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Biomechanical comparison of anterior cervical spine locked and unlocked plate-fixation systems

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Abstract Three different anterior plate-fixation systems are available for the stabilisation of the cervical spine: (1) the cervical spine locking plate (CSLP), (2) dynamic plates allowing vertical migration of the fixation screws, and (3) various types of plates that are secured with either monocortical or bicortical unlocked screws. Unicortical screw purchase does not involve the risk of posterior cortex penetration and possible injuries to the spinal cord. The development of locking plates with unicortical screw-fixation and intrinsic stability of the screw-plate interface, via an angle-stabilised connection, was an attempt to increase the stability of unicortical screw-fixation systems. The aim of the study was to compare the biomechanical properties of a non-locking, anterior-plate system with 4.5 mm screw fixation and a locking anterior-plate system,

in a single destabilised cervical spine-motion segment. Using fresh cadaveric cervical spine specimen C3–C7, multidirectional flexibility was measured at the C4–C5 level in an unconstrained test system, before and after destabilisation and fixation with an anterior plate with either locked or unlocked screw purchase. Direct comparison of the fixed cervical spine segments with unlocked and locked anterior-plate fixation did not demonstrate significant differences. This in vitro study documented that neither locked nor unlocked anterior-plate fixation can increase stability in all modes of testing. H-plate spondylodesis with unlocked screws seems to provide sufficient mechanical integrity in most cases of monosegmental lesions.

Keywords Cervical spine · Plate fixation · Biomechanics

Introduction

Since Orozco and Llovet [20], Böhler [6], and Tscherne [32] introduced anterior plate fixation for acute traumatic lesions of the cervical spine, several systems for anterior fusion-plate fixation have been developed. Combined anterior discoligamentous and posterior bony or ligamentous injuries have been successfully addressed with this technique [28], and excellent clinical results have been reported [1, 4, 10, 28]. Preliminary studies have shown that unicortical screw fixation can be used for anterior plate fixation with a comparable immediate stability of bicortical screw fixation [19, 23, 24, 29].

Furthermore, anterior plate systems with bicortical screw fixation have been repeatedly cited for the potential to cause neurologic injuries due to posterior cortex perforation [3, 27, 29, 31]. 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 increase the stability of unicortical screw-fixation systems. But the question remains as to whether these plates offer a crucial advantage over the non-locking plates.

For non-locking plate systems, larger 4.5 mm-diameter titanium screws for osteoporotic bone or for revision of screw placement have become available. These screws offer a safe use of anterior non-locking plate systems with unicortical screw purchase [5].

However, there is only limited biomechanical data in the literature regarding anterior plate fixation with locking screws, and these studies used constrained testing systems [11, 30]. In our human cadaveric spine model we simulated discoligamentous instability in a 6-degree-of-freedom physiologic testing system, according to recommendations by Panjabi and Wilke [22, 34].

The aim of the study was to clarify in this human cadaveric model with an unconstrained testing system, if locked, monocortical screw purchase shows biomechanical improvement compared to non-locking plate systems.

Materials and methods

Specimen

Fourteen cervical spine specimens from fresh human cadavers were used (average age: 41 years, range: 37–60). All specimens were radiographed 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, Fa. Siemens, Munich-Erlangen, Germany) of the first lumbar vertebral body of each cadaver [2]. 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., neither retrolisthesis nor anterolisthesis, was noted, and no additional pathology was identified in any specimen. The mean BMD of L1 for both groups was 140.7 mg Ca-HA/ml, with no significant difference between the two groups. All specimens were radiographed and re-examined 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, USA) were attached to the lamina of C4 and C5.

Instability test

As previously described [19] a three dimensional flexibility protocol was used to evaluate the effect of anterior plate fixation on the destabilised spine. This protocol required the application of “physiologically” realistic 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, as established by Panjabi and Wilke [22, 34]. Fig. 1 shows the experimental testing apparatus with a fixed specimen in a three-dimensional drawing.

The C7 mount was fixed to the test table and pure 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. 1).

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. A total of three cycles per specimen was completed for each testing phase. The three-dimensional displacements of the attached sensors at the C4/C5 lamina were measured during the third and final load cycle by a computer-linked 3D motion tracker. Specially designed computer software calculating displacement via Euler-angle analysis was used to determine intervertebral motion at C4/C5.

