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ORIGINAL ARTICLE

Cervical anterior transpedicular screw fixation. Part I: Study on morphological feasibility, indications, and technical prerequisites

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Abstract Multilevel cervical spine procedures can challenge the stability of current anterior cervical screw-and-plate systems, particularly in cases of severe three-column subaxial cervical spine injuries and multilevel plated reconstructions in osteoporotic bone. Supplemental posterior instrumentation is therefore recommended to increase primary construct rigidity and diminish early failure rates. The increasing number of successfully performed posterior cervical pedicle screw fixations have enabled more stable fixations, however most cervical pathologies are located anteriorly and preferably addressed by an anterior approach. To combine the advantages of the anterior approach with the superior biomechanical characteristics of cervical pedicle screw fixation, the authors developed a new concept of a cervical anterior transpedicular screw-and-plate system. An in vivo anatomical study was performed to explore the feasibility of anterior transpedicular screw fixation (ATPS) in the cervical spine. The morphological study was conducted based on 29 cervical spine CT scans from healthy patients and measurements were performed on the pedicle sizes, angulations, vertebral body depth, height and width at C2 to T1. Significant morphologic parameters for the new technique are discussed. These parameters include the sagittal and transverse intersection points of the pedicle axis with the anterior vertebral body wall, as well as the distances between sagittal intersection points from C2 to T1. On the basis of these results, standard spine models were reconstructed and used for the conceptual development of a preclinical release prototype of an anterior transpedicular screw-and-plate system. The morphological feasibility of the new technique is demonstrated, and its indications, biomechanical considerations, as well as surgical prerequisites are thoroughly discussed. In the future, the technique of cervical anterior transpedicular screw fixation might diminish the number of failures in the reconstruction of multilevel and three-column cervical spine instabilities, and avoid the need for supplemental posterior instrumentation.

Keywords Cervical spine · Pedicle · Instrumentation · Technique · Anatomy

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Abbreviations

ACP	Anterior cervical plate(s)
ACPS	Anterior cervical plate stabilization
ADD	Adjacent disc degeneration
ACDF	Anterior (segmental) cervical decompression with fusion
ATPS	Anterior transpedicular screw(s)
BMD	Bone mineral density
CAS	Computer-assisted surgery
CPS	Cervical pedicle screw(s)
CS-plate	Constrained plate
CTJ	Cervicothoracic junction
NC-plate	Non-constrained plate
SD	Standard deviation
VA	Vertebral artery

Introduction

In cervical traumatic, degenerative, and pathologic disorders, the problem frequently lies anteriorly and the anterior approach is commonly preferred to address these disorders with the use of anterior cervical interbody grafts/cages combined with plates [8, 31].

The anterior is more atraumatic than the posterior approach and complications are rare [15, 38]. There is no damage to the paravertebral muscles, and it allows for anterior instrumentation as far as T1 [34]. However, in anterior cervical spine surgery following one-level three-column injuries [16, 38, 103] or multilevel discectomies/corpectomies [7, 18, 22, 37, 39, 63, 82, 92, 93, 101] the biomechanical stability of current anterior cervical spine screw-and-plate systems is limited. Salvage operations as well as some primary intended plated reconstructions need supplemental posterior stabilization, hence a second surgical approach with its potential risks of increased morbidity and complications [5, 12, 27, 37, 54, 81].

Although the ideal stiffness of a cervical spine construct for a certain clinical situation and the number of corpectomy levels mandating combined anterior and posterior fixation is not known [46, 54, 58, 84], the fusion and complication rates at the anterior cervical spine have been shown to have a direct correlation to the mechanical stability of the fixation, and it seems that anterior plate length is predictive of failure [35, 41, 54, 61, 71]. On the other hand, posterior stabilization using posterior cervical pedicle screw (pCPS) fixation is the technique with highest primary stability [84]. The increased stability particularly gains importance in multilevel and severe traumatic three-column instabilities. In order to avoid additional posterior stabilization in patients who undergo anterior reconstructive surgery, an anterior cervical spine implant which offers higher primary stability in selected patients is desirable.

