Cervical anterior transpedicular screw fixation (ATPS)—Part II. Accuracy of manual insertion and pull-out strength of ATPS

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Abstract Reconstruction after multilevel decompression of the cervical spine, especially in the weakened osteoporotic, neoplastic or infectious spine often requires circumferential stabilization and fusion. To avoid the additional posterior surgery in these cases while increasing rigidity of anterior-only screw-plate constructs, the authors introduce the concept of anterior transpedicular screw (ATPS) fixation. We demonstrated its morphological feasibility as well as its indications in a previous study in Part I of our project. Consequently, the objectives of the current study were to assess the *ex vivo* accuracy of placing ATPS into the cervical vertebra as well as the biomechanical performance of ATPS in comparison to traditional vertebral body screws (VBS) in terms of pull-out strength (POS). Twenty-three ATPS were inserted alternately to two screws

into the pedicles and vertebral bodies, respectively, of six cadaveric specimens from C3–T1. For insertion of ATPS, a manual fluoroscopically assisted technique was used. Pre- and post insertional CT-scans were used to assess accuracy of ATPS insertion in the axial and sagittal planes. A newly designed grading system and accuracy score were used to delineate accuracy of ATPS insertion. Following insertion of screws, 23 ATPS and 22 VBS were subjected to pull-out testing (POT). The bone mineral density (BMD) of each specimen was assessed prior to POT. Statistical analysis showed that the incidence of correctly placed screws and non-critical pedicles breaches in axial plane was 78.3%, and 95.7% in sagittal plane. Hence, according to our definition of “critical” pedicle breach that exposes neurovascular structures at risk, 21.7% ($n = 5$) of all ATPS inserted showed a critical pedicle breach in axial plane. Notably, no critical pedicle perforation occurred at the C6 to T1 levels. Pull-out testing of ATPS and VBS revealed that pull-out

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resistance of ATPS was 2.5-fold that of VBS. Mean POS of 23 ATPS with a mean BMD of 0.566 g/cm^2 and a mean osseous screw purchase of 27.2 mm was 467.8 N. In comparison, POS of 22 VBS screws with a mean BMD of 0.533 g/cm^2 and a mean osseous screw purchase of 16.0 mm was 181.6 N. The difference in ultimate pull-out strength between the ATPS and VBS group was significant ($p < 0.000001$). Also, accuracy of ATPS placement in axial plane was shown to be significantly correlated with POS. In contrast, there was no correlation between screw-length, BMD, or level of insertion and the POS of ATPS or VBS. The study demonstrated that the use of ATPS might be a new technique worthy of further investigation. The use of ATPS shows the potential to increase construct rigidity in terms of screw-plate pull-out resistance. It might diminish construct failures during anterior-only reconstructions of the highly unstable decompressed cervical spine.

Keywords Cervical spine · Pedicle screw · Instrumentation · Accuracy · Pull-out strength

Introduction

The clinical interest in posterior cervical pedicle screw (pCPS) fixation increased after Abumi et al. [1] first introduced the concept and successfully applied it in more than 300 cases [2]. Since then, there has been increasing literature reporting on the ex vivo anatomic [3–13] and in vivo clinical feasibility [1, 9, 12, 14–20] of pCPS fixation. The cervical spine pedicles are very strong structural elements cortical in nature [21]. With pCPS fixation it is the cortical purchase of a pedicle screw that determines screw strength and pull-out force [22, 23]. Accordingly, transpedicular screw fixation provides greater resistance to pull-out than does lateral mass screw fixation [24–28] or screw fixation into the vertebral body [29]. The use of pCPS offers three-column rigid anchorage of implants [30, 31]. Hence, several biomechanical and clinical surveys demonstrated superior stabilization capabilities of transpedicular screw fixation for patients with poor bone quality, severe cervical spinal injury or degenerative and neoplastic multilevel instability, compared to anterior-only or common posterior lateral mass constructs [25–27, 29, 31–41]. In cases of thoracic and lumbar transpedicular fixation the incidence of improper pedicle screw placement is reported to be as high as 30%, and neurologic complications related to pedicle screw fixation range between 1.5 and 6% [5]. However, pCPS fixation has been considered inherently more risky than in the thoracic or lumbar spine and supposed to be technically more demanding, posing the potential risk of neurovascular injuries [12, 18]. Accordingly, anatomical variations in the size of the cervical pedicles and the risk of damaging the neurovascular structures limited the wide-spread application of pCPS. In

contrast, current work on the accuracy of pCPS insertion shows increased safety with the use of computer-assisted surgery [5, 6, 12, 16, 18], three-dimensional fluoroscopy (ISO-C-3D) [3, 42], and insertion of pCPS with screw diameter adapted to pedicle diameter [13], achieving correct pCPS placement in 90–100%. Although pedicle perforations with use of pCPS will never be reduced to zero and might cause temporary radiculopathy due to nerve root compression [1, 15, 20], or vertebral artery injury [1], almost all pedicle wall perforations reported in the literature occurred non-critically or were clinically silent [4, 6, 14, 17–19, 25]. The cervical pedicles seem to be tolerant to screw violation to some extent as many vertebral artery injuries (VAI) are asymptomatic [19, 43]. It is notable that spinal cord injury related to a malpositioned pCPS has never been reported [44].

In view of the increasing use of pCPS fixation with its biomechanical superiority and clinical success, the authors recently documented a significant number of clinical situations, including the multilevel decompressed cervical spine and other biomechanically challenging cervical spine disorders, that demand combined anterior-posterior stabilization or increased primary rigidity of the anterior-only fusion construct [21]. Conclusively, to enable increased stability with anterior-only constructs, the author described the concept of cervical Anterior Transpedicular Screw (ATPS) fixation [21]. The anatomical feasibility of ATPS insertion, its applicability within a rigid plate-screw system, as well as, the possible indications and merits of ATPS were proposed. As suggested in that publication, prior to clinical introduction of an ATPS-plate-system the accuracy with ex vivo insertions of ATPS with use of a manual technique has to be investigated prior to the use of computer-assisted or CT-based navigational surgery.

For the purpose of stabilizing the instrumented spinal section, the pull-out strength (POS) of screws is one of the most important indices of interest to both manufacturers and surgeons [45]. Accordingly, the biomechanical performance of ATPS also has to be investigated prior to clinical application. Therefore, this study was aimed at evaluating the accuracy of ex vivo manual insertion of ATPS and POS of ATPS compared to screws into the vertebral bodies.

Materials and methods

Laboratory setting

The first arm of the study consisted of the investigation of accuracy with manual insertion of ATPS. The second consisted of the biomechanical investigation of ATPS in terms of POS compared to screws in the vertebral body (VBS).

Six formalin-preserved cervicothoracic spines C0–T6 were harvested from four female and two male cadavers. Mean age of cadavers was 82 years (range 59–93 years). Specimens were subjected to assessment of Bone Mineral Density (BMD), measured in the antero-posterior and postero-anterior plane using dual-energy X-ray absorptiometry with a bone densitometer (Hologic QDR-4500 W, Waltham, MA). The averaged BMD of both scans was taken for statistical analysis. Mean BMD of all specimens was $0.553 \pm 0.094 \text{ g/cm}^2$ (range 0.399–0.694). To rule out any structural cervical pathology and to determine morphometry of the cervical vertebrae and pedicles intended for screw placement, the specimen were subjected to multi-slice computerized tomography (CT) scanning. The cervical spine CT-scans were performed on a 4-row helical CT scanner (SOMATOM Volume Zoom, Siemens/Germany) using a 14–18 cm field of view with $4 \times 1 \text{ mm}$ collimation and overlapping axial slice thickness of 1 mm. Sagittal reconstructions were performed using standard spine algorithms and files were stored digitally (PACS Magic View VC 42, Siemens, Erlangen/Germany). None of the specimens had evidence of infectious, neoplastic, or traumatic disease, nor congenital spinal deformations. However, all but one specimen showed advanced degenerative changes at least at three segments within C2–T1. Using the cursor digital CT measurements (0.1 mm increments) were performed on the reconstructed CT-scans in a commercially available software program (Escape Medical Viewer V3, Escape Thessaloniki, Greece). The authors measured anatomical parameters prior to ATPS for the purpose of referencing the anatomical dimensions entailed in our specimen compared to normalized data derived from a healthy population [21]. The definition of parameters measured and the technique of measurements have been previously reported [21]. The description and results of the measurement process are illustrated in Tables 1, 2, 3.