Fig. 1 Three-dimensional drawing of the construction. The cervical spine is fixed with a special jig to a rotary disc. This allows changing from flexion to lateral bending, without re-mounting the specimen. The upper level can be re-located in a three-dimensional coordinate system, in x, y or z directions, while the lower level can be moved in two directions. For axial rotation the lever arms (*dotted arrow*) and, therewith, the loading wires, can be twisted horizontally. Under the construction is the motor to apply various cyclic forces

Because of the nonlinear 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 was previously developed by White and Panjabi [33]. The NZ was defined as the displacement from the neutral position to the zero-load point of the third load cycle. NZ provides a quantitative measure of intervertebral laxity. The EZ was defined as the displacement between the end of the neutral zone and the end of the range of motion. The 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 deflections or rotations in response to each of the four applied moments were tabulated.

Statistical analysis and measurement error

Previous studies with the motion tracker found precision to be <0.3 degrees and accuracy <0.1 degrees [19]. We were able to confirm these results by conducting an error study in which several known translations and rotations of a sensor were analysed with a mobile microscope.

Fig. 2 Lateral view of fresh specimen in the testing apparatus, with the unlocked cervical spine H-plate. Note the complete discoligamentous disruption of the specimen

Fig. 3 Detail of the CSLP (left) with one locking screw and the unlocked H-plate (right). View with 22 mm titanium screws

The distribution of the parameters was summarised by reporting the mean value $\pm$ standard deviation (SD). Changes within the treatment groups before (intact spine) and after instrumentation were detected using a paired *t*-test. If the distribution of the sample data was not normal, the Wilcoxon signed rank test was performed. Differences between the two fixation devices were evaluated with an unpaired *t*-test. If the sample data were not normally distributed, the Mann–Whitney rank sum test was used instead. The tests were calculated with a desired power of 0.8 and a statistical level of $\alpha=0.05$, which was considered significant. All statistical analyses were performed with the software program Sigma Stat 2.0 by SPSS.

Test protocol

Each specimen was tested in two stages of preparation. All specimens were initially tested intact. In the second stage, specimens were destabilised 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 bone graft from the iliac crest was then placed in the

Table 1 Statistical analysis of the movement assessment of a monocortical plate system, including mean values $\pm$ standard deviation (SD), range (max–min), median (25%; 75%), decrease of motion and *p* values compared with the intact spine*

ROM (°)	Flexion*	Flexion	Extension*	Extension	Lateral bending*	Lateral bending	Rotation*	Rotation
Mean $\pm$ SD	3.11 $\pm$ 0.86	2.17 $\pm$ 1.05	4.64 $\pm$ 1.49	0.88 $\pm$ 0.61	3.07 $\pm$ 0.67	2.47 $\pm$ 0.81	3.79 $\pm$ 0.99	2.98 $\pm$ 0.81
Range (max–min)	2.1 (4.3–2.2)	2.7 (3.8–1.1)	4.5 (7.4–2.9)	1.5 (1.7–0.2)	1.6 (4.0–2.4)	2.4 (4.1–1.7)	3.2 (5.6–2.4)	2.6 (4.2–1.6)
Median (25%; 75%)	2.8 (2.4; 3.9)	1.7 (1.3; 3.1)	4.4 (3.5; 5.3)	0.7 (0.43; 1.53)	2.9 (2.45; 3.70)	2.4 (1.83; 2.65)	3.7 (3.30; 4.20)	2.9 (2.68; 3.48)
Decrease vs intact spine (%)	30.3		80.9		19.5		21.1	
<i>p</i> value (vs intact spine)	0.132		0.002		0.052		0.180	

*Intact spine

Table 2 Statistical analysis of the movement assessment of an interlocked plate system including mean values $\pm$ standard deviation (SD), range (max–min), median (25%; 75%), decrease of motion and *p* values, compared with the intact spine*

