Biomechanical analysis of expansion screws and cortical screws used for ventral plate fixation on the cervical spine

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Abstract Compared to bicortical screws, the surgical risk of injuring intraspinal structures can be minimized with the use of monocortical screws. However, this reduction should not be achieved at the expense of the stability of the fixation. With monocortical stabilization, the expansion screws have the potential of absorbing high loads. Therefore, they are expected to be a suitable alternative to bicortical screws for revision surgeries and in osteoporotic bone. The purpose of this *in vitro* study was to investigate the stiffness of the two screw-plate systems used for ventral stabilization of the cervical spine, by focusing on the suitability of expansion screws as tools for revision treatments. The study was conducted in ten functional units of human cervical spines. The device sample stiffness was determined for four conditions using a turning moment of 2.25 N m each around one of the three principle axes. The conditions were native, destabilized, primarily stabilized with one of the screw-plate systems, followed by secondary stabilization using the expansion screw implant. The stabilized samples achieved a comparable, in most cases higher stiffness than the native samples. The samples

undergoing secondary stabilization using expansion screws tend to display greater stiffness for all three axes compared to the primarily stabilized samples. The achieved tightening moment of the screws was higher than the one achieved with primary fixation. Both plates revealed similar primary stability. Revision surgeries with secondary instrumentation achieve a high stiffness of the screwed up segments. Monocortical expansion screws combined with a trapezoidal plate allow ventral stabilization of the cervical spine that is comparable to the plate fixation using bicortical screws.

Keywords Biomechanical analysis ·
Ventral spondylodesis · Cervical spine implants

Introduction

Ventral spondylodesis of the cervical spine is an established method to treat instabilities of the cervical spine [2, 4, 8, 12, 13, 16, 19, 25, 28]. When this technique was first used in the 1960s, it was performed with various modifications of bone grafts [1, 7, 15, 24]. The technique of ventral plate spondylodesis was introduced by Böhler [3] and Orozco [18, 20], and these implants were further developed by Caspar [5, 6].

The bicortical fixation using 3.5 or 4.5 mm cortical screws is used for all mentioned implants. This type of fixation is associated with the risk of iatrogenic damages of the cervical spinal cord when the cortical substance of the posterior vertebral body is penetrated. Monocortical implants were developed for this reason. We would like to mention especially the angle-stable “cervical spine locking plate” according to Morscher [18, 26]. The intrinsic stability of the angle-stable screwed connection in the implant allows

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the compensation of the stability disadvantage associated with monocortical connections. However, the limited possibility to line up the screws has a detrimental effect which may lead to complications such as injury of the vertebral arteries or screw-induced perforation of the intervertebral disk space in spite of the essentially anatomic alignment of the screws. For this reason, alternative possibilities to increase the stability of the screws within the bone were required. Expansion screws are capable of meeting these requirements. They combine the benefit of monocortical implantation with the free selection of the direction when the screws are placed.

The purpose of this in vitro study was to compare two screw-plate systems used for ventral stabilization of the cervical spine, focusing especially on the suitability of expansion screws for revision treatments. An additional focus was the suitability of the implant for osteoporotic bone.

Materials and methods

The in vitro studies were conducted with human samples of the lower cervical spine (cervical vertebral bodies 5/6). Samples from ten donors (6 females/4 males) aged 58–92 with an average age of 74.3 were analyzed. The spinal column samples together with surrounding muscle were

harvested within 48 h after death, triple-wrapped in plastic foil and frozen below -20°C .

Q-CT scans (SOMATOM, Siemens, Munich, Germany) were created for each vertebra to determine the cortical and spongy bone density of the right and left half of the vertebral body by means of a hydroxylapatite phantom. The average trabecular and cortical bone density were used for the analysis. The samples were analyzed for osteo-destructive processes by means of the CT scans. Sample no. 2 was excluded from the statistical evaluation due to extensive osteolysis in the fifth cervical vertebral body. The cervical spines were divided into monosegmental samples without muscle tissue with intact discoligament structure on the day the test was performed.

The prepared motion segments were caudally and cranially poured into a polymethyl methacrylate block (PMMA, Technovit® 4004) to retain the servohydraulic materials testing machine (Bionix 858, MTS, Eden Prairie, MN). To achieve a better fixation of the vertebrae in the PMMA, screws were first inserted into the facets from cranial and caudal.