Accuracy of ATPS insertion

Following CT measurements, the cadaver specimens were subjected to manual insertion of ATPS and VBS, which was performed at the university's anatomical institute. The specimen was fixed to a dissection table. For manual insertion of ATPS and VBS, standard C-arm fluoroscopy was used. The diameter of self-tapping titanium cannulated cortical screws used was 3.5 mm consistently (Synthes, Salzburg/Austria). Diameter of ATPS used was not matched to the individual pedicle dimension. For the purpose of pull-out testing (POT) after insertion of ATPS, all screws had a length of 50 mm. The total of six specimens enabled screw placement in a total of 36 vertebrae from

Table 1 Description of anatomical parameters measured

Parameter	Measurement	Description
IOPW	Left outer pedicle width	Distance medial border of transverse foramen to medial border of pedicle
rOPW	Right outer pedicle width	
IOPH	Left outer pedicle height	Distance upper to lower pedicle surface in sagittal plane
rOPH	Right outer pedicle height	
ltPA	Left transverse pedicle angle	Angle formed between transverse pedicle axis and mid-sagittal line
rtPA	Right transverse pedicle angle	
lsPA	Left sagittal pedicle angle	Angle formed between plane of anterior vertebral body wall at mid-sagittal line and sagittal pedicle axis
rsPA	Right sagittal Pedicle Angle	
ltIP	Left transverse intersection point	Transverse intersection point of transverse pedicle axis with anterior vertebral body wall
rtIP	Right transverse intersection point	
DltIP	Distance left transverse intersection point	Distance between transverse intersection point and mid-sagittal line at the anterior vertebral body wall at each cervical level C3–T1
DrtIP	Distance right transverse intersection point	
lsIP	Left sagittal intersection point	Sagittal intersection point of sagittal pedicle axis with anterior vertebral body wall
rsIP	Right sagittal intersection point	
DlsIP	Distance left sagittal intersection point	Distance between sagittal intersection point and cephalad endplate at each cervical level C3–T1
DrsIP	Distance right sagittal intersection point	

C3–T1. As the current pilot-study of ATPS also aimed at comparing POS of ATPS and VBS, the cervical vertebrae C3–T1 were randomly assigned to undergo ATPS or VBS insertion for the purpose of building comparable sample sizes. The VBS were randomly assigned in a pair wise fashion to spinal levels between C3 and T1. The VBS were placed traversing the vertebral body without contact of screw threads or tips within or beyond the vertebral cortices. The insertion of VBS aimed to achieve longest screw purchase through triangulation of screw trajectories with about 10 mm distance between the screws. Each vertebral body accommodating a pair of VBS was randomly assigned to get the first screw on the left or right side, and vice versa. ATPS were randomized to the left or right side in adjacent cervical vertebrae. Overall, the study protocol enabled placement of 24 ATPS and 24 VBS. Each vertebra

was selected randomly to undergo ATPS or VBS insertions in a fashion that each group achieved the same number of screws placed at each cervical level. According to the algebraic distributions of ATPS and VBS within six cervical levels C3–T1 and with a ratio of 1:2 screws (ATPS:VBS) per each adjacent vertebra level instrumented, the number of screws placed at all cervical levels differed in both groups (ATPS: $4 \times C3$, $4 \times C4$, $5 \times C5$, $4 \times C6$, $4 \times C7$, $2 \times T1$; VBS: $4 \times C3$, $4 \times C4$, $2 \times C5$, $4 \times C6$, $4 \times C7$, $6 \times T1$).

Technique of ATPS insertion

The anatomical and technical considerations of inserting ATPS and pCPS have been discussed in a previous report [21]. In the current study, all screws were inserted by the same surgeon (H.K.). The specimens were placed in supine position. The cervical spines were approached anteriorly with the lateral and posterior elements covered by the neck muscle envelope. At the anterior part of the cervical spine, the longitudinal muscles were bluntly removed laterally.

At first, a multiplanar fluoroscope was set to obtain an exact AP and lateral view of the cervical spine, and the mid-sagittal line of the vertebral body to be instrumented was marked. Next, a 1.2 mm diameter k-wire was placed approximately at that part of the anterior cortex of the selected cervical vertebra according to prior morphometric measurements of DltIP/DrtIP and DlsIP/DrsIP (Table 2). These CT-based measurements resemble the distances between the intersecting points of the projected pedicle axes, in both the transverse and sagittal plane, onto the

Table 2 Distances of sagittal and transverse intersection points C3–T1 in all specimen

Level	DlsIP Mean $\pm$ SD (range)	DrsIP Mean $\pm$ SD (range)	DltIP Mean $\pm$ SD (range)	DrtIP Mean $\pm$ SD (range)
C3	2.28 ± 0.90 1.19–3.72	2.00 ± 1.62 0.27–4.84	4.25 ± 1.24 2.14 to 5.61	3.76 ± 1.38 2.09 to 5.64
C4	2.37 ± 1.08 1.25–3.79	2.36 ± 1.22 1.59–4.84	3.26 ± 1.54 1.26 to 5.47	3.54 ± 1.26 1.26 to 4.58
C5	3.60 ± 2.17 1.45–7.35	3.85 ± 1.56 1.99–6.66	1.70 ± 4.83 –4.91 to 6.04	1.60 ± 3.95 –3.27 to 5.82
C6	4.02 ± 1.50 2.18–6.27	4.10 ± 1.28 2.26–5.82	1.02 ± 3.33 –3.35 to 5.25	0.73 ± 3.46 –4.19 to 5.56
C7	4.05 ± 1.31 2.32–5.19	3.95 ± 0.95 2.39–5.09	$–2.32 \pm 4.35$ –8.23 to 2.25	$–1.85 \pm 4.12$ –8.5 to 2.63
T1	4.98 ± 1.02 3.54–6.57	4.54 ± 0.99 3.79–6.41	$–3.44 \pm 5.27$ –9.29 to 3.38	$–3.95 \pm 5.00$ –9.61 to 3.79

Table 3 Morphometrical measurements of pedicle anatomy C3–T1 in all specimen

Level	ltPA Mean $\pm$ SD (Range)	rtPA Mean $\pm$ SD (Range)	lsPA Mean $\pm$ SD (Range)	rsPA Mean $\pm$ SD (Range)	LOPH Mean $\pm$ SD (Range)	roPH Mean $\pm$ SD (Range)	OPH Mean $\pm$ SD (Range)	IOPW Mean $\pm$ SD (Range)	ROPW Mean $\pm$ SD (Range)	OPW Mean $\pm$ SD
C3	47.18 ± 3.64 43.9–53.6	45.38 ± 2.88 42.0–49.4	96.42 ± 4.66 89.2–102.9	91.68 ± 6.82 80.7–99.2	4.98 ± 0.61 4.12–5.96	5.39 ± 0.71 4.91–6.82	5.18 ± 0.67 4.2–5.09	4.74 ± 0.32 4.2–5.09	4.69 ± 0.32 4.3–5.02	4.71 ± 0.1
C4	49.47 ± 3.63 43.5–51.7	48.17 ± 3.81 44.9–48.6	97.75 ± 3.28 95.1–102.5	96.08 ± 6.43 91.7–106.4	5.07 ± 0.53 4.12–5.59	5.30 ± 0.40 4.91–5.87	5.18 ± 0.46 4.2–5.39	4.87 ± 0.41 4.2–5.39	4.64 ± 0.63 3.85–5.52	4.76 ± 0.52
C5	49.2 ± 5.08 41.3–54.1	48.5 ± 5.81 37.6–53.7	101.95 ± 13.36 88.8–127.2	104.02 ± 13.43 88.0–127.4	5.12 ± 0.36 4.53–5.46	5.20 ± 0.50 4.27–5.64	5.16 ± 0.42 4.08–5.61	5.18 ± 0.60 4.08–5.61	5.67 ± 0.64 4.77–6.58	5.64 ± 0.65
C6	45.15 ± 4.73 35.5–49.1	44.13 ± 4.82 37.0–48.7	103.93 ± 4.73 97.3–108.6	102.22 ± 8.43 89.3–108.5	4.83 ± 1.01 3.16–6.25	5.25 ± 0.09 3.26–6.31	5.04 ± 0.93 4.56–6.87	5.52 ± 0.79 4.56–6.87	5.75 ± 0.25 5.28–5.98	5.63 ± 0.57
C7	36.73 ± 5.05 28.5–43.1	37.9 ± 5.79 27.8–41.5	96.05 ± 5.23 89.7–103.8	95.23 ± 6.26 90.2–106.1	5.53 ± 0.68 4.64–6.57	5.17 ± 0.68 3.87–5.41	5.35 ± 0.68 5.14–8.02	6.33 ± 1.11 5.14–8.02	6.78 ± 0.66 6.00–7.64	6.55 ± 0.90
T1	30.98 ± 4.38 25.5–36.0	29.65 ± 5.62 23.5–36.7	100.05 ± 4.88 90.8–104.5	99.93 ± 5.72 90.6–106.1	7.77 ± 0.81 6.51–8.70	7.11 ± 0.98 5.94–8.58	7.44 ± 0.93 6.49–9.98	8.24 ± 1.49 6.49–9.98	8.17 ± 1.36 6.63–9.83	8.20 ± 0.39