We performed an extended review of the literature concerning the superior biomechanical characteristics [45, 58, 59, 84], and clinical success of pCPS fixations [1–3, 50, 76, 107] with increasing safety utilizing CAS and ISO-C-3D fluoroscopy [42, 43, 57, 77]. Based on available anatomical data in the literature [10, 14, 17, 23, 24, 46, 49, 64, 68, 80, 95, 98] we investigated the requirements that would be necessary to develop a morphologically shaped design of a preclinical release prototype of an AnteriorTransPedicularScrew(ATPS)–plate system. Measuring specific anatomical parameters on fine CT scans, we conducted a quantitative evaluation of the morphology of the cervical spine regarding its feasibility for ATPS insertion. From data derived we calculated 'Standard Spine Models' resembling the anatomical general set-up for ATPS insertion and developed the concept for the first ATPS–plate system.

The anatomical feasibility and restrictions of ATPS insertion, as well as the biomechanical considerations, indications, and principales in designing implants accomodating ATPS are discussed the first time. With a quantitative understanding of the cervical pedicle and vertebral morphology at different spinal levels in light of ATPS, it should be possible to conduct further laboratory studies on this new field of cervical spine stabilization.

Methods

The cervical spine CT scans of 29 patients admitted to an emergency department (Katharinenhospital Stuttgart, Stuttgart, Germany) were evaluated as the basis of our study. There were 20 male and 9 female patients. Mean age was 44.8 years (18–81). The cervical spines were free from tumor, deformity, fracture and severe osteoporosis. CT scans with advanced degenerative changes were excluded. All studies were performed on the same CT scanner (LightSpeed Plus, General Electric, USA) using a 15- to 18-cm detail field of view, axial slice thickness of 1.0 mm, slice spacing of 1.25 mm, and pitch of 0.75. Coronal and sagittal reconstructions of the axial images were generated using standard algorithms and stored digitally. Using the cursor, digital CT measurements (0.1 mm increments) were performed with a customized shaped software (Escape Medical Viewer V3, Escape Thessaloniki, Greece). The parameters and distances used during the measuring process are illustrated in Fig. 1 and Table 1.

It is to be explained that in sagittal plane, the lsIP and rsIP, and in transverse plane, the ltIP and rtIP, respectively, resemble conceivable entry points for anterior

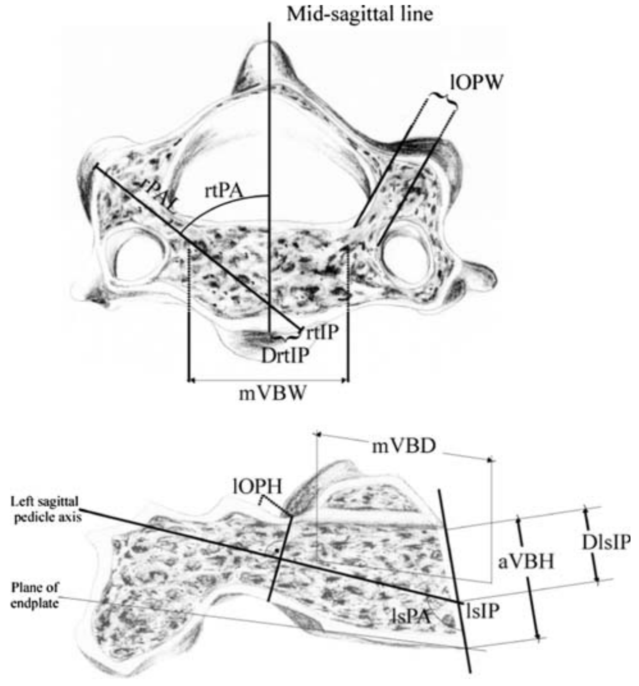


Fig. 1 Morphometric parameters measured in 29 CT scans. Transverse section shown *above* and left-sided sagittal section shown *below*

