Eur Spine J
DOI 10.1007/s00586-008-0588-y

ORIGINAL ARTICLE

En bloc spondylectomy reconstructions in a biomechanical in-vitro study

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Received: 12 July 2007 / Revised: 27 December 2007 / Accepted: 28 December 2007

Abstract Wide surgical margins make en bloc spondylectomy and stabilization a referred treatment for certain tumoral lesions. With a total resection of a vertebra, the removal of the segment's stabilizing structures is complete and the instrumentation guidelines derived from a thoracolumbar corpectomy may not apply. The influence of one or two adjacent segment instrumentation, adjunct anterior plate stabilization and vertebral body replacement (VBR) designs on post-implantational stability was investigated in an in-vitro en bloc spondylectomy model. Biomechanical in-vitro testing was performed in a six degrees of freedom spine simulator using six human thoracolumbar spinal specimens with an age at death of 64 (±20) years. Following en bloc spondylectomy eight stabilization techniques were performed using long and short posterior instrumentation, two VBR systems [(1) an expandable titanium cage; (2) a connected long carbon fiber reinforced composite VBR pedicle screw system)] and an adjunct anterior plate. Test-sequences were loaded with pure moments (±7.5 Nm) in the three planes of motion. Intersegmental motion was measured between Th12 and L2, using an ultrasound based analysis system. In flexion/extension, long posterior fixations showed significantly less range of motion (ROM) than the short posterior fixations. In axial rotation and extension, the ROM of short posterior fixation was equivalent or higher when compared to the intact state. There were only small, nonsignificant ROM differences between the long carbon fiber VBR and the expandable system. Antero-lateral plating stabilized short posterior fixations, but did not markedly effect long construct stability. Following thoracolumbar en bloc spondylectomy, it is the posterior fixation of more than one adjacent segment that determines stability. In contrast, short posterior fixation does not sufficiently restore stability, even with an antero-lateral plate. Expandable verses non-expandable VBR system design does not markedly affect stability.

Keywords En bloc spondylectomy · Biomechanical · Reconstruction · Stability

The study was supported by corporate (coLigne AG, Zurich, Switzerland) and institutional funds.

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Introduction

While less than 5% of all primary musculoskeletal tumors are located at the spine, 5–10% of all cancer patients develop metastatic spinal lesions during the course of their disease [2, 5, 24, 47, 53, 69]. For this patient group, apart from a few special cases, the chance of a curative treatment is primarily limited by the disseminated stage of disease and further tumoral spread. Surgical treatment had been prevented by the thoracolumbar spine's close proximity to the surrounding neurovascular structures, i.e., the aorta, caval vein, myelon and nerve roots. Therefore, an intralesional corpectomy by piecemeal resection was considered as the only feasible surgery [12, 22, 23, 26, 33, 54, 64, 68] followed by anterior–posterior stabilization of the resulting segmental spinal defect. However, the overwhelming majority of these intralesional resection patients have shown a poor oncological outcome [17, 44, 64]. Their elevated mortality rates were in fact caused by the intralesional procedure, which causes tumor-derived blood loss, local and systemic dissemination of tumor cells with substantially increased risk for local recurrence and further metastatic disease. As an alternative treatment, en bloc spondylectomy of spinal malignancies has attracted growing interest. It circumvents direct exposure of the tumor tissue and enables the surgeon to reach wide resection margins of the spine [8, 18, 20, 32, 35, 46, 48, 51, 52, 58–60, 70]. For selected patients, the en bloc resection is expected to decrease local recurrence rates and improve the patient's chances of overall survival. Different authors have described complete en bloc resections of spinal tumors by an isolated dorsal approach [46, 51, 52], thereby limiting the intraoperative comorbidity associated with an additional anterior surgery.

Clinical and biomechanical studies have demonstrated the influence of different constructs on stability of the thoracolumbar spine following corpectomies. In this context, single anterior stabilizations with vertebral body replacements (VBR) combined with plates or rods [10, 11, 13, 16, 34], posterior stabilizations with VBR and/or grafting [29, 31, 50] and combined anterior–posterior stabilizations [4, 25, 63] were performed with different results in terms of restoring spinal stability. In contrast, to date, there are very little biomechanical data available to show construct stability following spinal reconstruction after en bloc spondylectomy. Due to the radical resection of the entire affected vertebra that removes the posterior column and the associated stabilizing soft-tissue structures, there is an even greater need for a stable spinal reconstruction when compared to a simple corpectomy. To simply transfer the biomechanical data of previous corpectomy findings to the total en bloc spondylectomy situation seems inappropriate, as it does not closely imitate clinical reality with complete loss of spinal continuity. Therefore, this study aims to analyze the influence of differently combined anterior–posterior reconstruction options on primary spinal stability that follows an en bloc spondylectomy. Using an in-vitro model of thoracolumbar en bloc spondylectomy the authors tested the post-implantational stability of eight reconstructions that employ different VBR cage systems, different lengths of the posterior fixation and the option of an additional antero-lateral stabilization.