anterior vertebral cortex and the vertebral mid-sagittal line (for DltIP/DrtIP) and the cephalad edge of the vertebra (for DlsIP/DrsIP), respectively. Thus, the measurements aid with templating the approximated entrance points for a k-wire into the cervical pedicles in both the transverse and sagittal plane [21]. Next, we applied the technique using the “fluoroscopic ped axis view” as used with pCPS insertion [13, 20]. On the other hand, the appropriate real-time orientation of the entrance point and the screw track for the k-wire, respectively, was verified using C-arm fluoroscopic axial pedicle and oblique pedicle views (true AP and true lateral images of the pedicle, Fig. 1). For the “true AP view” the fluoroscope was turned until it depicted the approximate circle of the pedicle cortex wall in the transverse plane of the vertebral body, setting the axis of rotation to cervical longitudinal axis. For the ‘true lateral view’ the fluoroscope was turned until its beam was perpendicular to the longitudinal axis of the pedicle in sagittal plane. Finally, the tracking process for the k-wire was initiated in the transverse AP-direction with the k-wire tip matched with the pedicle centre. The pedicle angulations

measured in transverse and sagittal planes on CT-scans (Table 3) supported in tracking the three-dimensional plane for k-wire insertion. If the k-wire matched a track along the bisector line of the pedicle cortices in sagittal plane, that is approximately parallel to the upper vertebral endplates in the sagittal plane as verified with the true-lateral view, the k-wire was advanced forward under fluoroscopic control outside the corresponding lateral mass. The accuracy of the created trajectory was confirmed on both fluoroscopic “true AP” and “true lateral pedicle axis views”. In the normal lateral view of the cervical spine, we also controlled the tip of the k-wire. If it was located outside a pedicle margin prior to reaching the pedicle base, it was reorientated. A cannulated 2.5 mm power drill bit was used after the trajectory was determined by the placed k-wire. This was followed by placement of a 3.5 mm diameter self-tapping screw.

With the insertion of VBS, each screw was placed triangulated under fluoroscopic control in order to achieve maximum osseous purchase without contact of screw threads or tips.

Fig. 1 **a** sketches the planes of pedicles axis that have to be reconstructed using the X-ray beam perpendicularly aligned. **b** depicts perpendicular projection of two ATPS in transverse and sagittal plane. **c** shows CT slice with correct placement of corresponding ATPS. Lateral screw threads merged with medial border of transverse foramen according to a Grade 1 screw placement

Assessment of accuracy of ATPS inserted

Following screw placement, the cervical spines C3–T1 were harvested en block from the cadavers. One ATPS into a C3-pedicle became loose during harvesting and thus was removed from the accuracy part of the study. Hence, 23 ATPS remained. Using the same initial scanning protocol, postprocedural CT-images were acquired to ensure anatomic integrity. Axial and reconstructed sagittal images were assessed for accuracy of manual insertion of ATPS and position of VBS. Grading of the ATPS positions was performed with modified criteria derived from previously used classifications [10, 11, 17, 19, 20]. The modified classification scheme was applied both in the axial and sagittal planes and defined screw positions as follows:

Grade 1: Screw centred in the pedicle, at most causing only minor plastic deformation of the pedicle cortex.

Grade 2: Screw threads less than one-third of the screw cross section (<1.2 mm with a 3.5 mm diameter screw) penetrating the cortex.

Grade 3: Between one-third and one-half of the screw cross section penetrating the cortex (or deviation less <2 mm).

Grade 4: More than one-half of the screw cross section penetrating the cortex (or deviation ≥ 2 mm).

Grade 5: Deviation equal to or more than screw diameter.

With results reported, non-critical pedicle breaches were determined as such with Grade 1 and Grade 2 screw position. Critical pedicle breaches with the potential for posing risks to the vertebral artery (VA), nerve root or dural sac were determined as those with a Grade 3–5 screw position. With a new proposed score (Table 4), assessment of pedicle screw position was made both in the axial and sagittal planes with each one point assigned to each of the

five grades of screw position. Finally, the accuracy score in axial plane (range, 1–5 points) and the accuracy score in sagittal plane (range, 1–5 points) was summed up and described as the accuracy sum score with its maximum being 10 points and the minimum being 2 points.

Prior to POT each of the C3–T1 vertebrae was isolated from the cervical spine segments and all muscles were removed leaving the ligaments and facet capsule attached. Overall, three vertebrae had to be discarded prior to further study. One C7-pedicle screw and vertebra, respectively, were excluded from POT because the vertebral body fractured during the removal of the partially ossified adjacent disc. The aforementioned C3-vertebra was already discarded prior to postoperative CT scanning. One VBS at C6 had to be excluded because of screw loosening during the soft-tissue removal. As depicted in the CT-scans, no VBS had to be discarded because of screws contacting each other within the same vertebrae. For completeness, the morphometrical characteristics and differences concerning the means of Outer pedicle height (OPH), Outer pedicle width (OPW), and Distance Sagittal/Transverse Intersection Point (DsIP/DtIP) of those vertebrae included into final calculations are templated separately for the original cohort (Tables 2 and 3) and the vertebrae included into the assessment of accuracy and biomechanical POT (Table 5). Examples of ATPS insertion and assessment of accuracy are given in Figs. 2 and 3.

Assessment of pull-out strength

The ATPS and VBS, both 50 mm in length, extended out through the vertebral cortices following insertion. The total working length of screw available for bony purchase within the pedicle, lateral mass, and the vertebral body was measured using callipers with 0.1 mm increments. The

Table 4 Assessment score for cervical transpedicular screw placement. Accuracy of manual insertion of ATPS C3–T1 in 23 cervical vertebrae

	Axial plane Grade 1	Axial plane Grade 2	Axial plane Grade 3	Axial plane Grade 4	Axial plane Grade 5	Axial plane total score	Sagittal plane Grade 1	Sagittal plane Grade 2	Sagittal plane Grade 3	Sagittal plane Grade 4	Sagittal plane Grade 5	Sagittal plane total score	Total Score
Level	N	N	N	N	N	Mean	N	N	N	N	N	Mean	Mean Range
C3	-	1	-	2	-	3.34	2	1	-	-	-	1.34	4.67 3-6
C4	1	3	-	-	-	1.75	3	1	-	-	-	1.25	3.0 2-4
C5	1	1	2	-	1	2.8	2	2	-	-	1	2.2	6.0 3-10
C6	2	2	-	-	-	1.5	2	2	-	-	-	1.5	3.0 2-4
C7	4	-	-	-	-	1.0	3	1	-	-	-	1.25	2.25 2-3
T1	2	1	-	-	-	1.34	2	1	-	-	-	1.34	2.67 2-3
Total	10	8	2	2	1	1.96 1-5	14	8	0	0	1	1.52 1-5	3.48 2-10
	18 (78.3%)		5 (21.7%)				22 (95.7)		1 (4.35%)				
	Non-critical		Critical				Non-critical		Critical