transpedicular screws (ATPS) into the left and right pedicles, respectively. The entry points resemble the projection of the center of a corridor formed by the cervical pedicles onto the anterior vertebral cortex, both in coronal and sagittal plane. As with lsIP and rsIP, mean data of ltIP and rtIP at the levels C3–T1 were visualized to explain their meaning for insertion of ATPS (Fig. 2). At the axis body, the former parameters were not measured, as C2 is obviously not suitable for ATPS. The lsIP and rsIP at C2 resembling entry points for common vertebral body screws were arbitrarily set 10 mm above the axis endplate. The distances between sagittal intersection points were measured along the anterior cervical column and could be angled and interrupted at the superior and inferior corner of each vertebral body using a polygon measuring tool. Hence, the software used allowed us to take into account the lordotic curvature of the cervical spine. Regarding measurements of ltIP and rtIP, those pedicle axis which crossed the mid-sagittal line were scaled as ‘positive’ values, and those intersecting the anterior vertebral body lateral to mid-sagittal line were scaled as ‘negative’ values. Regarding measurements of lsPA and rsPA, values >90° direct cephalad in relation to the anterior vertebral body wall.

Table 1 Description of anatomical parameters measured

Parameter	Measurement	Description
aVBH	Anterior Vertebral Body Height	Distance cephalad to caudad endplate at mid-sagittal line
mVBD	Midbody Vertebral Body Depth	Antero-posterior vertebral body depth at mid-sagittal line
mVBW	Midbody Vertebral Body Width	Transverse distance from left to right border of vertebral body at mid-vertebral line
lOPW	Left Outer Pedicle Width	Distance medial border of transverse foramen to medial border of pedicle
rOPW	Right Outer Pedicle Width	
lOPH	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	
lPAL	Left Pedicle Axis length	Distance anterior vertebral body wall to posterior marging of lateral mass along the transversepedicle axis
rPAL	Right Pedicle Axis length	
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	
DlsIPCx+Cx+1	Interlevel Distance left sagittal IntersectionPoints: Cx+Cx+1	Interlevel distance between sagittal intersection points, e.g. distance between lsIP of C3 and lsIP of C4, or C6 and C7
DrsIP Cx+Cx+1	Interlevel Distance right sagittal IntersectionPoints: Cx+Cx+1	

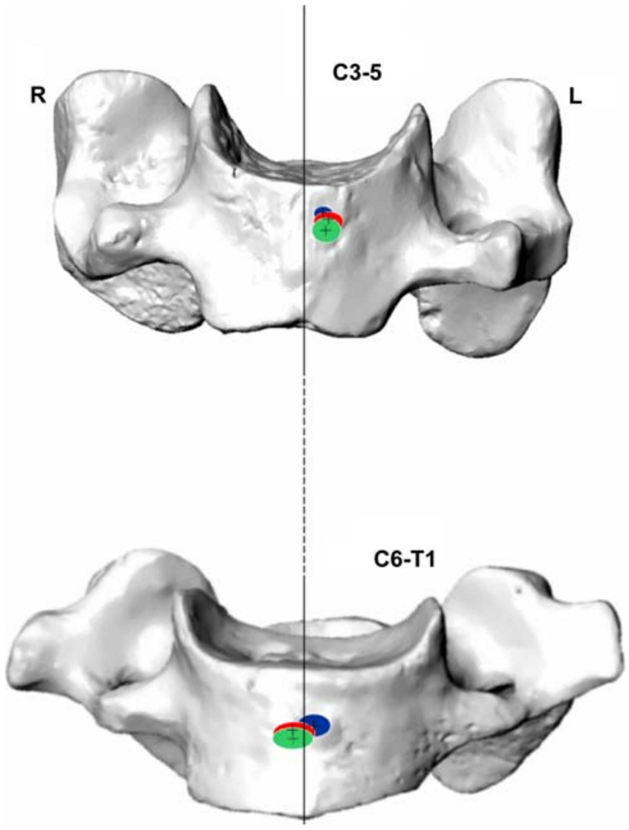


Fig. 2 Computer model depicts projection of cervical pedicle axis with rsIP and rtIP on the anterior surface of vertebral bodies C3–C5 and C6–T1. The center cross from cephalad to caudad at C3–C5 and C6–T1 resembles mean data of rsIP and rtIP, and as such the conceivable entry points for ATPS into the *right* pedicles. The ellipsoid spots (*blue*, *red*, *green*) surrounding the center cross resemble the standard deviations for rsIP and rtIP

