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Biomechanical analysis of anterior cervical spine plate fixation systems with unicortical and bicortical screw purchase

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Abstract Anterior plate fixation with unicortical screw purchase does not involve the risk of posterior cortex penetration and possible injuries of the spinal cord. However, there are very few biomechanical data about the immediate stability of non-locking plate fixation with unicortical or bicortical screw placement. The aim of the present study was to evaluate the immediate biomechanical properties in terms of flexibility of a non-locking anterior plate system with 4.5-mm screw fixation and unicortical or bicortical screw purchase applied to a single destabilized cervical spine motion segment. Using fresh cadaveric cervical spine specimens C3–C7, multidirectional flexibility was measured at the level C4–C5 before and after destabilization and fixation with an anterior plate with either unicortical or bicortical screw purchase. The results showed that fixed cervical spine segments with anterior plate and bicortical screw purchase were more rigid than intact specimens in all modes of testing. The difference was statistically significant for flexion and extension ($P < 0.001$). Plate fixation with unicortical screw purchase had statistically significant decreased ranges of

motion compared to the intact specimen only in extension. Neither unicortical nor bicortical screw purchase decreased the range of motion significantly in axial rotation compared to the intact specimens. This in vitro study documented that neither unicortical nor bicortical screw purchase with non-locking plate fixation can increase stability in all modes of testing, in axial rotation in particular. Direct comparison between the group with uni- and that with bicortical screw fixation did not reveal significant differences, and therefore no advantage was shown for either type of screw fixation. Therefore, we demonstrated that both uni- and bicortical screw purchase with non-locking plate fixation can decrease immediate flexibility of the tested motion segment, with better results for bicortical purchase. No significant differences were found comparing the two groups of screw fixation. These data suggest that unicortical screw fixation can be used for anterior plate fixation with a comparable immediate stability to bicortical screw fixation.

Keywords Cervical spine · Anterior plate fixation · Biomechanics

Introduction

Anterior fusion and plate fixation for acute traumatic lesions of the cervical spine has become increasingly popu-

lar [12]. Combined anterior discoligamentous and posterior bony or ligamentous injuries have been successfully addressed with this technique [26]. Since the introduction of anterior plate fixation by Orozco and Llovet-Tapias [19], Böhler [5] and Tscherne et al. [31], excellent clinical

results have been reported [1, 3, 9, 26]. Despite this, anterior plate systems with bicortical screw fixation have been repeatedly cited for the potential to cause neurologic injuries due to posterior cortex perforation [2, 25, 27, 29]. Also, biomechanical studies have suggested that anterior plate fixation alone was insufficient when posterior structures were injured [11, 13, 30, 32].

The development of locking plates with unicortical screw fixation and intrinsic stability of the screw-plate interface, via an angle-stable connection, was an attempt to address the aforementioned concerns [19]. Larger, 4.5-mm-diameter titanium screws for osteoporotic bone or revision screw placement have also become available for non-locking plate systems. These screws offer a safe use of anterior non-locking plate systems with unicortical screw purchase [4].

Yet there is a paucity of biomechanical data in the literature regarding anterior plate fixation with non-locking screws in a human cadaveric model evaluated in an unconstrained testing system.

We developed a human cadaveric model that simulated discoligamentous instability in a physiologic testing system with six degrees of freedom, according to the recommendations of Panjabi and Wilke [20, 34].

The goal of the study was to compare the immediate stability of a single level C4-C5 motion segment with anterior plate fixation and either unicortical or bicortical screw purchase in a human cadaveric model with an unconstrained testing system.

Materials and methods

Specimens

Fourteen cervical spine specimens from fresh human cadavers were used (mean age: 43 years, range: 18–62 years). All specimens were X-rayed prior to the study to exclude marked degenerative changes, tumors or relevant osteoporosis. Bone mineral density (BMD) determinations were made by DE-QCT BMD evaluation (Somatom plus S and OsteoCT software, Siemens, München-Erlangen, Germany) of the first lumbar vertebral body of each cadaver. The specimens reviewed prior to the instability tests demonstrated minimal to moderate osteoarthritic changes. Moderate osteoarthritic changes were considered to include non-bridging osteophytes and endplate sclerosis. No evidence of segmental instability, i.e. either retro- or anterolisthesis, was noted, and no additional pathology was identified in any specimen. The mean BMD of L1 for both groups was 141.2 mg Ca-HA/ml, without significant difference between the two groups. Major osteoporosis or deviations from the mean BMD led to exclusion from the study. All specimens were again examined and X-rayed after the performance of the tests.