Fig. 2 **a** and **b** intraoperative radiographs with placed k-wire at C5 and orthograde projection of ATPS at C4. Postoperative axial CT-slices demonstrate correct placement of ATPS assigned as Grade 1 placement. **d** demonstrates halo around screw threads, which might

decrease the accuracy or overestimate slight pedicle breaches in CT-scans. Asterisk mark VA in transverse foramen; right filled arrow medial margin of dural sac

Fig. 3 **a** and **b** depict intraoperative radiographs delineating the technique of tracking and inserting the k-wires for placement of cannulated 3.5 mm ATPS in to the left C6 pedicle. Postoperative sagittal and axial CT-slices **c–f** show correct placement of ATPS into

C4 and C6 pedicles in axial plane (**f**, Grade 1 screw placement) with the C4 screw resembling a Grade 2 placement in sagittal plane, that is a noncritical breach (fig. **c–e**). right filled arrow upper and lower margins of C5 nerve root

“screw length” was defined as the actual working length, in other words, only the millimeters of thread engaging bone. A special jig with several spikes was designed to firmly grip each disarticulated vertebra. The jig was attached to a material testing machine (Z010, Zwick Roell, Ulm/Germany, Fig. 4). The screw length of 50 mm provided for the placement of the screw’s head to be about 10 mm clear to allow for attachment to the material testing machine with the coupling device attached in a manner to fit around the screw head and to produce a force collinear to the longitudinal axis of the screw. A sum of 22 VBS and 23 ATPS was subjected to POT. As VBS were placed in a pair wise fashion with alternating order to the left and right, each vertebra served as its own internal control. The VBS inserted first underwent POT at first instance. All screws were pulled out at a rate of 5 mm/min. In each test, the load-displacement curve was recorded using a computerized data collection system (TestXpert V11.02, Zwick Roell, Ulm/Germany). Load and displacement data were taken continuously until the screw had been visibly removed from the vertebral body (usually about 10 mm). The peak load-to-failure was measured in Newtons. Finally, with each test the mode of failure, i.e. shear versus fracture was noted.

Statistical analysis

All statistical analyses were performed by one of the authors (W.H.). Pearson’s Chi-Square test was done to

Fig. 4 Arrangement for biomechanical assessment of uniaxial pull-out testing of both ATPS and VBS

Table 5 Differences in morphometrical characteristics of vertebral anatomy in assessment of accuracy (ACC) and pull-out-testing (POT)

Level	OPH (POT)	OPH (ACC)	OPW (POT)	OPW (ACC)	DsIP (POT)	DsIP (ACC)
	Mean $\pm$ SD Range	Mean $\pm$ SD Range	Mean $\pm$ SD Range	Mean $\pm$ SD Range	Mean $\pm$ SD Range	Mean $\pm$ SD Range
C3–T1	5.45 $\pm$ 0.91	5.47 $\pm$ 0.89	5.84 $\pm$ 1.22	5.92 $\pm$ 1.25	3.42 $\pm$ 1.69	3.49 $\pm$ 1.69
	3.62–7.56	3.62–7.56	4.3–8.91	4.3–8.91	0.27–6.66	0.27–6.66

analyze cross tables. In addition, correlative (Pearson's and Spearman's correlation coefficient) and linear regression analyses were applied, as well, as two-sided *t*-tests and ANOVA with post hoc testing to analyze data sample. Statistical significance was established at $p < 0.05$. All computations and illustrations were performed using Statistica 6.1 (StatSoft, Tulsa, OK).

Results

Morphological characteristics of cadaver specimen

Means, standard deviations and ranges of anatomical parameters measured in the six harvested spines, such as OPW and OPH, were within physiological ranges according to the previously published data of healthy subjects (Tables 2 and 3) [21]. The measurements were located at the lower percentiles of the physiological range, closely resembling the dimensions found with direct morphological ex vivo measurements [21].

The percentages of all pedicles with an OPW of <4.5 mm, 4.5–5.0 mm, and >5.0 mm were 13% ($n = 9$), 14% ($n = 10$), and 74% ($n = 53$), respectively. The percentages of all pedicles with an OPH of <4.5 mm, 4.5–5.0 mm, and >5 mm were 8% ($n = 6$), 13% ($n = 9$), and 79% ($n = 57$), respectively. Calculations for differences between left and right cervical pedicles failed to reach statistical significance ($p = 0.69$). The ANOVA model showed that there was a positive relation between increasing OPW and the cervical levels with the OPW increasing from cephalad C3 to caudad T1 ($p < 0.0002$). With OPH, there was a positive correlation with a significant increase from C6 to T1 ($p < 0.027$).

Accuracy

Overall, 23 cervical pedicles were instrumented using ATPS and included in the accuracy calculation. In this group, the percentage of OPW <4.5 mm was 8.7% ($n = 2$); 4.5–5.0 mm, 13.0% ($n = 3$); >5.0 mm, 78.3% ($n = 18$) (Table 6). Morphologic characteristics of pedicles instrumented (Table 5) were similar to the means of all cadaver spine, so are a representative sample (Tables 2 and 3).

Table 6 The frequency of pedicle breaches in axial plane according to Grade 1–5 if calculated for OPW

Axial accuracy	OPW			% of all screws
	<4.5 mm	4.5–5.0 mm	>5.0 mm	
Grade 1	0	0	10	10
Total (%)	0.00	0.00	43.48	43.48
Grade 2	1	1	6	8
Total (%)	4.35	4.35	26.09	34.78
Grade 3	0	1	1	2
Total (%)	0.00	4.35	4.35	8.70
Grade 4	1	0	1	2
Total (%)	4.35	0.00	4.35	8.70
Grade 5	0	1	0	1
Total (%)	0.00	4.35	0.00	4.35
% of all screws	8.70	13.04	78.26	100.00

Statistical calculations using Pearson's Chi-Square test depicted that there was a significant correlation between accuracy in axial plane and the increasing OPW in terms of the three above formed groups ($p = 0.038$). In other words, with increasing pedicle size there is a higher accuracy rate. Those pedicles with OPW >5 mm showed correct placement and noncritical perforations assigned as Grade 1 and 2 in 89% of ATPS (Table 6). Similarly, there was a significant correlation between increasing accuracy in sagittal plane and an increased OPH of 4.5–5.0 mm and >5 mm ($p = 0.021$).

With the proposed score to assess pedicle screw placement (Table 4), the mean accuracy in axial plane was scored as 1.96 points (range 1–3.3), and 1.52 (range 1–5) in sagittal plane. The accuracy sum score showed a mean of 3.48 points (range 2–10) with a possible total of 10 points. Figure 5 reveals that the incidence of non-critical pedicle breaches in axial plane was 78.3 and 95.7% in sagittal plane. Hence, according to our definition of any 'critical' pedicle breach that poses neurovascular structures at risk, 21.7% ($n = 5$) of all ATPS inserted showed a critical pedicle breach in axial plane, and 4.4% ($n = 1$) in sagittal plane. Notably, critical breaches were observed only at the C3–C5 levels with the smaller OPW and OPH in average, both in axial and sagittal planes (Table 3). The overall percentage of critical pedicle perforation in axial plane at

distinct cervical levels C3–T1 was 8.7% at C3, 0% at C4, 13.0% at C5, and 0% at C6 to T1. The mean pedicle width for correctly placed ATPS and non-critical perforations was 5.1 ± 0.8 mm, whereas, it was 6.1 ± 1.3 mm for critical perforations.