Material and methods

For biomechanical testing fresh frozen human thoracolumbar spines (Th11–L3) of four male and two female donors were chosen. The average age at death was 64 (±20) years with an average weight of 71.7 (±8.2) kg. For the sake of standardization and homogeneous study conditions all vertebral bodies used for biomechanical testing were analyzed (qCT including EFP calibration) for cancellous bone mineral density (BMD) using a preoperative CT scan (GE Lightspeed 16©, GE Medical Systems, USA) with digital reconstruction. Determination of BMD showed an average of 87.9 (±20.8) mg/cm^3. Average BMD at the mentioned average age at death lies in the range of the second standard deviation below average controls [6] and is—concerning to the WHO definition—nonosteoporotic. Spinal specimens with structural disorders, posttraumatic abnormalities and deformities or previous spinal surgery were excluded.

Prior to biomechanical testing all specimens were vacuum sealed in double plastic bags and stored at −30°C. Specimens were thawed overnight at 6°C degrees and prepared at room temperature right before testing started. All paraspinal muscle tissue was detached from the bone surface of the specimens leaving the supporting ligamentous structures untouched.

The middle vertebra (L1) was aligned horizontally for the subsequent embedding of the cranial (Th11) and caudal (L3) ends in polymethylmethacrylate (PMMA) cement (Technovit 3040©, Heraeus Kulzer, Wehrheim, Germany). Flanges were mounted to the cranial and caudal PMMA blocks of the specimens, allowing a rigid fixation to the frame of the spine simulator (Fig. 1). Biomechanical investigations were conducted at room temperature. To avoid tissue dehydration specimens were kept moist with isotonic saline solution for the study period in accordance to international standards [40, 65]. Biomechanical testing of the spines was performed in six degrees of freedom spine simulator (Fig. 1) respecting the recommendations for testing of spinal implants [39, 67]. The spine simulator was constructed as previously described by Knop et al. [31] and updated with electronic control and measurement features as described below.

The flexibility tests were performed in the three main motion planes using pure moments of ±7.5 Nm (1) flexion/extension (±My); (2) lateral bending left/right (±Mx); (3) axial rotation left/right (±Mz). Specimens were loaded under continuous moment control with a constant displacement rate of 0.6°/s. The moments and forces induced at the cranial end of the specimen were continuously recorded by a six-component load cell (Schunk FT Delta SI 660–60, Lauffen/Neckar, Germany). Segmental motion of the bridged segment Th12–L2 was measured using an ultrasound based motion analysis system (Winbiomechanics, Zebris©, Isny, Germany, resolution 0.1°) (see Fig. 1).

The range of motion (ROM) and neutral zone (NZ) of the bridged segment Th12–L2 were determined from the hysteresis curves. To allow a preconditioning of the

Fig. 1 PMMA embedded specimen with reconstruction of the first lumbar vertebra fixed to the six degrees of freedom spine simulator

specimens and minimize the viscoelastic effect only the third load cycle was evaluated and used for further analysis and comparison.

For a baseline, first the intact specimens (T11–L3) were loaded with pure moments of ±7.5 Nm. After the intact test of the specimens an en bloc spondylectomy of the first lumbar vertebra was performed. For this purpose, specimens were fixed in an X-ray jig, which allowed the application of an axial preload of 100 N during implantation. All surgical procedures were performed by authors who are experienced senior orthopedic surgeons and who also perform en bloc excisions in clinical practice. En bloc spondylectomy of the middle vertebra (L1) was conducted with routinely used clinical instruments. The surgical approach and technique was carried out in accordance to established surgical techniques and previous reports [14, 46, 51, 52, 58]. First, the pedicle screws were placed in the adjacent vertebras Th11, Th12, L2 and L3. The dorsal parts of the vertebra including both laminae and the adjacent facet joints were resected to liberate the dural sac. Nerve roots on one side of the L1 vertebra were cut in order to permit a smooth rotation and further removal of the vertebral body around the longitudinal axis of the spinal cord. After dissection of the two adjacent discs and intermediate unilateral stabilization of the spine the vertebral body including the remaining pedicles was resected en bloc by rotating the vertebra out and gently passing the dural sac through the laminectomy gap.