The specimens were carefully dissected, freed of muscle attachments, and then fixed at C3 and C7 to a jig with transfixing screws. Two sensors of a 3D motion tracker (Polhemus Inc, USA) were attached to the lamina of C4 and C5.

Instability test

A three-dimensional (3D) flexibility protocol was used to evaluate the effect of anterior plate fixation on the destabilized spine. This

Fig. 1 The fresh specimen in the testing apparatus, frontal view. The upper lever is freely movable in the *x*, *y* and *z* directions. Ball bearings allow movement of the mounted spine along the *x*-axis (*a*), and the *z*-axis (*b*). Range of motion (ROM) is measured by the sensors (*c*) of the computer-linked three-dimensional (3D) motion tracker. The apparatus has a rotary disc (*d*) for turning the spine

protocol required the application of “physiologic” loads to the spine specimens and measurement of the resulting segmental motion, with minimal constraints of the natural motion patterns. A testing device was constructed that met the specific requirements for analysis of spinal motion segments established by Panjabi and Wilke [20, 34]. The experimental testing apparatus is shown with a fixed specimen in Fig. 1 and as a schematic 3D drawing in Fig. 2.

The C7 mount was fixed to the test table and moments were applied to the C3 mount. Nondestructive moments of flexion, extension, right lateral bending, and right axial rotation were applied. The loads were transmitted via a system of weights and pulleys that connected the loading frame to an electric motor (Fig. 2).

Each moment was applied in a graduated manner at a rate of 10 Ncm/s, to the maximum value of 350 Ncm, unloading completely between cycles. The maximum value was determined after several preliminary trials, following the technique of Yamamoto et al. [35], who recommend that biomechanical examinations of the spine should always be performed to the maximum moment short of causing a plastic deformation. A total of three cycles per specimen were completed for each testing phase. The 3D displacements of the attached sensors at the C4 and C5 lamina were measured during the third and final load cycle, using a computer-linked 3D motion tracker. Computer software designed specially for calculat-

Fig. 2 Three-dimensional drawing of the construction. The cervical spine is fixed with a special jig to a rotary disc, which allows changing from flexion to lateral bending without remounting the specimen. The upper level is relocatable in the x , y and z directions in a 3D coordinate system, while the lower level can be moved in two directions. For axial rotation the lever arms (highlighted with an arrow) and therewith the loading wires can be twisted horizontal. Under the construction is the motor for applying different cyclic forces

ing displacement via Euler angle analysis was used to determine intervertebral motion at C4-C5.

Because of the non-linear load displacement of the spine, three parameters were used to document segmental instability: neutral zone (NZ), elastic zone (EZ) and range of motion (ROM). This terminology had previously been developed by White and Panjabi [33]. The NZ provides a quantitative measure of intervertebral laxity, and was defined as the displacement from the neutral position to the zero load point of the third load cycle. The EZ was defined as the displacement between the end of the neutral zone and the end of the range of motion. ROM, representing the maximal attained motion, was defined as the displacement from the neutral position to the maximal load point during the third load cycle. For clarity, only the main deflexions or rotations in response to each of the four applied moments were tabulated.

Statistical analysis and measurement error

Previous studies have shown the motion tracker to be precise to within 0.3° and accurate to within 0.1° [18]. We confirmed these

Fig. 3 Detail picture of the H-plate (Pilling Weck, Karlstein am Main, Germany)

results by conducting an error study in which several known translations and rotations of a sensor were analyzed with a mobile microscope.

The distribution of the parameters was summarized using the mean value $\pm$ standard deviation (SD). Differences between the fixation devices as well as comparisons between the intact spine and the fixation methods were evaluated using the Mann-Whitney rank sum test. A statistical level of $\alpha=0.05$ was considered as significant. All statistical analyses were performed with the Sigma Stat/Sigma Plot software program.