Statistical calculations using Spearman-Rank-Test demonstrated that there was no significant correlation between accuracy in the axial plane and OPH ($p = 0.26$), accuracy in the axial plane and DsIP ($p = 0.28$), accuracy in the sagittal plane and OPH ($p = 0.48$), accuracy in the sagittal plane and both OPH and OPW, respectively ($p = 0.48$ and $p = 0.18$), accuracy in sagittal plane and DsIP ($p = 0.90$), accuracy in sagittal plane and the product of [OPH $\times$ OPW] ($p = 0.23$), accuracy sum score and OPH ($p = 0.47$), and accuracy sum score and DsIP ($p = 0.57$). However, there was a strong negative correlation between accuracy in the axial plane and OPW ($p < 0.0001$, $r = -0.67$), accuracy in the axial plane and the product of [OPH $\times$ OPW] ($p = 0.026$, $r = -0.46$), as well as, accuracy sum score and OPW ($p = 0.001$, $r = -0.64$). These findings indicate that the OPW has a significant impact on accuracy in axial plane. In particular, the square diameter of the pedicle canal in terms of the product [OPH $\times$ OPW] was shown to be a valuable new parameter to be investigated in the assessment of accuracy with cervical pedicle screw placement. Furthermore, statistical calculations depicted that there was no correlation between the accuracy sum score and the distinct cervical levels (C3 to T1) instrumented ($p = 0.06$). Although the author experienced a distinct learning curve and comfort with increasing number of ATPS inserted, statistical analysis did not reveal significant correlations between the order of ATPS instrumented and the accuracy sum score ($p = 0.95$).

The author's definition of a critical breach was arbitrarily set, but erring on the side of caution, with most breaches identified unlikely to cause harm to the VA or spinal cord. Statistically significant correlations between distinct accuracy scores in sagittal plane did not exist,

which was shown to be a factor of an overall limited sample size and small number of critical pedicle perforations in the sagittal plane ($n = 1$). Concerning the risk of exposing the VA and spinal cord to injury, postoperative fine-cut CT-scanning depicted that in all but one case (92.3%, $n = 12$) pedicle perforations occurred laterally. With one screw, the VA was definitely injured. With the other perforating ATPS, harm to the VA was not suggested as far as it could be seen in the CT-sections (Figs. 2 and 3) and proven by anatomical dissection in two cases. Only once, a Grade 1 breach occurred medially without endangering the spinal cord. The only critical breach in the sagittal plane occurred inferiorly, with the noncritical breaches (88.9%, $n = 8$) equally distributed cranially and caudally (Fig. 3).

Biomechanical evaluation

Following exclusion of damaged vertebrae and pedicles, or loosened screws during harvesting of the cervical vertebrae, 23 ATPS and 22 VBS remained for assessment of POS. During POT, mode of failure for ATPS and VBS was observed as a shear fracture of the screw through the vertebral bone in each case. Tables 7 and 8 depict the characteristics of POT in both groups. Table 9 (electronic supplementary material) puts results into comparison with data reported in the literature (electronic supplementary material). Mean POS of 23 ATPS with a mean BMD of 0.566 g/cm^2 and a mean working length of 27.2 mm was 467.8N. In comparison, POS of 22 VBS screws with a mean BMD of 0.533 g/cm^2 and a mean working-length of 16.0 mm was 181.6N. The difference in ultimate pull-out strength between the ATPS and VBS group was significant ($p < 0.000001$, Fig. 5). POS of VBS was 38.8% of ATPS. Hence, in the current study, 3.5 mm diameter ATPS showed a statistically significant increased POS compared to screws in the vertebral bodies.

Table 7 Characteristics of pull-out testing of vertebral body screws C3–T1

Level	Screws tested <i>N</i>	Mean $\pm$ SD	Pull-out strength (Newton) Min	Max	Mean $\pm$ SD	
					BMD (g/cm^2)	Length of osseous screw purchase (mm)
C3	4	156.90 ± 94.13	48.09	269.01	0.571 ± 0.058	13.03 ± 2.28
C4	4	168.32 ± 110.10	51.37	287.79	0.546 ± 0.170	16.38 ± 1.50
C5	2	313.0 ± 15.49	302.07	323.97	0.524	16.25 ± 5.09
C6	3	174.94 ± 52.20	133.24	233.48	0.441 ± 0.072	14.67 ± 1.07
C7	4	192.57 ± 65.46	128.75	266.42	0.624 ± 0.081	16.13 ± 1.82
T1	6	158.94 ± 73.74	30.98	221.53	0.566 ± 0.191	18.23 ± 2.35
Total	23	181.55 ± 82.57	30.98	323.97	0.533 ± 0.095	16.0 ± 2.53

Table 8 Characteristics of pull-out testing of ATPS C3–T1

Level	Screws tested <i>N</i>	Mean $\pm$ SD	Pull-out strength (in Newton) Min	Max	Mean $\pm$ SD	
					BMD (g/cm ²)	Length of osseus screw purchase
C3	3	412.26 $\pm$ 67.19	337.9	468.62	0.591 $\pm$ 0.090	28.52 $\pm$ 3.50
C4	4	471.99 $\pm$ 148.99	258.21	650.45	0.555 $\pm$ 0.047	26.70 $\pm$ 1.14
C5	5	438.71 $\pm$ 102.26	288.34	570.20	0.558 $\pm$ 0.111	28.34 $\pm$ 5.29
C6	4	500.36 $\pm$ 177.08	316.05	704.02	0.598 $\pm$ 0.076	27.53 $\pm$ 6.71
C7	3	593.89 $\pm$ 31.89	566.34	628.83	0.556 $\pm$ 0.057	27.70 $\pm$ 4.04
T1	3	396.95 $\pm$ 31.85	360.2	416.54	0.539 $\pm$ 0.148	21.95 $\pm$ 2.06
Total	22	467.83 $\pm$ 125.76	258.21	704.21	0.566 $\pm$ 0.084	27.20 $\pm$ 4.37

Fig. 5 Statistically significant superior pull-out resistance of ATPS compared to VBS, templated for each cervical level instrumented C3–T1 ($p < 0.000001$).

Concerning the usage of ATPS, statistical analysis revealed that there was no correlation between POS and BMD ($p = 0.72$), POS and screw-length ('osseous screw purchase', $p = 0.23$), POS and OPW or OPH of cervical pedicles instrumented ($p = 0.75$ and $p = 0.45$), POS and DsIP ($p = 0.71$), or POS and the product of [OPH $\times$ OPW] ($p = 0.86$). In addition, no correlation was found if calculation of POS was separated for each level instrumented C3–T1 ($p = 0.44$). However, there was a positive correlation between the accuracy of ATPS inserted in axial plane ($p = 0.007$, $r = -0.55$), as well as, the accuracy sum score ($p = 0.012$, $r = -0.53$) and the resistance to pull-out of ATPS. Due to the small number of critically misplaced screws in the sagittal plane the correlative analysis between POT and accuracy in sagittal plane failed to reach statistical relevance ($p = 0.13$).

Concerning POS of VBS, no significant correlation between POS and BMD was found ($p = 0.057$). Neither existed a significant correlation if POS was calculated for screw-length ($p = 0.996$), nor if calculations were

performed for each cervical level instrumented C3–T1 ($p = 0.31$). Regression analysis was performed adjusting screw-length for BMD, but did not show significant correlation between screw-length and POS with the use of VBS. In general, screw-length in terms of osseous working length did not have a significant impact on both VBS and ATPS if calculated separately. To assess the influence of the order of screw pull-out at each single vertebra undergoing insertion of two VBS, pull-out was performed alternately with the left or right screw first. Statistical analysis revealed that there was no influence on pull-out resistance whether the right or the left VBS was pull-out at first or second ($p = 0.47$).

Discussion

Pedicle perforations with pCPS fixation cause major concerns due to the potential risk of neurovascular injury. Therefore, the first objective of the current study had to be the investigation of accuracy of ATPS placement using a manual, fluoroscopically assisted technique.