Reconstruction was performed using different combinations of anterior and posterior stabilizations. To restore the stability of the anterior column either a pedicle fixation connected long carbon fiber reinforced polymer (LCFRP) VBR (Trabis© in ostaPek© 66.6% carbon fiber and 33.3% PEKEKK, coLigne AG, Zurich, Switzerland) or an expandable nonpedicle fixation connected VBR cage system (X-tenz© of DePuy, Kirkel-Limbach, Germany) were implanted. The cross section of the LCFRP VBR was 30 × 40 mm and of the expandable cage 26 × 33 mm for all specimens. The height of the VBR was measured of the preoperative CT of the intact specimen and reconstructed with modular VBR parts or varied by expansion. Both were combined with a long (Th11/12–L2/3) or short (Th12–L2) titanium posterior pedicle screw and rod fixation system (evos© coLigne, Zurich, Switzerland). For standardization 6.25 × 40 mm pedicle screws were used in all specimens. The used internal fixator has a poly axial fixation option. The titanium rods with a diameter of 6 mm can be fixed to the pedicle screws by connectors of different sizes. The artificial pedicle is built up of a threaded rod (diameter 5 mm), which is screwed in the VBR. The rod is the guidance for a sleeve (diameter 10 mm), which has a spherical end that allows a poly axial fixation of the artificial pedicle to the rod of the internal fixator.

All sequences were tested with and without an additional antero-lateral angular stable plate fixation (LCP 3.5, 5 hole) between Th12 and L2 cranial and caudal to the resected vertebra (LCP©, Synthes, Switzerland).

In order to distribute the potential effect of possible screw loosening—inherent in all test sequences—the following test settings were carried out in alternating sequences.

- TLN connected long carbon fiber reinforced polymer VBR pedicle screw system, posterior fixation of four adjacent segments (Th11/12–L2/3) without an antero-lateral plate fixation (Fig. 2a).
- TLP connected long carbon fiber reinforced polymer VBR pedicle screw system; posterior fixation (Th11/12–L2/3) and an antero-lateral plate fixation (Fig. 2a).
- TSN connected long carbon fiber reinforced polymer VBR pedicle screw system; posterior fixation of two adjacent segments (Th12–L2) without an antero-lateral plate fixation (Fig. 2a).
- TSP connected long carbon fiber reinforced polymer VBR pedicle screw system; posterior fixation (Th12–L2) with an antero-lateral plate fixation (Fig. 2a).