The samples were mounted in the testing machine between a six component power sensor (MKA, Huppert, Herrenberg, Germany) and the actuator (Fig. 1). Torsion moments were applied directly to the materials testing machine above the actuator. Flexion–extension moments were created by means of an articulated lever arm which

Fig. 1 **a** Test stand with sample (1 XY-table, 2 weight disks for the application of initial load, 3 actuator of the materials testing machine, 4 turning knuckle for the application of lateral deflection (turned 90° for extension/flexion), 5 sample, 6 point support for weights for the simulation of preliminary tension. **b** Sample with PMMA spacer. **c** Sample with T-plate and expansion screws

transmits the axial force of the actuator into a bending moment. Lateral tilt moments were applied analogously after turning the sample by 90°. An angle sensor allowed the measurement of the bending angle of the samples. The distortion of the sample resulting from the influencing moment consecutively causes the deflection of the lower sample retainer. This deflection is made possible with a freely moveable *x/y* table, where the lower sample retainer was mounted on. Path-dependent, the angle speed was set to 0.5–5.0°/s to prevent the effect of the load speed on the determination of the biomechanical properties of the samples [29]. Moments of ± 2.25 N m were applied in all motion directions.

In addition to the moments, an initial load of 100 N with a general axial/vertical effect was applied by means of weight disks (Fig. 1). It simulates the natural conditions under which the weight of the head and tension of the muscles act upon the cervical spine [10, 11, 17]. The applied moments generated an additional axial compression proportional to the moment. Since, the study in hand is a comparable study, the same effect was observed for all configurations.

Two different implant systems were tested (Fig. 2):

- Titanium implant with 5×14 mm trapezoidal geometry (Allocon) fixated by means of expansion screws ($4.5(5) \times 14$ mm) (hereinafter referred to as “T-plate”).

- Titanium implant with H-shaped geometry (3.5×13 mm) (Ulrich), bicortically fixated by means of 3.5-mm cortical screws (AO) (hereinafter referred to as “H-plate”). The screw length (18–22 mm) was selected according to the determined depth of the vertebral body.

Based on the bone density value determined before the experiment, the samples were divided into two groups (A $n = 6$, B $n = 3$) in such a way that the average bone density was identical in both groups. The different group sizes are due to the question (Table 1).

The samples were always tested around all three movement axes in the same order under various conditions, first, around the transversal axis (extension/flexion); second, around the sagittal axis (lateral tilt right/left); and third, around the vertical axis (axial rotation right/left). Three load cycles each were applied. The first two cycles were used to condition the sample, the third cycle was used for evaluation purposes.

The measured data were used to calculate the range of motion (ROM) and the neutral zone (NZ) for every direction. The ROM corresponds to the entire extent of deformation with a load change between the maximum turning moment of 2.25 N m and the minimum turning moment of -2.25 N m. The NZ corresponds to the

Fig. 2 Implants and screws used for the study (*left* T-plate with expansion screw, *right* H-plate with cortical screw)

Table 1 Different conditions used to test the two groups

1. Native

All samples were measured in all three spatial axes without additional manipulations.

2. Destabilized

Specific destabilization was used to simulate a discoligamental injury of the cervical spine. For this purpose, the facet joint capsules, flaval ligaments, interspinous ligaments, and the anterior longitudinal ligaments as well as the intervertebral disk were separated in the two front thirds. The posterior longitudinal ligament remained intact.

3. Stabilized

Prior to the instrumentation, the intervertebral disk space was emptied and prepared for the insertion of a PMMA spacer. The spacer simulates a corticospinous bone graft, stabilized by means of an H-plate.

4. Secondarily stabilized

After removing the H-plate, a T-plate was used for stabilization above the same bore holes.

Points 1–3: Groups A and B

Point 4: Group A

difference of the sample deflection between ascending and descending flank of the moment development at 0 N m. It is the measurement for the laxity of the samples in neutral position. These examinations were performed in accordance with the guidelines of the task force for preclinical tests issued by the German Association for Spinal Column Surgery [30].

The tightening moments of every screw were measured using a torsion meter (Stahlwille, Wuppertal, Germany). Since the BMD was determined separately for every side of the vertebral body, it was possible to conduct an analysis of the relationship between the BMD and the tightening moment for every screw bearing.

Analyses of variance and regression were performed to check the determined differences for statistical significance (SPSS 9.0.1, SPSS Inc., Chicago, IL). Analyses of regression were performed to determine the connection between the screw tightening moment and the bone density. Unifactorial analyses of variance (with Tukey-B post-hoc comparisons in case of more than two groups) were used to examine the change of the ROM and NZ of the samples under various conditions and to compare these parameters among the analyzed screw-plate systems. All analyses were performed with a level of significance of 5% ($\alpha = 0.05$).