Technical concerns with ATPS insertion

Successful placement of pCPS and ATPS requires the accurate identification of the pedicle path. Therefore, the author applied a technique similar to that of Yakawa et al. [20] and Roh et al. [13] used for pCPS insertion. Pedicle axis views (true AP views) were obtained using fluoroscopy to match the tip of a k-wire with the screw entry point and pedicle orientation. True lateral radiographs of the pedicle were obtained to enable tracking of the k-wire in sagittal plane. For the true AP view, the X-ray beam is angulated with reference to the sagittal plane and the pre-operatively assessed tPA and sPA, to make it centered with the longitudinal pedicle axis. For the true lateral view, the

X-ray beam is angulated with reference to the coronal plane and the preoperatively assessed tPA and sPA, to make it perpendicular to the pedicle [10, 46]. With pCPS insertion, techniques for the identification of the pedicle entry points and instrument tracking included the assessment of anatomical landmarks and measures at the lateral mass surfaces [4, 8, 11, 47], the use of laminoforaminotomies [8, 10], the funnel technique [6], using a pedicle locator device [9, 11], the Abumi technique [1, 17, 19, 48] or computer-assisted navigation [3, 5, 8, 12, 13, 16, 18, 42]. With the first time investigating insertion of ATPS, the combination of anatomical measurements (DltIP/DrtIP and DlsIP/DrsIP) and the technique with obtaining a ‘true AP’ and ‘true lateral view’ of the pedicles was found valuable defining entry points at the anterior vertebral cortices and tracking of the k-wire during its advancement. Theoretically, similar to the laminoforaminotomy technique it would be possible to define the pedicle orientation using a fine probe advanced through a disc space towards the pedicle base. Also, as with the Abumi technique, opening of the pedicle entrance using a fine probe resembles a conceivable alternative. However, we sought to explore the accuracy of ATPS using a simple, morphologically based technique supplemented with fluoroscopy first. The technique demonstrated can serve as a benchmark for ongoing laboratory studies using refined techniques, including CAS.

The k-wire inserted prior to drilling, and the insertion of cannulated pedicle screws reduce the risk of screw malpositioning and lateral breakouts of the screws from the pedicles [12]. In the current study, during controlled advancement of k-wires the tunnel-like opening of the pedicle-vertebral junction could be felt with the tip of the k-wire jamming against the cortical boundaries of the pedicle base if not centered onto the pedicle canal. In addition, using the ‘true AP view’ and a plain lateral fluoroscopic view, reorientation of the k-wire was performed if its tip outreached the cortical pedicle boundaries prior to achieving the pedicle-vertebral junction. Thus, redirectioning was facilitated if radiographs were indicated. Nevertheless, pedicle breaches occurred laterally in all but one instance. Similarly, with pCPS lateral perforation of the pedicles was reported more common than medial and the predilection often attributed to the thinner lateral pedicle base and wall [4, 8, 14, 17, 19, 20]. A technical problem for pCPS insertion is the marked convergence of the screws which ranges (30°–50°) and paravertebral muscles that can hinder the maintenance of an adequate insertion angle, tending to push the instruments medially deviating their tips laterally [15, 17], thus increasing the risk for lateral breach. With the ATPS, insertion is not hindered by soft-tissue pressure because ATPS at the cephalad and caudad level of a conceivable screw-plate construct into the left pedicles and is sought to be placed through a right-sided

approach and vice versa [21]. A previous study showed the even bilateral placement of anterior transarticular screws at C1-2 [49], that demands acute insertion angles, was successful. Hence, the transverse angulations (Table 3) of left or right pedicles for, i.e., k-wire insertion are not sought to resemble serious problems within its clinical use.

Assessment of accuracy

A large variation in reported accuracy may exist partly due to the lack of consensus in which range pedicle screw placement accuracy is considered satisfactory [50]. A literature review by the authors (Table 10, electronic supplementary material) demonstrated that the accuracy of pCPS placement in sagittal plane was not continuously assessed using sagittal CT-reconstructions [17, 19, 20]. As concerns the relevancy of pedicle perforation, it is notable that there is no unanimity with grading its severity. The non-uniformity in defining a “major”, “critical” or “complete” pedicle perforation and breach, respectively, denoting the potential for neurovascular injury, deserves attention. Critical pedicle breaches were determined as risk of neurovascular injury with the pCPS breaching the pedicle wall and with >50% of pCPS diameter located outside the pedicle [15, 19, 20]; deviating more than 2–4 or 4 mm at all from the pedicle [17]; encroachment of the VA canal of >25% [15]; and “threatening” or frank injury to the spinal cord, VA, and nerve roots [6, 8, 10, 14, 15, 19]. For the purpose of detailed and reproducible reporting of accuracy, the authors tended to analyse accuracy using a new CT grading scale, as previous classifications [10, 11, 17, 19, 20] were judged incomplete for benchmark purposes.

Concerning the accuracy with insertion of ATPS and pCPS, the authors sought that a numerical system with a descriptive analysis supporting taxonomy (noncritical vs critical pedicle breach) during its clinical application is appropriate. The proposed scoring system allows for assessment of accuracy in axial and sagittal planes and it takes into account the morphometrical deviation of any pedicle screw from the cortical pedicle boundaries according to the diameter of screw. The latter might be more appropriate with *in vivo* studies using post-insertional CT-scans. Morphometrical analysis (measurement in ‘millimeters’) might be more useful with *ex vivo* studies using direct visualization of the pedicle perforations. According to the scoring system, the evidence of any of the 5 distinct grades of pedicle screw placement is assigned 1–5 points both in axial and sagittal planes. The accuracy sum score is calculated from both the results of the sagittal and axial plane assessment. In the current study, the mean accuracy sum score in axial plane was 1.96 with a possible minimum of 1 and maximum of 5. The proposed score

allows for comparison of upcoming studies concerning the use of pCPS and ATPS.

Postoperative CT-scanning is recommended to assess malplacement of pCPS [51], although CT sometimes tends to be overly sensitive to screw malposition [52] and there is a certain error in evaluating screw perforation using CT-scans [51] because the CT scanning produces a metal artefact around screws, sometimes exaggerating the screw outline [16, 20]. Hence, in the current study alike previous ones [17, 20, 51] it was difficult to grade some of the pedicle screw locations exactly, particularly in the sagittal CT-reconstructions and if the pedicle wall was obscured by halation of the screw or the screw itself. Therefore, according to Neo et al. [17], the grade of misplacement was determined with reference to adjacent CT sections, the distance between the screw and the contralateral pedicle wall, and the transverse angle of the screw. For example, when the screw was in contact with the cortex of the transverse foramen or the spinal canal in axial plane, and the transverse angle of the screw was acceptable; the screw was classified as Grade 1 (correct placement), even if the cortex of the transverse foramen or the pedicle–vertebral junction was unclear. Obviously, this grading is more or less subjective. But, deviations from the pedicle judged as ‘critical’ were determined with an obvious cut-off, although the definition of critical breaches was arbitrary. To refine definition of critical breaches studies on the ‘vertebral artery-to-pedicle distance’ are indicated and under construction.

Accuracy of ATPS insertion

According to our review of articles (Table 10) delineating pedicle perforations following the insertion of pCPS with use of varying manual techniques, the cumulated ex vivo rate of those pCPS placed correctly and with only non-critical breaches is 72.3% on average [4, 6–8, 10, 11]. In comparison, with fluoroscopically assisted insertion of ATPS, our incidence of accurately placed ATPS and those with non-critical breaches was 78.3% in axial plane and 96% in sagittal plane. In an in vivo study of Neo et al. [17], using a manual insertion technique with fluoroscopic guidance, deviation >2 mm from the pedicle occurred in 15% which was 21.7% in the current series. Overall, in vivo and ex vivo accuracy of inserting pCPS, including correct placement and non-critical pedicle perforations, can be as high as 97–99% [3, 10, 13] and 98–100% [12, 16, 18], respectively, with increasing safety using third generation CAS-systems. In fact, using CAS allowing for real-time instrument tip position, the accuracy increased to 93% in average [3, 5, 7, 8, 12, 13]. Ito et al. [14] showed that the incidence of ‘major’ pedicle breaches can be significantly

diminished using CAS. Richter et al. [16] demonstrated the perforation rate using CAS (1.2%) being statistically lower than that of manual insertion (6.7%). In another report Ito et al. [42] investigated the accuracy of pCPS placement by the use of the Iso-C-3D fluoroscopy and CT-based navigation in the cervical and thoracic spine ($n = 152$ pCPS). Clinically and in postoperative CT scans there was no neurovascular injury. Only three screws violated the margin of a thoracic pedicle wall. Also, Langston et al. [53] showed that the use of the Iso-C-3D C-arm enabled accurate percutaneous placement of pCPS in 97.6% in a laboratory study. Hence, with the ATPS the accuracy is strongly supposed to be lifted using CAS, and is the issue of an ongoing laboratory study.