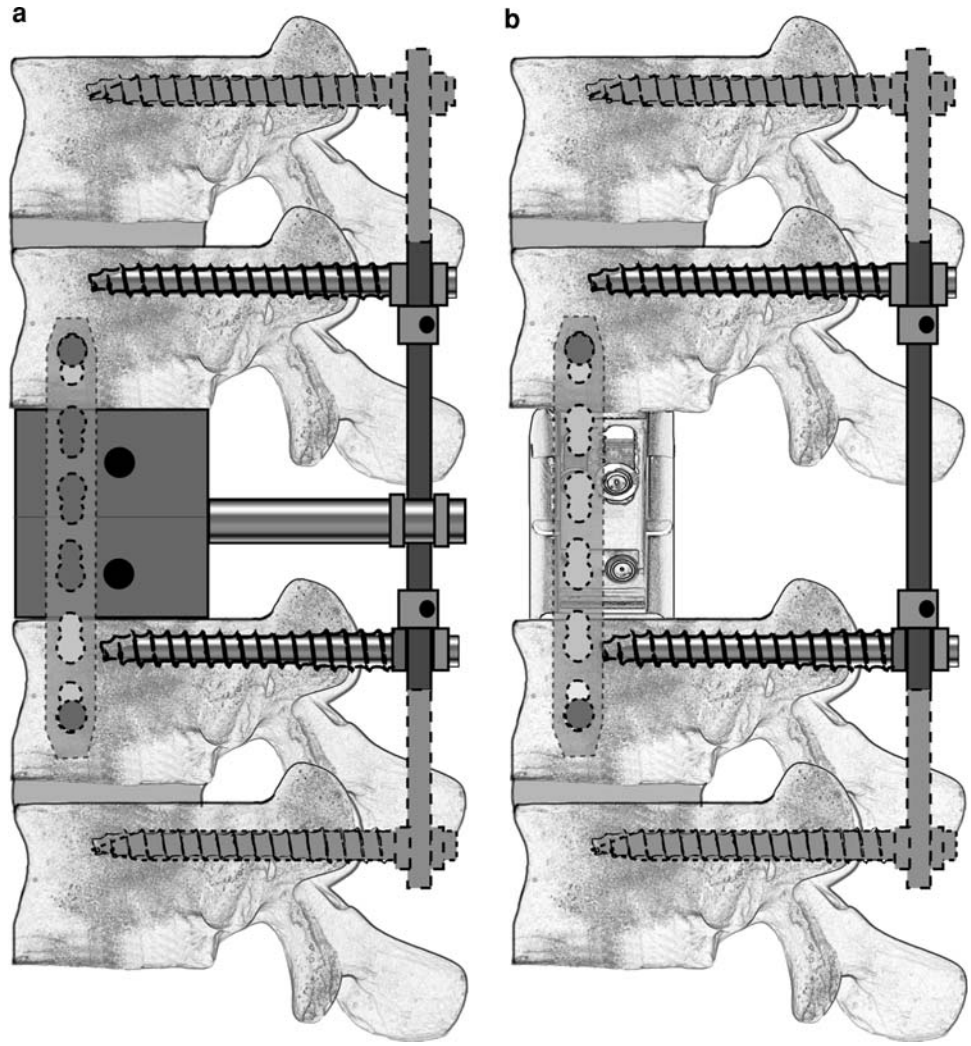

Fig. 2 **a** The Trabis connected long fibre carbon composite VBR pedicle screw system used for anterior column reconstruction combined with a posterior fixation. The test sequences TLN/TLP/TSN/TSP resulted from the optional use of long posterior fixations and/or an additional antero-lateral plate. **b** The X-tenz expandable cage system used for anterior column reconstruction combined with a posterior fixation. The test sequences XLN/XLP/XSN/XSP resulted from the optional use of long posterior fixations and/or an additional antero-lateral plate

XLN expandable VBR cage system combined with a titanium posterior pedicle screw and rod fixation system of four adjacent segments (Th11/12–L2/3) without an antero-lateral plate fixation (Fig. 2b).

XLP expandable VBR cage system combined with a posterior fixation (Th11/12–L2/3) and an antero-lateral plate fixation (Fig. 2b).

XSN expandable VBR cage system and posterior fixation of two adjacent segments (Th12–L2) without an additional antero-lateral plate fixation (Fig. 2b).

XSP expandable VBR cage system and posterior fixation (Th12–L2) and an additional antero-lateral angular stable plate fixation (Fig. 2b).

To ensure a correct positioning of the implants, standardized a.p. and lateral X-rays were taken. To determine alignment changes of the spinal segments due to manipulations during the reconstruction, the angulations between the endplates adjacent to the resected vertebra were measured.

Statistical analysis was performed using the SPSS© software package (Microsoft Windows release 12.0; SPSS Inc., Chicago, IL, USA). Data and results of the ROM and NZ of the three motion planes are presented as means and standard deviations (SD). To analyze for differences between the implant constructs repeated measures analysis of variance (ANOVA) and Bonferroni post hoc analysis were performed. The level of significance was set at $P < 0.05$.

Results

In the present study an increasing primary stability of a construct was defined as a reduction of the ROM while loading the specimens in the three main motion planes with pure moments of ±7.5 Nm. Results of the ROM and the NZ in the three planes of motion for the different test-sequences are displayed in Table 1. ROM values normalized to the intact state are shown in Fig. 3 a–c.

Table 1 Results of the range of motion (ROM) and neutral zone (NZ) in axial rotation, lateral bending, extension and flexion segregated for the test-sequences

	Intact (INT)	Trabis system long posterior fixation (TLN)	Trabis system long posterior fixation + antero-lateral plate (TLP)	Trabis system short posterior fixation (TSN)	Trabis system short posterior fixation + antero-lateral plate (TSP)	X-tenz system long posterior fixation (XLN)	X-tenz system long posterior fixation + antero-lateral plate (XLP)	X-tenz system short posterior fixation (XSN)	X-tenz system short posterior fixation + antero-lateral plate (XSP)
Axial rotation									
ROM	4.79 ± 3.39	2.46 ± 1.34	2.32 ± 0.76	4.71 ± 2.42	4.17 ± 3.15	2.71 ± 1.30	2.56 ± 1.04	5.40 ± 4.30	4.83 ± 3.74
NZ	1.02 ± 1.06	0.81 ± 0.47	0.80 ± 0.51	1.80 ± 0.89	1.34 ± 1.44	0.81 ± 0.47	0.79 ± 0.33	1.80 ± 1.76	1.63 ± 1.35
Lateral bending									
ROM	8.37 ± 2.76	1.02 ± 0.84	0.61 ± 0.29	5.95 ± 3.61	5.00 ± 3.34	0.87 ± 0.55	0.63 ± 0.53	7.21 ± 5.54	5.41 ± 3.46
NZ	2.05 ± 1.18	0.52 ± 0.75	0.20 ± 0.10	2.43 ± 2.19	2.13 ± 1.73	0.26 ± 0.23	0.17 ± 0.24	3.42 ± 3.32	2.43 ± 2.23
Extension									
ROM	−6.04 ± 1.22	−1.54 ± 0.24	−0.77 ± 0.47	−7.74 ± 3.12	−3.02 ± 2.17	−1.56 ± 0.74	−0.55 ± 0.62	−7.95 ± 3.23	−2.70 ± 1.11
NZ	−1.92 ± 1.10	−0.13 ± 0.07	−0.24 ± 0.13	−3.06 ± 2.62	−1.31 ± 1.57	−0.14 ± 0.17	−0.29 ± 0.54	−3.01 ± 2.84	−0.81 ± 0.50
Flexion									
ROM	6.33 ± 0.88	0.53 ± 0.30	0.41 ± 0.36	2.54 ± 0.96	1.54 ± 0.74	0.60 ± 0.37	0.18 ± 0.13	3.10 ± 1.82	1.79 ± 0.67
NZ	1.01 ± 0.80	0.28 ± 0.20	0.21 ± 0.27	0.73 ± 0.83	0.61 ± 0.27	0.51 ± 0.33	0.11 ± 0.09	1.00 ± 0.66	0.84 ± 0.61