Results

The secondary implantation of the expansion screws achieves a tightening moment comparable to the one achieved with primary implantation using cortical screws ($P = 1.00$; Table 2). The tightening moments of the expansion screws in primary stabilization are pronounced (but not significantly) higher than the ones of cortical screws ($P = 0.076$). With secondary stabilization, the tightening moment of expansion screws is increased

Table 2 Screw tightening moments (average value and standard deviation) in combination with trabecular and cortical BMD

	Tightening moment (N cm)	Trabecular BMD (mg CaHA/mL)	Cortical BMD (mg CaHA/mL)
Cortical screws	42 ± 36	193 ± 97	326 ± 97
Primary expansion screws	69 ± 28	207 ± 70	307 ± 58
Secondary expansion screws	47 ± 36	193 ± 97	326 ± 97

Table 3 Amount of declared variance and probability level for the linear correlation between tightening moment and trabecular or cortical BMD

	Trabecular BMD		Cortical BMD	
	r^2	P	r^2	P
Cortical screws	0.730	<0.001	0.647	<0.001
Primary expansion screws	0.691	<0.001	0.177	0.173
Secondary expansion screws	0.819	<0.001	0.636	<0.001

compared to the primary application (not significant, $P = 0.253$). The tightening moments of the screws revealed a significant correlation with the cortical and trabecular BMD for all screw conditions (Table 3). Only the correlation between cortical BMD and the tightening moment of the primarily implanted expansion screws was not significant.

Compared to the native status, the ROM of the samples almost doubled after destabilization (Tables 4, 5). With respect to the motion directions extension/flexion, the added movement in group B in Table 4) and group B in Table 5 was significant. Compared to the native

Table 4 ROM and NZ for group B under different conditions (load ± 2.25 N m; average values $\pm$ standard deviations; $n = 6$)

Motion direction [°]	Parameter	Condition			
		Native	Destabilized	Stabilized, H-plate, cortical screws	Secondarily stabilized, T-plate, expansion screws
Extension/flexion	ROM	12.2 $\pm$ 3.1	23.9 $\pm$ 9.7*	10.8 $\pm$ 8.1	9.8 $\pm$ 8.3
	NZ	4.3 $\pm$ 1.7	10.9 $\pm$ 3.6*	5.1 $\pm$ 5.0	4.4 $\pm$ 5.3
Lateral tilt	ROM	3.6 $\pm$ 1.7	6.3 $\pm$ 3.1*	3.6 $\pm$ 2.2	2.7 $\pm$ 1.9
	NZ	0.7 $\pm$ 0.4*	2.1 $\pm$ 1.5***	1.6 $\pm$ 1.6*****	1.1 $\pm$ 0.9***
Torsion	ROM	3.5 $\pm$ 1.1	6.7 $\pm$ 2.3*	3.5 $\pm$ 1.6	3.6 $\pm$ 2.5
	NZ	0.5 $\pm$ 0.1	1.7 $\pm$ 0.9*	1.5 $\pm$ 1.0*	1.5 $\pm$ 1.6*

Significant differences ($P < 0.05$) within a single motion direction are denoted with an asterisk “*”

Table 5 ROM and NZ for group B under different conditions (load ± 2.25 N m; average values $\pm$ standard deviations; $n = 3$)

Moving direction [°]	Parameter	Condition		
		Native	Destabilized	Stabilized, T-plate, expansion screws
Extension/flexion	ROM	11.5 $\pm$ 2.3**	17.6 $\pm$ 4.2***	8.3 $\pm$ 2.8*
	NZ	3.5 $\pm$ 0.5	10.9 $\pm$ 6.4*	2.8 $\pm$ 1.8
Lateral tilt	ROM	4.7 $\pm$ 3.1	6.8 $\pm$ 3.1	4.7 $\pm$ 3.3
	NZ	1.7 $\pm$ 1.9	4.1 $\pm$ 4.9	3.1 $\pm$ 2.6
Torsion	ROM	5.5 $\pm$ 3.3	7.5 $\pm$ 4.6	5.1 $\pm$ 3.5
	NZ	0.7 $\pm$ 0.4	2.1 $\pm$ 2.2	2.2 $\pm$ 1.9

Significant differences ($P < 0.05$) within a single motion direction are denoted with an asterisk “*”

situation, the stabilization using the H-plate slightly decreased the ROM for the extension/flexion in group A, achieved it for the lateral tilt, while the ROM was 14% larger after stabilization compared to the native situation for torsion loads (all differences are not significant). In group B, the ROM was significantly reduced after stabilization with the T-plate compared to the native situation (Table 5).

With respect to the lateral flexion and torsion load, the same tendency as the one observed for the extension/flexion was applied to the range of motion. However, significant increases in movement due to destabilization were only determined in group A (Table 4). Assuming an identical tendency, the size of group B was too small to achieve significance (Table 5).

The percentage increase of the NZ as a result of destabilization was clearly higher than the one for the range of motion (Tables 4, 5). In terms of the direction of the extension/flexion, the stabilization was capable of achieving the NZ of the native situation in both groups. In contrast to the ROM, the NZ tended to be greater for torsion and lateral flexion load under all conditions, including the stabilized status (significant in group A, tendency in group B). A significantly higher value compared to the native situation was only achieved with the secondary stabilization under lateral flexion load in group A. The trabecular bone density revealed a positive influence on the range of

Fig. 3 Extension/flexion-associated ROM depending on the trabecular BMD

motion for both groups and all stabilized conditions, albeit not a significant one (Fig. 3).