Risk factors for pedicle perforations

As it is with insertion of pCPS [15, 19] there was a learning curve for ATPS insertion, too. Although we did not observe a significant correlation between the accuracy and the order of ATPS inserted, which might be related to the fact that each cervical spine was instrumented from the smaller pedicles of C3 to that of T1; the time for insertion decreased while the comfort with increasing number of screws inserted increased. Besides a learning curve, degenerative alterations of local anatomy can hamper accuracy with pCPS placement [14, 17]. All specimens except one depicted moderate to severe degenerative changes in at least three levels. In particular in cases with severe distortion of local anatomy by osteophytic formation at the anterior vertebral cortices maintaining the radiographically defined entry point with the tip of the k-wires was difficult. Hence, especially in cases with advanced degenerative changes at the site of entry point the addition of CAS would be valuable.

The current study confirmed that the cervical pedicle dimensions tend to increase in size from C3 to T1 [21], and that the pedicle transverse diameter (OPW) is the main determinant of critical pedicle perforations and of the maximum screw sizes to be used [6, 54, 55] with increasing accuracy of pedicle screw insertions at the caudad levels C6 to T1 [7, 10, 11, 15]. In a study of Karaikovic et al. [6] using the funnel technique, critical perforations occurred in 10.5% at C5, 5.3% at C6, and 0% at C7, which were 13.0% at C5 in the current series, but 0% at C6 to T1. Kareikovic reported that the average OPW was 4.2–4.8 mm for correctly placed pCPS or noncritical perforations, and 3.8 mm for pedicles with critical perforations, which were 5.1 mm and 6.1 mm in the current study, respectively. Both studies depict that with increasing OPW, the incidence of critical pedicle perforations drops. Kareikovic’s, Ludwig’s [7], and the current study demonstrated 100% accurate placement

of the pedicle screws at C7. These findings concur with previous studies demonstrating that pCPS can be performed with increasing safety at the C6 to T1 levels. [7, 11]. In contrast, critical perforations are more frequent in the upper cervical vertebrae C3–C5.

In a study of Reinhold et al. [11] the most minor pedicle wall violations were attributed to the disproportion between 3.5 mm screw diameter and the OPW. Accordingly, it might be wise to adapt screw diameter to pedicle size [13], which was not done in the current study, but might have diminished the incidence of critical pedicle perforations at the more cephalad levels. Similar to the study of Ludwig et al. [7], we found a significantly increased risk of injury to neurovascular structures in axial plane with those pedicles having an OPW of about 5 mm. Pedicles with OPW > 5 mm showed correct placement or noncritical perforation assigned as Grade 1 and 2 in 89% compared to 40% in those pedicles with OPW of < 5 mm. Ludwig's study indicated that using a 3.5 mm diameter screw and if 4.5 mm was used as a cut-off for attempting screw insertion, only 2% of the screws inserted would be likely to result in harm. The results concurred with clinical recommendations defining cut-offs of 4.0–4.5 mm using 3.5 mm screws at C3–7 [7, 12, 16, 56], and 5 mm for pedicle screws in T1 [54]. At all with our current results following fluoroscopically assisted manual insertion of 3.5 mm diameter ATPS, safe placement is assumed at the C6 to T1-levels with pedicles showing an OPW of ≥ 5 mm. Using ATPS in pedicles with smaller dimensions would indicate adaptation of screw size (i.e., 2.7 mm screws) according to the OPW. Besides too small pedicle dimensions, anomalies such as a medialized vertebral artery might increase the rate of complications with pedicle perforations [15, 18]. Therefore, preoperative evaluation of the VA with CT-angiography focussing on its course and side-related differences in size would be indicated if ATPS will be used clinically by times.

Safety concerns with ATPS insertion

Obviously, any VAI, nerve root or dural injury caused by a misplaced pedicle screw resembles a critical breach. In a cadaver study of Ludwig et al. [8], in 58% of 26 critical perforations at all the VA was at risk, and in 19% the nerve root. In this context it is of note that many VAI go silent and undetected [1, 15, 19, 43], and catastrophic neurological injuries are not reported. In a series of Kast et al. [15], only two misplaced screws had clinical relevance, whilst 26 of 28 (93%) misplaced screws were clinically silent. With usage of postinsertional CT-angiography for screws deviating laterally > 2 mm in five patients, Neo et al. [17] observed continuity of the VA in all patients with the VA

running laterally to the screw in the violated transverse foramina. In the current study, no ATPS posed risk to the spinal cord or nerve root as seen on CT-scans, but one screw with lateral deviation assigned as Grade 5 caused obvious VAI. With the other ATPS, as seen in fine CT-cuts (Figs. 1, 2) and with anatomical dissection in two specimens, pedicle perforation did not cause VAI. As concerns VAI, Sanelli et al. [57] reported that the area of the transverse foramen occupied by the VA varied markedly with a fairly low median value of 34%. The VA does not occupy the whole part of the transverse foramen and a minimal violation may not be as risky as thought with the vertebral veins being located medial to the arteries [44]. In addition, tangential openings of the inferior pedicle cortex were judged less critical, as the nerve roots run along the superior part of the pedicle [4]. Actually, there is some room between the nerve root and the surface of the inferior wall (1.4–1.7 mm [58, 59], Fig. 3), and the dural sac and the surface of the medial wall (2.4–3.1 mm [58], Figs. 1, 2), whereas no meaningful safety margin exists between the pedicle and the superior nerve root [44, 58, 59]. In a selected review of literature (Table 10), the authors found five temporary somatomotoric deficits and no permanent neurovascular injury. Using lateral mass screw (LMS) fixation as an alternative to pCPS, the spinal nerve and the VA are also exposed to risk of injury [1]. LMS do not seem safer than pCPS in general [15, 60], and neurovascular complications were found to be as high as 10% [19]. Nevertheless, although the cervical pedicles' neurovascular surroundings allow for some safety margins with most pedicle wall perforations occurring are non-critical [4, 6, 14, 18, 19, 25], the potentially fatal consequences of any neurovascular injury during insertion of pCPS and ATPS remain a serious concern. Therefore, highest accuracy should be the goal also with the ATPS technique. The usage of current computerized navigation systems and in particular the mobile CT-scanning technology, resembling promising new techniques, might lift the accuracy rate of ATPS insertion into ranges between 90 and 100%. Hence, further studies focussing on the increase of accuracy rates are indicated and under construction.

Biomechanical considerations

Prior to any clinical application of the ATPS technique, the biomechanical characteristics of ATPS are to be investigated. In addition, prior to the assessment of ATPS within a screw-plate-system, the authors intended to assess the pull-out resistance of ATPS. The screw–bone interface is known to be a major determinant of stability, and obtaining adequate purchase is essential using either VBS, LMS or pCPS [24]. Accordingly, several authors employed POT

with their main characteristics concerning VBS, LMS and pCPS templated in Table 9. Besides the review of POT outlining the superiority of pCPS compared to LMS as well as VBS, the authors tended to investigate the POS of VBS as an internal control for the biomechanical performance of ATPS inserted. The authors tempted to apply 'ideal VBS'. The studies of Conrad et al. [61] and Hitchon et al. [62] showed that the length of VBS had a significant effect on POS concerning differences observed between 12 mm and 14 mm/16 mm screws. Regarding bicortical fixation of VBS, Maiman et al. [63] only observed an increased mean POS with bicortical fixation but without reaching significance, and with the results of Pitzen et al. [64] no significant differences in POS were noted between uni- or bicortical anchorage of VBS. However, as several biomechanical studies including the complete screw-plate system indicated that bicortical fixation increases construct rigidity in terms of POS of the whole construct [65–67], the authors intended to achieve longest osseous screw purchase possible using slight triangulation of VBS [62] and bicortical fixation. Accordingly, screw-length in VBS measured 16.0 mm on average. Approximately, 84% of all VBS had a length more than 14 mm which might explain why there was no correlation between screw-length and POS, as it was in the study of Hitchon for VBS of 14–16 mm length.