ROM (°)	Flexion*	Flexion	Extension*	Extension	Lateral bending*	Lateral bending	Rotation*	Rotation
Mean $\pm$ SD	2.59 $\pm$ 0.65	1.94 $\pm$ 0.72	3.13 $\pm$ 1.17	1.40 $\pm$ 0.84	2.47 $\pm$ 0.89	1.66 $\pm$ 0.81	3.14 $\pm$ 1.08	2.60 $\pm$ 1.29
Range (max–min)	1.8 (3.3–1.5)	2.1 (2.9–0.8)	2.5 (4.4–1.9)	2.0 (2.6–0.6)	2.8 (3.6–0.8)	2.3 (2.8–0.5)	3.0 (4.5–1.5)	3.7 (4.4–0.7)
Median (25%; 75%)	2.8 (2.10; 3.03)	1.9 (1.48; 2.53)	3.3 (1.92; 4.25)	1.2 (0.73; 2.23)	2.6 (2.10; 2.98)	1.6 (1.03; 2.25)	3.2 (2.30; 4.00)	3.2 (1.50; 3.28)
Decrease vs intact spine (%)	24.9		55.3		32.9		17.3	
<i>p</i> value (vs intact spine)	0.101		0.002		0.014		0.120	

*Intact spine

C4/C5 interspace after curettage and evacuation of disc material in routine fashion. The vertebral body endplates were not decorticated (Fig. 2).

At this point, specimens were randomly assigned to one of two groups with the following plate-fixation patterns. In group I ($n=7$), the unlocked cervical spine H-plate (Pilling Weck, Karlstein am Main, Germany) was monocortically fixed with 4.5 mm×16 mm titanium screws. In group II ($n=7$) the cervical spine locking plate (CSLP) (Synthes, Bochum, Germany) with 4 mm×14 mm titanium screws and four locking screws were attached to the C4/C5 level (Fig. 3). All specimens were then cycled through the instability test, and intervertebral motion for the C4/C5 segment was recorded.

Results

The numerical data for group I and group II are presented in Tables 1 and 2, respectively. Both include mean values $\pm$ standard deviation (SD), range (maximum–minimum), median (25%, 75%), decrease of motion and p -values compared to the intact spine.

In each table, there are four column-pairs, one for each of the four physiologic motions tested: flexion, extension, right lateral bending, and right axial rotation. Each column-pair includes motions at the C4/C5 segment, before and after destabilisation and plate fixation.

In group I (H-plate/4.5 mm×16 mm screws) load-displacement curves at 350 Ncm demonstrated statistically significant decreased ROM of the plated specimen, in comparison with the intact specimen in extension ($p=0.002$). Flexion, lateral bending and rotation were also less in the plated specimen, but this decrease was not statistically significant (Fig. 4).

Group II (cervical spine locking plate) demonstrated a statistically significant decrease in ROM, compared with

Fig. 4 Movement analysis (flexion, extension, lateral bending and rotation) of the intact spine vs fixation with the unlocked plate system, ** $p=0.002$

Fig. 5 Movement analysis (flexion, extension, lateral bending and rotation) of the intact spine vs fixation with the CSLP System, ** $p=0.002$; * $p<0.05$

Fig. 6 Box plot analysis of two different fixation devices for the stabilisation of the cervical spine (locked vs unlocked plate system) # $p>0.05$

the intact specimen, as was achieved with the plated specimen in extension ($p=0.002$) and lateral bending ($p<0.05$) (Fig. 5). However, the mean values for ROM in the plated specimen were less than those for intact specimens in all four physiologic motions in both groups.

The comparison of the average ROM between groups I and II revealed no statistically significant difference (Fig. 6).

No fractures, screw loosening or plate loosening were noted in the post-experimental radiographs.

Discussion

Anterior fusion and plate fixation have become increasingly popular in the treatment of acute cervical spine fractures and dislocations [1, 7, 8, 9, 14, 16, 19, 31]. Although Orozco [20] originally recommended bicortical screws, 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 [31]. Larger-diameter titanium screws that can be used with non-locking plates have also become available. In comparison with locking-plate fixation in traumatic lesions, the use of non-locking plates with unicortical screw fixation offers advantages like multidirectional screw placement, as well as lower implant costs without the aforementioned risks.