From axial and reconstructed images it is difficult to determine the real anatomical pedicle axis and to measure its length [14]. We measured the pedicle axis length (PAL) from the anterior border of the vertebral body through the center of the pedicle and lateral mass in transverse plane. The software used enabled tracking the PAL in different axial planes. Hence, the real PAL, e.g., at C6 slightly from postero-superior to antero-inferior in relation to the anterior vertebral cortex, could be measured closer to its real anatomical course (Fig. 4).

In order to discuss the clinical feasibility of ATPS insertion and to enable developing prototype designs of an ATPS-plate with its holes incorporating transpedicular screws, 'Standard Spine Models' were calculated from average data of all patients and interlevel distances between sagittal intersection points C2–T1 ($\mathrm{DlsIP}_{\mathrm{C}x+\mathrm{C}x+1}$/$\mathrm{DrsIP}_{\mathrm{C}x+\mathrm{C}x+1}$, see Table 1), respectively. These 'Standard Spine Models' mark the varying distances between sagittal intersection points, which resemble the entry points for ATPS and the center of a screw perforation at the ends of a plate to be designed, respectively. Calculations were performed for each conceivable combination of vertebrae to be instrumented between C2 and T1. The distance between sagittal intersection points at each level was added by 1 mm for the vertebral disc as a factor for the height restoring by use of a graft/cage. Based on the calculated 'Standard Spine Models' from average data of all patients, additionally four models according to ±1 and 2 SD for each conceivable combination of vertebrae to be instrumented were calculated. It should be noted that a conceivable ATPS-plate, at its ends, can incorporate cannulated ATPS unilateral, and a vertebral body screw triangulated adjacent but beneath the ATPS on the contralateral side (Fig. 4). Both the distances of the center of plate holes in sagittal plane, as well as the size and location of plate holes in frontal plane would have to respect the varying interlevel differences, which are evaluated in our study.

Descriptive statistics including mean values, standard deviations and ranges were used to summarize data. A repeated measures ANOVA was used in which the factor 'cervical level' with factor levels C2–T1 was measured on the same individual. Gender was used as 'between-subjects' factor to compare males and females. Post hoc comparisons were done to compare different factor levels. Categorized whisker plots with 95% confidence intervals for the means were constructed to illustrate the corresponding effects. $P < 0.05$ was considered statistically significant. All analyses were done with Statistica 6.1 (StatSoft, Inc., 2004, Tulsa, USA).

Results

Analysis of data showed homogenous results, in which only three individuals, one female and two male, depicted large anatomical dimensions on CT scans. The CT data pool comprised 203 cervical vertebrae. The process of measuring resulted in a total of 3,712 parameters which are described as mean, SD, and ranges in Tables 2, 3, 4, 5, 6 and 7.

There were no statistically significant interlevel differences in aVBH, VBD, and VBW between male and female patients, but between aVBH of C2 and C3 for both gender ($P < 0.00001$). There was an increase from C5 to T1 for aVBH and VBD, and from C4 to T1 for VBW, respectively (Table 2). Measurements of PAL showed statistically significant differences only between the levels C2 and C3 ($P = 0.03$). There was a slight decrease in magnitude of pedicle angulations in transverse plane from C4 to T1, whereas statistically significant differences of ltPA and rtPA calculated from merged data of all 29 patients existed between the levels C2 and C3 ($P = 0.03$), C3 and C4