BMD can be a significant determinant of the axial POS of VBS [63, 64, 67]. However, with the VBS we did not find significant correlation between POS and BMD. The reason for failing to prove significant correlation between POS and BMD might be related to the fact that BMD can vary among vertebral levels in the same individual [68]. But, compensate for individual variation of BMD and bone quality in general, to address the possibility of undetected loosening of VBS in the formalin-fixed cadaver vertebrae prior to POT, and to control for traumatic changes of the bony micro-architecture that could happen during placement of two screws in one vertebra, we performed statistical comparisons according to each set of screws placed side by side within the same vertebra. However, the order of insertions and POS was not correlative and there were no significant differences between left and right VBS. The overall reduced POS of our VBS inserted in comparison with data found in literature (Table 9) might be related to the increased overall BMD in previous studies [62] compared to the fairly low mean BMD (0.533 g/cm^2) of the current specimen. In addition larger screw diameter (4.0 mm) used [63] as compared to the current study (3.5 mm) might contribute to the differences displayed (Table 9).

As concerns the performance of ATPS inserted, the current study showed that POS of ATPS (mean 468 N) was about 2.5-fold that of VBS (mean 182 N). Results concur with findings reported in literature (Table 9) demonstrating

that the mean POS of pCPS as a factor contributing to the overall construct rigidity outperforms that of LMS and VBS. Osteoporosis nonuniformly affects the relative strength of the cortical and cancellous structures within the pedicle, vertebral body, and posterior elements, which is the track of an ATPS. However, we observed no correlation between the BMD and POS of ATPS. In addition, the osseous purchase length of the ATPS inserted showed no impact on POS. The reasons might refer to the fact that in pedicle screws the threads are usually engaged in the subcortical section, and the regional BMD of the pedicle is significantly denser than that of the anterior vertebral body [75]. This may be the reason why deeper insertion of the pedicle screw as well as overall BMD of the specimen had little effect on fixation stress in previous studies concerning pCPS [25] and in the current study. Similarly, Kowalski et al. [28] performing pCPS insertion using the Abumi technique and a second technique without decortication of the entire lateral mass did not find significant differences for POS, because with both techniques the screws engaged the cortical pedicle canal. In a study of Jones et al. [25] a 2.7 mm unicortical screw was used in 23% instead of a 3.5 mm screw when the OPW was $<5.0 \text{ mm}$. Notably, there was no significant difference in the POS of the 2.7 mm and the 3.5 mm screws. The smaller 2.7 mm screw in a narrow pedicle may have achieved purchase equivalent to the larger 3.5 mm screw in a correspondingly wider pedicle. At all, the cortical purchase in the pedicle has a greater effect on POS than the cancellous purchase in the vertebral body or lateral mass.

Notably, Jones et al. [25] demonstrated that even under ideal laboratory conditions, cortical wall violations with pCPS occurred in 13% of vertebra instrumented. In this context, it was worthy that our study design allowed a correlative analysis between accuracy and POS of ATPS. The statistical analysis revealed a significant correlation between accuracy in axial plane as well as accuracy sum score and an increase in POS. In other words, with the pedicle screw contained within or at the cortical pedicle boundaries (with screws showing a Grade 1 and Grade 2 placement, respectively), there was an increased POS. Our findings show that the accuracy of screw position within the pedicle boundaries is another significant factor that increases POS of screws in the cervical pedicles.

Although single-screw POS is important clinically, the bending moments applied to the screws and screw-plate junctions under physiologically loading cycles are more crucial. Therefore, our results do not represent the situation with repetitive motion in daily life. In addition, due to pedicle-vertebra morphology ATPS fixation is deemed possible with one ATPS and an adjacent VBS at each cervical vertebra [21]. In this context it strikes that in a multilevel C4-6 corpectomy model Schmidt et al. [39]

demonstrated that the pCPS construct, with only four pCPS at all, outperformed the anterior-only screw-plate system. With multilevel constructs using CS-plates loosening at the screw–bone interface occurs frequently [21] if they do not adequately resist translational forces, resulting in degradation of the screw–bone interface and subsequent failure due to axial loading [69]. Therefore, the authors believe that augmentation of multilevel anteriorly instrumented constructs using ATPS in selected cases will significantly increase overall construct rigidity. But, as in the study of Schmidt et al. [39], the characteristics of ATPS within a screw-plate system are to be investigated. Biomechanical tests of ATPS as part of a screw-plate system will have to show the amount of added stability gained using each two ATPS and VBS at the cephalad and caudad ends of the plate.

Nonetheless, the current study yielded for a direct comparison of the biomechanical merits of ATPS compared to VBS in terms of pull-out resistance. The POS of the ATPS was 468 N, 2.5-fold that of VBS. Compared to previous studies, values for ATPS were lower than reported for pCPS (637–1,214 N) [24, 25, 28] (Table 9). The reason for differences observed might be related to the increased age of our specimens tested (mean 82 year) as compared to prior studies [24, 28] and advanced osteoporosis of our specimen (mean BMD: 0.533 g/cm²) that goes with overall reduced mechanical properties at the cervical pedicles [24, 70]. In particular, the weaker bone that is observed in the formalin-fixated specimen compared to the fresh-frozen might have caused the overall decreased POS of both ATPS and VBS (Table 9). Accordingly, using fresh-frozen specimen Johnston et al. [24] noted 40% of their pCPS maintained a strong enough interference fit at the screw–bone interface that the pedicle itself fractured before the screw was pulled out. In contrast to their and other studies [25, 28], we noted that all ATPS rather demonstrated a shear failure than overt fractures. Hence, main differences in POS are sought to be caused, as we had to use formalin-fixated cadavera in this pilot study on ATPS.

Limitations

As in previous studies, the main limitation of the current study was related to the relatively small number of cadaveric specimens studied. The percentage of vertebrae discarded prior to accuracy or biomechanical testing varies, with up to 4.5–20% [6, 18, 25, 62, 63, 71]. In the current study, four ATPS and VBS had to be discarded. Small sample size can lead to low statistical power. However, because of the expense and costs required to test a larger sample of specimen and in particular to test fresh-frozen specimen, Type II errors are difficult to avoid. In addition,

due to the difficulties of equalizing the number of each level instrumented at C3–T1 assigned for ATPS or VBS some cervical levels were under- or over represented, as it was in a previous study [24]. Nonetheless, we believe the current study provides potentially useful information regarding the performance of ATPS in terms of accuracy and pull-out strength. Results gained and lessons learned will be of benefit for the upcoming work.

Conclusion

The current study demonstrated that insertion of APTS using a manual fluoroscopic-guided technique the first time was safe in the caudad cervical levels, C6–T1. A review of selected literature revealed that the fast developments of computer-assisted navigation has the potential to increase safety also with insertions of ATPS at the more cephalad levels. Like prior studies investigating the fixation strength of posterior cervical pedicle screws, the current study on ATPS indicated a clear biomechanical advantage with the POS being higher than for VBS and LMS. Pedicle screw fixation is a powerful technique. It provides superior fixation for reconstructing the highly unstable multilevel decompressed cervical spine and reduces the likelihood of construct failure [65]. Coincidentally, there is a meaningful set of cervical pathologies that are to be addressed via an anterior approach but demand combined anterior- and posterior instrumentation [21, 65]. To avoid second posterior surgery, the concept of ATPS was developed yielding for increased construct stability in biomechanically challenged instrumentations at the anterior cervical spine. The use of ATPS within a screw-plate system has the potential to significantly enhance construct rigidity by transpedicular screw anchorages, and further research on the topic is encouraged.

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