The risk of a screw loosening and backing out of the plate and the attendant threat to tracheoesophageal or neurovascular structures has often been described [8, 15, 26, 28]. The cervical spine locking plate was an attempt to avoid this problem. Yet, there is a paucity of literature reviewing the biomechanics of anterior plate fixation in a complete discoligamentous disrupted model [12, 17, 19, 23, 29].

The aim of the present study was to compare the immediate stability of a single level C4/C5 motion segment with non-locking anterior plate fixation versus a locking plate using a human cadaveric model with an unconstrained testing system.

The 4.5 mm screws are known as revision screws. These screws are useful in clinical practice in cases where smaller screws cannot be embedded safely. Large-diameter screws (4.5 mm and 4.0 mm) have also been used in recent biomechanical studies with unicortical screw fixation [25, 27]. It was thus decided, for reasons of comparability and to explore the possible advantage of using large-diameter screws, to use 4.5 mm revision screws for unicortical screw fixation.

Our cadaveric model simulated complete discoligamentous disruption. Although this may not represent a true physiologic model, it represents a maximally unstable injury. The experimental protocol differed from those of other investigators who had used standard material-testing machines that constrained the degrees of freedom of the model [13, 17, 31].

Earlier studies, using models that were more physiologic, showed that the immediate stability of intact and injured-stabilised motion segments that used bicortical screws did not significantly differ from those with monocortical screw purchase [19]. These data are in agreement with the results of Panjabi [22], who described a comparable immediate stability in the fixation of unicortical anterior plate

screws versus fixation of bicortical anterior plate screws in a porcine cadaveric model. Also, Richter et al. [27] 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.

From these deliberations, the question remains: is a locking-screw mechanism able to increase the stability of the anterior plate fixation? We found no statistical differences between the two groups using non-locking and locking plate systems.

The CSLP system uses a unicortical screw with a locking hub mechanism to compensate for the loss of posterior cortical-screw purchase and to lower the risk of screw back out [11]. The idea to increase the intrinsic stability of the screw-plate interface, via an angle-stable connection, is common for a number of internal fixation systems, such as the "fixateur interne" for dorsal instrumentation of the thoracic and lumbar spine. An internal fixator implanted dorsally to stabilise a fractured vertebral body, without anterior column support, fulfils a different purpose than an anterior plate fixation. The dorsal system is used to shield from stress until the anterior column is capable of withstanding load. In the case of anterior plate fixation with a pressure-tight tricortical bone graft, the implant has more of a neutralising effect. Therefore, the principles of angle-stability are not simply transferable from an instrumentation at the back to an anterior fixation. On the contrary, an implant inserted from the anterior with an angle-stable screw-plate interface could theoretically thwart the axial loading that is indispensable for bony fusion of the spondylosis.

Another advantage that is achieved with the locking plate is that screw loosening is impossible with the angle-stable connection. In our experiments, we did not detect any screw loosening in the non-locking plates, although no endurance tests with multiple cycles were performed. In contrast, Smith [30] induced implant failure via large angular displacement hyperflexion, finding plate and screw displacement in non-locking plates but not with the CSLP. In the clinical experience, there is a significant difference in the kind of implant failure: if the screws are locked, the whole implant breaks out, potentially a risk for visceral structures, while in unlocked constructs, only the screws come loose.

The risk of screw loosening can only be avoided through optimal embedding of the screws. In a situation in which the screw is not placed optimally in the initial procedure, such as placement within partly fractured vertebrae during plate fixation, a correction of the position may be required. With the unlocked cervical spine H-plate, this corrective procedure is possible at any time. With the CSLP, the direction of the screws is restricted, and in our opinion this is a considerable disadvantage. In cases that require

extreme positioning of the screws, unlocked screws may prove even more advantageous.

Conclusion

The comparison of anterior, cervical spine fixation systems with locked and unlocked screw purchase in a non-constrained testing machine did not suggest any advantage using the CSL plate. Neither locked nor unlocked fix-

ation of anterior plates can increase stability in all modes of testing. Direct comparison of the two plates did not demonstrate significant differences. In summary, the H-plate spondylodesis with unlocked screws seems to provide sufficient mechanical integrity in most cases of monosegmental lesions.

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