Table 2 Anterior vertebral body height, vertebral body depth, and vertebral body width C2–T1 (in mm)

	aVBH			VBD			VBW		
Level	Male Mean ± SD	Female Mean ± SD	All patients Range	Male Mean ± SD	Femal Mean ± SD	All patients Range	Male Mean ± SD	Female Mean ± SD	All patients Range
C2	20.80 ± 0.66	19.43 ± 0.98	15.82–32.45	15.59 ± 0.46	15.28 ± 0.69	12.48–22.52	21.00 ± 0.72	19.47 ± 1.07	17.36–33.12
C3	16.10 ± 0.34	15.34 ± 0.50	13.73–19.74	16.54 ± 0.40	15.70 ± 0.59	13.83–22.32	22.59 ± 0.67	19.83 ± 0.99	18.13–35.69
C4	15.32 ± 0.29	14.47 ± 0.44	12.96–18.40	16.39 ± 0.44	15.60 ± 0.65	13.05–22.52	22.44 ± 0.73	20.21 ± 1.10	18.29–37.64
C5	14.73 ± 0.40	13.57 ± 0.60	10.85–19.47	16.29 ± 0.41	15.41 ± 0.61	13.47–21.65	23.64 ± 0.90	21.29 ± 1.35	19.02–42.18
C6	14.78 ± 0.32	14.11 ± 0.47	11.70–17.52	16.61 ± 0.34	16.14 ± 0.51	13.46–21.04	25.01 ± 0.86	23.76 ± 1.29	20.55–41.53
C7	16.18 ± 0.40	15.23 ± 0.62	12.88–20.30	17.09 ± 0.35	16.68 ± 0.53	13.46–21.60	29.80 ± 1.11	28.49 ± 1.65	23.91–50.62
T1	17.83 ± 0.38	16.79 ± 0.57	14.61–21.97	17.57 ± 0.41	17.53 ± 0.61	14.78–23.25	32.71 ± 1.12	29.79 ± 1.67	26.28–55.82

Table 3 Pedicle transverse and sagittal angle (°), and pedicle axis length C2–T1 (in mm)

Level	ltPA* Mean ± SD (range)	rtPA* Mean ± SD (range)	lsPA* Mean ± SD (range)	rsPA* Mean ± SD (range)	lPAL* Mean ± SD (range)	rPAL* Mean ± SD (range)
C2	42.09 ± 6.21	40.30 ± 4.57	55.91 ± 8.16	55.10 ± 8.68	28.34 ± 4.40	27.90 ± 3.88
	(29.69–54.70)	(30.90–49.80)	(43.70–76.10)	(40.30–82.50)	(19.60–40.39)	(21.93–39.92)
C3	49.00 ± 3.82	47.71 ± 3.41	94.76 ± 5.51	94.09 ± 5.74	34.22 ± 4.92	34.63 ± 4.85
	(38.60–56.00)	(40.40–52.70)	(82.30–106.00)	(80.50–104.20)	(29.55–57.11)	(30.51–56.93)
C4	52.03 ± 3.01	51.09 ± 4.07	103.40 ± 5.87	104.43 ± 7.34	34.39 ± 4.68	34.08 ± 4.55
	(46.30–60.10)	(42.90–58.30)	(91.30–113.20)	(86.00–120.4)	(28.09–52.87)	(29.76–54.34)
C5	51.71 ± 4.10	51.75 ± 4.55	107.51 ± 5.85	108.46 ± 6.00	35.89 ± 4.23	35.76 ± 4.71
	(45.00–62.80)	(45.50–61.30)	(93.80–117.2)	(94.80–116.60)	(28.93–55.25)	(30.47–53.10)
C6	48.67 ± 5.03	47.47 ± 4.25	110.73 ± 5.27	111.18 ± 4.59	36.37 ± 3.91	35.51 ± 4.61
	(37.40–61.10)	(40.00–59.00)	(101.90–122.20)	(101.80–120.2)	(28.11–50.19)	(27.59–53.26)
C7	40.21 ± 6.47	40.80 ± 5.79	104.17 ± 5.64	105.74 ± 5.46	34.95 ± 4.94	34.74 ± 5.07
	(28.40–57.80)	(29.20–54.50)	(87.40–115.90)	(94.70–116.60)	(27.63–52.80)	(25.75–53.22)
T1	36.10 ± 4.96	35.90 ± 3.80	103.01 ± 4.81	102.52 ± 5.69	35.89 ± 5.27	35.53 ± 5.03
	(28.10–47.70)	(27.20–44.80)	(92.90–112.30)	(90.0–113.80)	(28.75–56.35)	(28.63–56.35)