Results are displayed as means and standard deviations (SD)

Long posterior fixation without antero-lateral plate (TLN/XLN)

Long posterior fixations without an antero-lateral plate (TLN/XLN) showed—except for axial rotation—in all planes of motion lower ROM ($P < 0.05$) compared to the intact state (INT). In axial rotation there was a nonsignificant reduced ROM for the Trabis cage system with long posterior fixation (TLN) when compared to the same system with a short posterior fixation without antero-lateral plate fixation (TSN). Both sequences (TLN/XLN) showed a significantly increased stability in lateral bending and flexion/extension compared to XSN. There were no differences in the ROM between TLN and XLN for all motion planes.

Long posterior fixation with antero-lateral plate (TLP/XLP)

Adding an antero-lateral angular stable plate to the long posterior fixation construct (TLN/XLN) resulted in a further, significant decrease in ROM for lateral bending and flexion/extension when compared to the intact state. ROM of TLP/XLP was significantly decreased when compared to short fixation modes without a plate in lateral bending (XSN solely) and flexion/extension (XSN and TSN). In all planes of motion no differences between TLP and XLP were demonstrated.

Short posterior fixation without antero-lateral plate (TSN/XSN)

In axial rotation all VBR systems with short posterior fixation without a plate (TSN and XSN) showed similar (TSN) or even increased (XSN) ROM values compared to the intact state. In lateral bending, however, there was a slight reduction of the ROM compared to the intact state. The combined ROM in flexion/extension showed a small decrease in comparison to the intact specimen. Splitting up the ROM in flexion and extension revealed a decrease in flexion ($P < 0.05$) and an increase in extension. There were no differences in ROM between TSN and XSN in the tested planes of motion.

Short posterior fixation with antero-lateral plate (TSP/XSP)

The short posterior fixation sequences with an additional antero-lateral angular stable plate (TSP/XSP) showed a significant increased stability in comparison to the intact state in overall flexion/extension ROM values. In axial