Discussion

Two plate and screw systems for ventral fixation of the cervical spine were investigated within the scope of this

study. The samples used for this purpose were osteopenic. This is due to the selection of samples which were harvested from elderly and in part systemically ill donors (e.g., rheumatoid arthritis) [9, 14]. For these samples, we were able to determine a proportional relationship between the BMD and the screw tightening moment. Consequently, this study confirms the correlation which has been described several times before [22, 23, 31]. In addition, it was confirmed that the screws with larger diameters allow a greater tightening moment than the ones with smaller diameters and therefore presumably allow better load transmission.

Moreover, the relation between the ROM in extension/flexion and the BMD indirectly depends on the above. The ROM of stabilized segments decreases more with greater BMD versus segments with a smaller BMD.

Compared to a similar publication by Richter et al. [21], which in part investigated identical or similar implants, the significantly greater absolute values for ROM and NZ in this publication are striking. The key difference between the two studies is that we used an axial initial load which better represents the physiological situation, but possibly increases the distortion as a result of the applied turning moment. The limited comparability is due to the fact that in vitro studies are only capable of simulating in vivo conditions to a limited degree. The main issue is the missing physiological stabilization of the cervical spine by the musculature. Experimental set-ups always only imitate simplified load conditions and therefore, only relative differences between implants are recognizable.

An additional cause for the greater distortion could be due to the fact that two samples from rheumatoid donors were included in this study. Although the two studies were comparable with respect to the age and average BMD, these samples with their strikingly high ROM and NZ in the native status were in part responsible for the differences.

However, essentially similar results were found with respect to the differences of different tested implants. Richter et al. [21] also identified the benefits of expansion screw plates versus bicortically fixed H-plates. The revision situation examined in the present study additionally allows the conclusion that the revision using expansion screws (combined with the corresponding plate) achieves a comparable situation as the one achieved with primary stabilization using bicortical screws.

Based on our point of view, the screw-bone-interface is the relevant parameter for the stability of an implant. The expansion screw represents an implant that follows this approach and meets the expectations in this regard based on our results. This is illustrated by the tendency of higher tightening moments and confirmed with the numerically slightly higher limitation of the movement of samples stabilized by means of expansion screws. We would

especially like to emphasize the reduction of the neutral zone for the extension/flexion load to the native value with primary treatment using expansion screws. Please note that the tightening moments of the expansion screws were determined before the expansion to prevent the expanded screws from being stripped during the measurements. The stability after the expansion is expected to be greater.

The use of expansion screws for revision surgeries at least achieves the same status as the one achieved after primary treatment with cortical screws, even though the osseous situation is worse. On one hand, this is due to the improved screw-bone-interface and on the other hand to the difference of the plate geometry.

In principle, the study confirmed that the range of motion can be limited using ventral spondylodesis via a plate and an intervertebral PMMA interponat, especially on extension/flexion level; this is particularly true for the primarily implanted T-plate using expansion screws.

Again, the primarily implanted H-plate was capable of reducing the range of motion in lateral tilt and torsional lateral tilt to the native situation; the stiffness tendency achieved by means of a T-plate with primary and secondary implantation was even greater.

However, it was observed that the weakness of exclusive ventral spondylodesis under torsional and lateral tilt load cannot be waived completely, even with the use of a modified plate geometry and expansion screws. The results of the publication by Ulrich et al. [27] show that the combination of the ventral and dorsal approach can significantly reduce the ROM, even with rotation.

The monocortical fixation of the expansion screws reduces the risk for intra-operative injuries of the cervical spinal cord because the posterior cortical substance is spared. The identical or even slightly better stiffness of implants fixated with expansion screws is a significant benefit compared to bicortically stabilized implants, especially for revision surgeries. The advantage compared to the cervical spine locking plate mentioned at the beginning of this paper is that the direction of the screws is not specified and can therefore be matched to the intra-operative findings.

Also, the tightening moment of expansion screws has a significant correlation with the spongy bone mass. However, the average moments achieved here are higher, and the identical bone quality is expected to create the stability of the stabilization. With monocortical stabilization, only the spongy bone structure appears to be relevant for the stabilization; this statement is also supported by the missing significance of the relation between the cortical BMD and the primary expansion screw tightening moment.

The greater ranges of motion of stabilized samples with lower bone mass indicate that the relative movements

involving the screw-bone-interface are taking place. The T-plate is not angle-stable and the intrinsic stability of the implant is the result of the form closure between the plate and screw. Because of the looser screw tightening, the stability is expected to be lower, therefore, we expect at least a combined effect of relative movement of the implant in the bone and the screw heads in the plate.

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