Test protocol

Each specimen was tested in two stages of preparation. All specimens were initially tested intact. In the second stage, specimens were destabilized to simulate a complete discoligamentous instability, with dissection of the anterior longitudinal and posterior longitudinal ligaments, the annulus, and the C4-C5 facet capsules, as well as all posterior ligamentous support. A fresh cadaveric tricortical iliac crest bonegraft was then placed in the C4-C5 interspace after curettage and evacuation of disc material in routine fashion. The vertebral body endplates were not decorticated.

At this point, specimens were randomly assigned to two groups with the following plate fixation patterns: In group I ($n=7$), the H plate was bicortically fixed with 4.5-mm $\times$ 22-mm titanium screws. In group II ($n=7$) unicortical fixation with 4.5-mm $\times$ 16-mm titanium screws was achieved. In both groups non-locking single level H-plates (Pilling Weck, Karlstein am Main, Germany) (Fig. 3) were used at the C4-C5 level. All specimens were then cycled through the instability test and intervertebral motion for the C4-C5 segment recorded.

Results

The numerical data for group I and group II are presented in Table 1 and Table 2 respectively. For each of the four physiologic motions tested: flexion, extension, right lateral bending and right axial rotation, each table shows the post-destabilization values for ROM – mean, standard error of mean, range (max–min) and median with 25th and 75th percentiles – as well as the difference between the intact values and the significance of the difference.

Table 1 Bicortical plate system (group I, $n=7$): range of motion (ROM) of C4-C5 immediately after instrumentation, and comparison with the intact values

ROM	Flexion	Extension	Lateral bending	Rotation
Mean $\pm$ SEM	1.78 $\pm$ 0.64 $^{\circ}$	0.88 $\pm$ 0.44 $^{\circ}$	1.78 $\pm$ 1.09 $^{\circ}$	3.40 $\pm$ 1.17 $^{\circ}$
Range (max–min)	1.8 $^{\circ}$ (2.7 $^{\circ}$ –0.9 $^{\circ}$)	1.2 $^{\circ}$ (1.5 $^{\circ}$ –0.3 $^{\circ}$)	3.2 $^{\circ}$ (4.1 $^{\circ}$ –0.9 $^{\circ}$)	3.2 $^{\circ}$ (5.0 $^{\circ}$ –1.8 $^{\circ}$)
Median (25%;75%) ^a	1.6 $^{\circ}$ (1.30 $^{\circ}$;2.275 $^{\circ}$)	0.7 $^{\circ}$ (0.550 $^{\circ}$;1.275 $^{\circ}$)	1.4 $^{\circ}$ (1.150 $^{\circ}$;2.025 $^{\circ}$)	3.7 $^{\circ}$ (2.30 $^{\circ}$;4.225 $^{\circ}$)
Decrease vs intact spine (%)	48.6	80.9	28	5.6
<i>P</i> -value vs intact spine	<0.001	<0.001	0.165	0.902

^a Values for the 25th and 75th percentile respectively

Table 2 Unicortical plate system (group II, $n=7$): range of motion (ROM) of C4-C5 immediately after instrumentation, and comparison with the intact values

ROM	Flexion	Extension	Lateral bending	Rotation
Mean $\pm$ SEM	2.17 $\pm$ 1.05 $^{\circ}$	0.88 $\pm$ 0.61 $^{\circ}$	2.47 $\pm$ 0.81 $^{\circ}$	2.98 $\pm$ 0.81 $^{\circ}$
Range (max–min)	2.7 $^{\circ}$ (3.8 $^{\circ}$ –1.1 $^{\circ}$)	1.5 $^{\circ}$ (1.7 $^{\circ}$ –0.2 $^{\circ}$)	2.4 $^{\circ}$ (4.1 $^{\circ}$ –1.7 $^{\circ}$)	2.6 $^{\circ}$ (4.2 $^{\circ}$ –1.6 $^{\circ}$)
Median (25%;75%) ^a	1.7 $^{\circ}$ (1.3 $^{\circ}$;3.1 $^{\circ}$)	0.7 $^{\circ}$ (0.425 $^{\circ}$;1.525 $^{\circ}$)	2.4 $^{\circ}$ (1.825 $^{\circ}$;2.65 $^{\circ}$)	2.9 $^{\circ}$ (2.675 $^{\circ}$;3.475 $^{\circ}$)
Decrease vs intact spine (%)	29	80.4	19.4	3.3
<i>P</i> -value vs intact spine	0.097	<0.001	0.165	0.128

^a Values for the 25th and 75th percentile respectively

Fig. 4 Movement analysis (flexion, extension, lateral bending and rotation) of the intact spine versus fixation with bicortical screws (** $P<0.001$, Mann-Whitney rank sum test)

In group I (H plate/4.5-mm $\times$ 22-mm screws, bicortical purchase), load displacement curves at 350 Ncm demonstrated statistically significant decreased ROM of the instrumented specimen in comparison with the intact specimen in flexion ($P<0.001$) and extension ($P<0.001$). ROM for rotation and lateral bending was also less in the instrumented specimen, but this decrease was not statistically significant (Fig. 4).