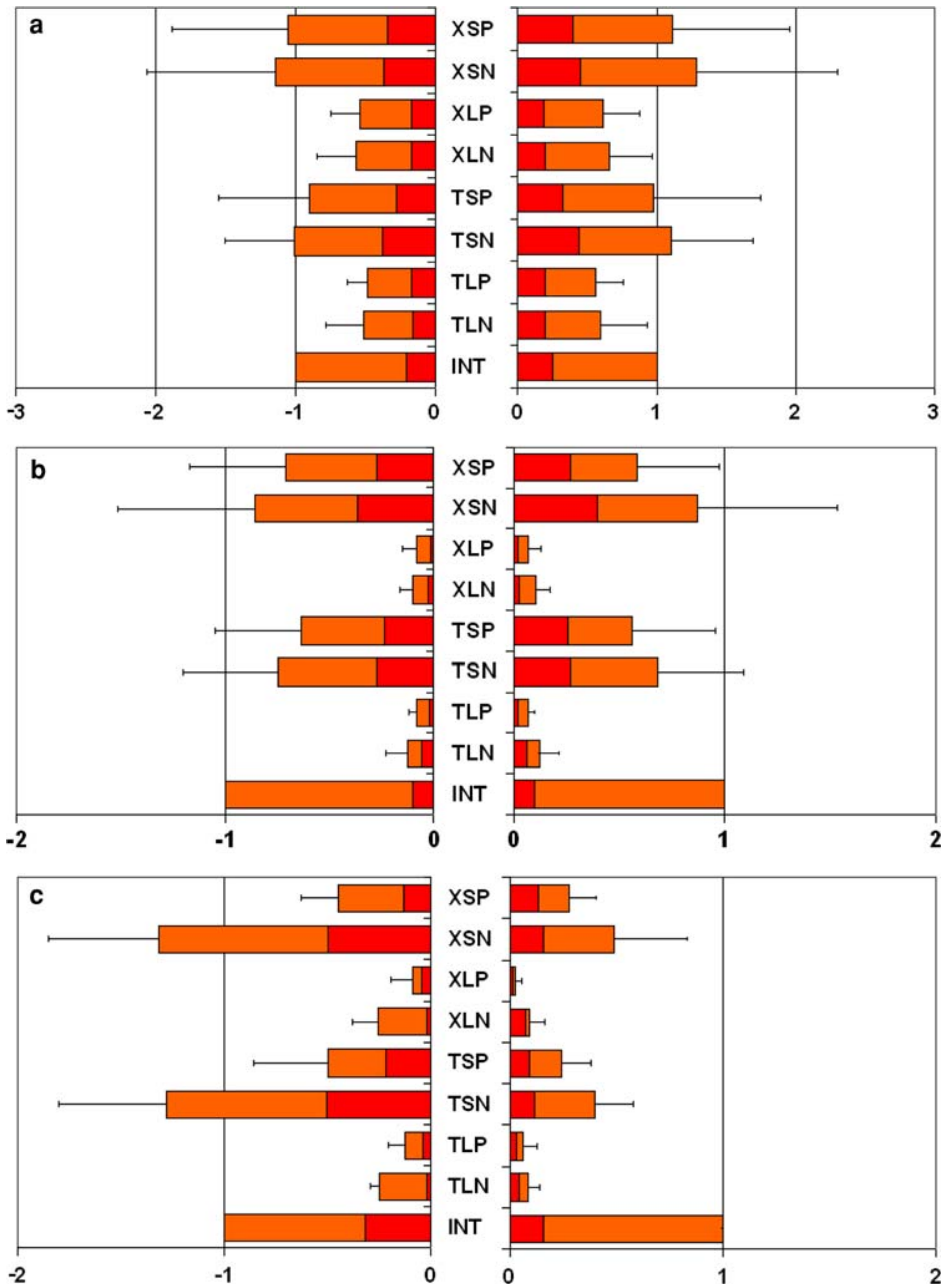

Fig. 3 **a** Range of motion (ROM) with standard deviation (SD), and neutral zone in axial rotation normalized to the intact state. *INT*, intact state; *TLN*, Trabis system + long posterior fixation; *TLP*, Trabis system + long posterior fixation + antero-lateral plate; *TSN*, Trabis system + short posterior fixation; *TSP*, Trabis system + short posterior fixation + antero-lateral plate; *XLN*, X-tenz system + long posterior fixation; *XLP*, X-tenz system + long posterior fixation + antero-lateral plate; *XSN*, X-tenz system + short posterior fixation; *XSP*, X-tenz system + short posterior fixation + antero-lateral plate. **b** Range of motion (ROM) with standard deviation (SD), and neutral zone in lateral bending normalized to the intact state. *INT*, intact state; *TLN*, Trabis system + long posterior fixation; *TLP*, Trabis system + long posterior fixation + antero-lateral plate; *TSN*, Trabis system + short posterior fixation; *TSP*, Trabis system + short posterior fixation + antero-lateral plate; *XLN*, X-tenz system + long posterior fixation; *XLP*, X-tenz system + long posterior fixation + antero-lateral plate; *XSN*, X-tenz system + short posterior fixation; *XSP*, X-tenz system + short posterior fixation + antero-lateral plate. **c** Range of motion (ROM) with standard deviation (SD), and neutral zone in flexion (+)/extension (−) normalized to the intact state. *INT*, intact state; *TLN*, Trabis system + long posterior fixation; *TLP*, Trabis system + long posterior fixation + antero-lateral plate; *TSN*, Trabis system + short posterior fixation; *TSP*, Trabis system + short posterior fixation + antero-lateral plate; *XLN*, X-tenz system + long posterior fixation; *XLP*, X-tenz system + long posterior fixation + antero-lateral plate; *XSN*, X-tenz system + short posterior fixation; *XSP*, X-tenz system + short posterior fixation + antero-lateral plate

rotation these constructs reached values similar to the intact state. XSP and TSP were more stable ($P < 0.05$) in flexion/extension than the equivalent sequences without an antero-lateral plate (XSN/TSN). While the sequences with short posterior fixation without antero-lateral plate (TSN/XSN) showed relative high flexion/extension ROM values, implantation of the plate significantly stabilized the bridged segment. The ROM of TSP did not significantly differ from the corresponding values for XSP.

X-ray analysis

Analysis of the post-implantational a.p. and lateral radiographs to assess the endplate angulation of the segments adjacent to resection level did not reveal any significant changes in the spinal alignment of the specimens.