*There were no significant differences between left and right sides in females and males, respectively

($P = 0.03$), and between C6 and C7 ($P = 0.02$) (Table 3). With the lsPA and rsPA C3–T1 there were no significant gender- or side-related, and no significant interlevel differences. From the anterior vertebral body cortex, the pedicle axis increased upwards from C3 to C6 (94°–111°) with a following slight decrease from C6 to T1 (111°–103°; Table 3).

Concerning outer pedicle width (OPW) of all patients, there were no significant differences between left and right sides (Table 4). However, merging left and right OPW, gender as well as vertebral level was proven as a statistically significant factor ($P = 0.00035$, $P = 0.00001$; Graph 1). With post hoc analiysis, OPW at T1 was shown to be significantly larger in males than in females ($P = 0.028$). The OPW showed the tendency to increase from cephalad C5 to caudad T1 in males, and from C4 to T1 in females (Graph 1). Significant differences in males were observed between OPW of C2 and C3 ($P = 0.0003$), C5 and C6 ($P = 0.016$), C6 and C7 ($P = 0.00001$), and C7 and T1 ($P < 0.00001$). In females significant differences were observed between the levels C2 and C3 ($P = 0.01$), C4 and C5 ($P = 0.048$), C6 and C7 ($P = 0.027$), and C7 and T1 ($P < 0.00001$). The frequency of OPW below 5 mm was 31.0% at C3, 39.7% at C4, 38.0% at C5, 20.7% at C6, 0% at C7 and T1. The frequency of OPW below 4 mm was 10.3% at C3, 5.2% at C4, 5.2% at C5, 0% at C6, C7 and T1. With OPH, all but one pedicle showed measurements larger than 5.0 mm

Concerning OPH of all patients, there were no significant differences between left and right sides, however gender was also proven as a statistically significant factor ($P = 0.017$, Table 5). Statistical analysis revealed significant differences in males between OPH of C2 and C3 ($P = 0.08$), C4 and C5 ($P = 0.01$), C6 and C7

Table 4 Outer pedicle width C2–T1 (in mm)

Level	lOPW/rOPW[a] Male Mean ± SD (range)	lOPW/rOPW[a] Female Mean ± SD (range)	lOPW/rOPW[a] All patients Mean ± SD (range)	lOPW All patients Mean ± SD (range)	rOPW All patients Mean ± SD (range)
C2	6.04 ± 1.63	5.24 ± 1.06	5.79 ± 1.52	5.70 ± 1.60	5.89 ± 1.45
	(2.98–10.14)	(3.32–7.05)	(2.98–10.14)	(2.98–10.14)	(3.42–10.14)
C3	5.45 ± 0.85	4.61 ± 0.51	5.19 ± 0.85	5.10 ± 0.85	5.27 ± 0.84
	(3.67–7.81)	(3.72–5.56)	(3.67–7.81)	(3.67–7.15)	(3.72–7.81)
C4	5.65 ± 0.98	4.63 ± 0.51	5.33 ± 0.98	5.30 ± 0.88	5.36 ± 1.09
	(4.06–8.73)	(3.74–5.82)	(3.74–8.73)	(4.01–7.34)	(3.7–8.73)
C5	5.63 ± 0.86	5.11 ± 0.70	5.47 ± 0.84	5.50 ± 0.80	5.44 ± 0.80
	(3.71–8.31)	(3.71–6.46)	(3.71–8.31)	(3.74–8.31)	(3.71–7.81)
C6	6.03 ± 0.84	5.49 ± 0.67	5.86 ± 0.82	5.96 ± 0.84	5.75 ± 0.81
	(4.23–8.83)	(4.01–6.50)	(4.01–8.83)	(4.97–8.83)	(4.01–7.81)
C7	6.87 ± 1.00	6.03 ± 0.42	6.61 ± 0.94	6.63 ± 0.93	6.59 ± 0.96
	(5.37–10.20)	(5.38–7.05)	(5.37–10.20)	(5.37–9.36)	(5.39–10.20)
T1	9.04 ± 1.54	7.73 ± 0.91	8.63 ± 1.50	8.74 ± 1.56	8.53 ± 1.45
	(7.08–13.93)	(5.77–9.54)	(5.77–13.93)	(5.85–13.93)	(5.77–13.93)