In group II (H plate/4.5-mm $\times$ 16-mm screws, unicortical purchase), statistically significant decreased ROM com-

Fig. 5 Movement analysis (flexion, extension, lateral bending and rotation) of the intact spine versus fixation with unicortical screws (** $P<0.001$ Mann-Whitney rank sum test)

pared to the intact specimen was achieved with the instrumented specimen in extension only ($P<0.001$). It should be noted, however, that the mean values for ROM in the instrumented unicortical specimen were also less than for intact specimens in all four physiologic modes of testing (Fig. 5).

No statistically relevant differences were found between the two fixation devices, either according to the ROM values or to the decrease of ROM in the instrumented unicortical specimen relative to the intact spine (Table 3).

Table 3 Comparison between the mean values of the bicortical plate system (group I) and the unicortical plate system (group II) for decrease of range of motion (ROM) and elastic zone (EZ) relative to the intact spine

	Flexion	Extension	Lateral bending	Rotation
Decrease in ROM (mean±SEM)				
Unicortical	0.94°±1.43°	3.75°±1.81°	0.60°±0.65°	0.80°±1.39°
Bicortical	1.68°±0.71°	3.77°±1.15°	0.75°±0.75°	0.22°±1.49°
<i>P</i> -value ^a	0.25	1.0	0.62	0.53
Decreased EZ (mean±SEM)				
Unicortical	0.67°±1.14°	1.95°±1.74°	0.92°±0.64°	0.18°±0.80°
Bicortical	1.11°±1.05°	2.47°±0.71°	0.60°±0.72°	-0.15°±0.89°
<i>P</i> -value ^a	0.62	0.12	0.45	0.38

^a*P*-value for difference between unicortical and bicortical fixation in terms of the decrease in ROM/EZ relative to intact values

In the radiographs taken after the experiments, no fractures, or screw or plate loosening were noted.

Discussion

Anterior fusion and plate fixation have become increasingly popular in the treatment of acute cervical spine fractures and dislocations [1, 6, 7, 8, 15, 16, 29]. Although Orozco and Llovet-Tapias [19] originally recommended bicortical screw purchase, many surgeons have used plates with unicortical screws, obviating the need for intraoperative fluoroscopy and eliminating the potential risk of neurologic injury with posterior cortical screw penetration [29]. Larger diameter titanium screws that can be used with non-locking plates have also become available. In comparison to locking plate fixation in traumatic lesions, the use of non-locking plates with unicortical screw fixation offers the surgeon advantages such as multidirectional screw placement and lower implant costs, without the aforementioned risks. Yet there is a paucity of literature reviewing the biomechanics of anterior plate fixation in a complete discoligamentous disrupted model [11, 17, 27].

The goal of the present study was to compare the immediate stability of a single level C4-C5 motion segment with non-locking anterior plate fixation and either unicortical or bicortical 4.5-mm-diameter screw purchase in a human cadaveric model with an unconstrained testing system. The 4.5-mm screws are so called “revision screws.” These screws are useful in clinical practice in any case when smaller screws cannot be embedded safely. Large-diameter screws (4–5 mm) have also been used in recent biomechanical studies [22, 25] with unicortical screw fixation. Therefore, we decided for reasons of comparability and the possible advantage of using large-diameter screws to use 4.5-mm revision screws for uni- and bicortical screw fixation. However, there is still no proof in the literature that the use of large-diameter screws is a requirement for unicortical screw fixation in the cervical spine.

Our cadaveric model simulated complete discoligamentous disruption. Although this may not represent a truly

physiologic model, it represents the most unstable injury. The experimental set-up differed from those of other investigators who had used standard material testing machines that constrained the degrees of freedom of the model [14, 17, 29].