Discussion

In the late 1970s and early 1980s [46, 51, 52] of the last century spine surgeons described the first en bloc spondylectomies. Since then, an increasing number of surgeons have performed and modified this procedure in order to apply the principles of tumor surgery [8] to the spine: attain wide resections, achieve long term local and systemic tumor control. The previously described techniques were modified [7, 32, 37, 58, 59], prognostic surgical scores [56, 57, 60, 61] were established considering the underlying tumor biology, the number/presence of extraspinal metastases and an estimation of life expectancy. With the results of these scores and the tremendous advance in spine surgery technique the indication from primary spinal tumors is now extended to selected cases of solitary spinal metastases with biologically favorable tumor entities [1, 54, 62, 70]. Thanks to advances in tumor screening and diagnostics, the number of patients who may benefit from this extensive surgical treatment continues to increase. Various authors have shown that en bloc spondylectomy, combined with multimodal therapies, can effectively reduce local recurrency rates and markedly prolong overall long-term survival [37, 53, 54, 61, 70]. However, to provide an acceptable patient outcome and quality of life, the basic knowledge of short- and long-term postoperative implant stability is a mandatory tool to carry into surgery. In contrast to the widely performed but biomechanical different corpectomy situation, there are only a few studies that inconsistently deal with the biomechanical defect after vertebral en bloc resections. This lack of detailed information leads to an incomplete understanding of spinal stability after en bloc excisions and subsequent complex reconstructions. In this context, for instance, the individual influence of different VBR systems, the posterior fixation length and the type of anterior stabilization on overall construct stability following en bloc spondylectomies remains only partly understood. Therefore, the aim of this study was to determine the post-implantational three-dimensional stability in different combined anterior–posterior reconstruction set-ups in a thoracolumbar en bloc spondylectomy defect model.

Influence of VBR design

Changing the VBR system for anterior column reconstruction did not markedly alter the determined ROM. Expandable VBR systems with supplementary posterior fixations are widely used in tumor and trauma surgery to restore the segmental defects of the anterior column. Distracted in situ, they are designed to maximize the endplate contact and to reduce the failure rate of secondary dislocation [30]. They enable the surgeon to choose the optimal reconstruction height in situ and to induce distraction forces on the adjacent endplates. In contrast, the connected long carbon fiber reinforced polymer cage does not allow for in situ distraction. It has to be assembled ex situ and endplate forces can only be applied by secondary performing compression loads induced via the posterior fixation. Despite these different implant features and material properties the results of the present study demonstrated only minimal differences in the post-implantational stability between expandable and nonexpandable VBRs. Similar results have been shown for rather more stable corpectomy models [31, 43] and indeed, for the defect situation after en bloc resections [38], we also were not able to reveal an advantage of the expandability of an VBR. However, it seems conceivable that expandability of a VBR implant may decrease secondary VBR dislocation [21, 30]. At the same time, the mechanism that enables expansion can occupy the space for bone graft and be less desirable where bone in growth is desired as a secondary part of regaining spinal stability.

Influence of additional antero-lateral fixation

Adding an antero-lateral plate fixation increased stability of the constructs in short and—to a lesser degree—in long posterior constructs. The stabilizing effect was evident in flexion and even more pronounced in extension. In surgical procedures placing an additional anterior/antero-lateral fixation undoubtly requires an extension of the classical dorsomedian approach. With the patient lying in a prone position an additional lateral incision is then used (t-shaped approach) with more ribs which have to be resected laterally. Consequently, the danger of pleura and lung lesions, the risk of vessel injuries, and the complications in wound healing are expected to increase with additional incisions and increased exposure. Since in the current study additional antero-lateral angular stable plate fixation after en bloc spondylectomy and expandable VBR did not markedly alter three-dimensional primary stability in long posterior constructs, the surgeon has to balance between the need for further stability and the risk of increased morbidity and complications. Although extensive surgery may conflict with the impaired general condition, the generally accepted aim in cancer patients is to reach maximum stability. As opposed to spinal surgery for posttraumatic (thoracolumbar fractures) or degenerative diseases, a later complete spinal fusion cannot be expected as a result of the preexisting neoplasia and the influence of accompanying multimodal oncological therapies, i.e., chemotherapy, radiation [9, 15] on local bone healing capacities. At this point the connected VBR pedicle screw system may be less invasive and equally effective in preventing dislocation.

