improved interlocking between the surface of the implant and the vertebral endplates, therefore increasing rotational stiffness.

This study demonstrated that all stand-alone implants were not able to restore normal stability of the motion segment in extension. Therefore, anterior stabilization performed using stand-alone nonexpandable or expandable cages is not suitable for VB replacement in the cervical spine.

In contrast, the cages plus anterior stabilization and the cages plus anteroposterior instrumentation significantly increased stiffness in all test modes compared with the intact motion segment. Therefore, the cage plus anterior or combined anteroposterior stabilization provide sufficient stiffness for VB replacement and should be preferred over a stand-alone implant. In comparison with the stand-alone implants, additional anterior plating demonstrated a further increase in stiffness of up to 254%, especially in extension. This was due to the position of the anterior plate mimicking the stabilizing effect of the anterior longitudinal ligament as previously demonstrated by Panjabi, et al.[27] Although additional anterior plating significantly increased positive biomechanical results, additional posterior stabilization increased rotational stiffness up to 102%. Therefore, additional posterior instrumentation should be considered in severe rotational instability of the cervical spine.

A question that cannot be answered by this in vitro study concerns the level of stiffness required to obtain long-term stability and fusion by this fixation method. High stiffness may result in stress-shielding inhibiting long-term fusion;[22] however, it may be assumed that the more spinal motion is eliminated the greater is the chance of a definite spinal fusion.

Conclusions

Results indicate that design variations of expandable cages for VB replacement in the cervical spine are of little biomechanical importance; however, the anatomically shaped endplates of the Synex-C seem to be favorable in increasing rotational stiffness. In comparison with a tricortical iliac crest bone graft and a nonexpandable cage, expandable cages have no significant biomechanical advantages. Because of the low extension and rotational stiffness none of the implants tested can be recommended as a stand-alone device for VB replacement in the cervical spine. Additional anterior plating provided sufficient biomechanical stability and increased stiffness especially in extension. Therefore, additional posterior stabilization should only be considered in severe rotational instability of the cervical spine.

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