Bicortical screw purchase obtained a higher stability in flexion and lateral bending compared to the intact specimens. Anterior plating with unicortical screw purchase achieved a significantly higher stability relative to the control group only in extension. However, given the limited number of specimens, the differences between the two groups stabilized with plate fixation were not statistically significant.

Our results of anterior plate fixation with tricortical interbody graft are consistent with those of Richter et al. [25], Ryken et al. [27] and Panjabi [21], who used comparable testing systems.

Clausen et al. [10] compared the biomechanical stability of a unicortical CLS-plate and the Caspar plate with bicortical screw purchase, and found less stabilization for unicortical screws, even with a locking system, for extension.

With a testing mode allowing six degrees of freedom in every motion segment, the immediate stability of intact and injured-stabilized motion segments were no different, even in our three-column instability model. In contrast, earlier biomechanical studies [11, 28, 32] have shown disrupted and then anteriorly stabilized cervical spines to be less stable than intact specimens. In tests of immediate stability in segments fixed with Caspar plates secured with 3.5-mm unicortical or bicortical screws in a constrained testing system, Ryken et al. [27] found no significant differences between the two types of screw fixation. Pitzen et al. [22] also demonstrated no statistically significant difference in stability between unicortical and bicortical screws, using a self-tapping conical screw with an outer diameter of 4.0 mm. Panjabi [21] described, in a porcine cadaveric model, a comparable immediate stability in unicortical versus bicortical anterior plate screw fixation without specifying the diameter of screws used. Richman et al. [24] compared the AO Morscher plate with unicortical

self-locking screws, a Caspar plate with bicortical screws and lateral mass plates and found no significant differences between the two anterior forms of fixation in flexion, extension and axial rotation. However, comparison with these results is difficult because they used a one-level corpectomy model that was tested in a MTS machine.

Richter et al. [25] evaluated the immediate stability of non-locking H-plate fixation with unicortical 5.0 mm expansion screws versus AO 3.5-mm bicortical screw purchase. This group observed a comparable immediate biomechanical stability and recommended unicortical expansion screw placement for anterior plate systems.

Our results using 4.5-mm revision screws and an unconstrained human cadaver testing model are similar to the aforementioned studies using porcine cadaveric models and/or non-constrained testing systems. We found no statistical differences between the unicortical and bicortical screw placement groups, using large-diameter screws in a non-locking plate system. Concerning the biomechanical data, it appears that unicortical screw fixation with large-diameter screws can be recommended as an alternative to bicortical screw fixation, thus avoiding the potential risks and disadvantages of bicortical purchase in clinical use.

However, our biomechanical analysis also demonstrated that the immediate decrease in flexibility compared to the intact state was significant in three of the four tested motions for bicortical screw fixation in contrast to unicortical. Therefore, compared to unicortical fixation, bicortical screw fixation may provide increased immediate multidirectional stability.

The limitations of biomechanical studies should be noted. The use of human cadaveric specimen may be adversely affected by interspecimen variability or poor specimen quality. The authors tried to minimize these prob-

lems by using radiographic screening and BMD determinations to exclude significant osteoporosis. There was no statistically significant difference in the mean BMD of groups I and II, indicating a uniform pool of specimens. Also, neither cyclic testing of implants nor the pullout strength of the different modes of screw fixation was evaluated. Pitzen et al. [23] measured peak torque and pullout force for unicortical and bicortical screws in human cervical vertebrae and found no significant difference. Both peak torque and pullout force are influenced only by BMD for both types of fixation.

Therefore, this study design only provides biomechanical data for primary stability. Another question in this context would be whether the influence of screw length is only due to the fact that the posterior cortical shell has been penetrated, or whether screw length itself is a factor in biomechanical results.

Conclusion

The use of a non-constrained testing machine for biomechanical measurement of flexibility of a single cervical spine motion segment provided comparable results to biomechanical data of comparable in vitro studies. The results demonstrated that both uni- and bicortical screw fixation lead to a decrease in immediate flexibility of the tested motion segment, with better results in bicortical fixation.

Direct comparison of the uni- with the bicortical screw fixation group, however, did not reveal significant differences between them. In summary, these data support the results of earlier biomechanical studies. Unicortical screw fixation can be used for anterior plate fixation with a comparable immediate stability to bicortical screw fixation.

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