Influence of posterior fixation length

In the present study the length of posterior fixation was found to be the most decisive factor for construct stability following a thoracolumbar en bloc spondylectomy. All long posterior fixation modes demonstrated a superior stability compared to both the intact state and the corresponding short posterior testing results. Furthermore, short posterior fixation modes were not able to provide sufficient stability especially in extension when used without an antero-lateral stabilization. Nevertheless, the described en bloc spondylectomy technique is typically performed by a single posterior approach enabling the resection and replacement of the tumor-affected vertebra. In a maximum unstable en bloc spondylectomy situation that additionally comprises the entire dorsal structures of the spinal column, the complete load acting across the defect has to be transmitted by the implanted construct. Additionally, even with a fully reconstructed anterior column, the forces acting on the construct especially in extension are induced as cantilever bending moments to the pedicle screws [36]. Therefore, load sharing by a higher number of screws reduces the bending moment on each single screw. Load sharing, in turn, promotes delay and decrease in early implant failure and loosening. Accordingly, several studies using more stable corpectomy models [25, 31, 43, 49, 63] showed an improvement of overall construct stability by multisegmental posterior fixations. These results are further underlined when compared to similar single anterior reconstruction techniques [63]. While an increased stabilizing effect of an additional antero-lateral plate was demonstrated for short posterior fixation modes, this effect was much less pronounced when combined with long posterior fixations (more than one level). This finding may reflect the fact that the protective effect of additional antero-lateral angular stable plating on short posterior fixation is masked by the primary stabilizing effect of a long posterior construct. Thus, the biomechanical advantage of an optional anterior plate fixation in previous studies needs to be seen differentially as it may depend on the length of posterior fixation [43, 63].

However, a simple comparison of the results obtained in the present en bloc spondylectomy study with corpectomy studies seems not appropriative [28]. By leaving the posterior spinal structures untouched during corpectomy, more than one third of overall segment stability [27] remains intact. On the contrary, the most radical resection technique of en bloc spondylectomy with complete spinal discontinuity, ultimately leads to a defect situation with a maximum degree of biomechanical instability that is different from previously described corpectomy models [28, 31, 43, 63]. In contrast to the widely used corpectomy models only a few authors have biomechanically investigated thoracolumbar spinal reconstructions after en bloc spondylectomy. Previous studies investigating en bloc spondylectomies used different test set-ups and parameters to evaluate the stability of the reconstruction and cannot be directly compared to the present study. In a similar spondylectomy model Oda et al. [38] also showed increased stability in long posterior fixations compared to a short posterior fixation. Compared to the intact state, Shannon et al. [50] also reported an increase in stability for long posterior fixations independent of the anterior column reconstruction. They even found an increase in stability for isolated posterior fixation without a reconstruction of the load bearing anterior column. In our study test sequences using short posterior fixations without additional plates showed higher or similar ROM values in axial rotation and extension compared to the intact state indicating a non-sufficient primary stability. The differences between the present and the previously reported results (Shannon, Oda et al.) are possibly due to various factors especially the discrepancies of testing devices and protocols. In contrast to the pure moment loading (±7.5 Nm) protocol used in the present study, Shannon et al. applied bending moments of 4 Nm in a hydraulic testing machine and assessed the stiffness of the tested constructs by measuring the axial displacement using an extensometer.

Limitations of the present study include different aspects. The ROM was assessed to compare the primary stability of the investigated implant settings using pure moments in a six degrees of freedom spine simulator. Application of pure moments has known limitations strongly depending on set up features used for testing. Gedet et al. [19] demonstrated varying results for different mechanical components in a spine simulator suggesting that parasitic shear forces circumvent measurement of pure moments even amplified in multilevel specimens. However, using pure moments for implant testing is a widely accepted method to imitate in vivo circumstances [39, 66, 67]. In contrast to the present study, different publications investigated the effect of compressive preload [41, 42, 45, 55] on biomechanical testing of spinal specimens. Inducing preloads higher (500–1200 N) than the physiologic 350 N [3] in upright standing resulted in ROM reductions between 15 and 25% [41]. The present study used preloads of 100 N for implantation while motion analysis was performed without. The authors suggest that a similar influence of preloads on all test sequences—especially on the vertebral body replacement systems—will not change the results in relation to each other. Nevertheless, inducing natural compressive preloads can improve a set-up aiming to imitate in vivo circumstances.

In the presented study six human specimens were used to investigate eight reconstruction options in an alternating fashion. At this point the small sample size may be a possible limitation. In addition, any secondary influences of in vivo factors such as tissue healing and bony consolidation cannot be analyzed. Due to the in-vitro model used in the current experiments any in vivo influence of paraspinal muscles cannot be assessed. Finally, the present results do not allow to draw conclusions about intermediate and long term stability of the spinal reconstructions as no cyclic loading was performed. Despite these restrictions in transferring the results to the clinical situation [38, 50] the described model and testing set-up can be reliably used to quantitatively assess post-implantational primary stability following a defined en bloc spondylectomy defect and subsequent reconstruction.

Conclusions

Post-implantational stability following en bloc spondylectomy is mainly influenced by the number of pedicle screws placed for posterior fixation. Load distribution to a higher number of screws secures construct stability and decreases the danger of primary implant failure and loosening. Compared to long posterior fixations, even with an antero-lateral plate, short posterior fixations showed a minor stability. In addition, the stabilizing effect of an additional antero-lateral plate is markedly higher in short posterior fixation constructs. The expandability of the VBR for anterior column reconstruction showed no significant increase in stability, emphasizing the notion of a secondary effect of VBR characteristics on primary post-implantational stability.

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