[a] There were no significant differences between left and right sides in females and males, respectively

Table 5 Outer pedicle height C2–T1 (in mm)

Level	lOPH/rOPH[a] Male Mean ± SD (range)	lOPH/rOPH[a] Female Mean ± SD (range)	lOPH/rOPH[a] All patients Mean ± SD (range)	lOPH All patients Mean ± SD (range)	rOPH All patients Mean ± SD (range)
C2	7.67 ± 0.94	7.02 ± 1,13	7.47 ± 1.03	7.43 ± 0.99	7.50 ± 1.09
	(5.73–9.22)	(5.00–9.02)	(5.00–9.22)	(5.72–9.12)	(5.00–9.22)
C3	7.28 ± 0.90	6.82 ± 0.96	7.14 ± 0.93	7.14 ± 1.06	7.13 ± 0.81
	(4.76–9.08)	(5.91–9.66)	(4.76–9.66)	(4.76–9.66)	(5.74–8.76)
C4	7.46 ± 0.83	6.93 ± 1.08	7.30 ± 0.94	7.33 ± 0.97	7.27 ± 0.92
	(5.79–9.38)	(5.50–9.63)	(5.50–9.63)	(5.79–9.63)	(5.50–9.38)
C5	6.99 ± 0.75	6.73 ± 1.10	6.91 ± 0.87	6.91 ± 0.90	6.9 ± 0.86
	(5.48–8.83)	(5.10–9.63)	(5.10–9.63)	(5.10–9.63)	(5.29–8.83)
C6	7.26 ± 0.72	6.65 ± 1.14	7.08 ± 0.91	7.13 ± 0.96	7.02 ± 0.86
	(5.72–8.83)	(5.05–9.20)	(5.05–9.20)	(5.10–9.20)	(5.05–9.02)
C7	7.87 ± 0.84	7.37 ± 1.23	7.72 ± 0.99	7.61 ± 0.92	7.82 ± 1.07
	(6.35–9.40)	(5.77–10.97)	(5.77–10.97)	(6.07–9.02)	(5.77–10.97)
T1	9.48 ± 0.92	8.88 ± 1.43	9.30 ± 1.13	9.32 ± 1.13	9.27 ± 1.14
	(7.61–11.30)	(6.57–12.13)	(6.57–12.13)	(7.59–12.13)	(6.57–11.95)

[a] There were no significant differences between left and right sides in females and males, respectively

($P = 0.00005$), and C7 and T1 ($P < 0.00001$). In females significant differences were observed between C6 and C7 ($P = 0.01$), and C7 and T1 ($P < 0.00001$). Merging left and right OPH, there was a tendency towards a decrease of OPH from C2 to C5 in males and from C2 to C6 in females with a reversal increase in males from C5 to T1, and in females from C6 to T1.

There were no meaningful gender related differences ($P = 0.195$) in merged data of left and right interlevel distances between sagittal intersection points C2 to T1 ($\mathrm{DlsIP}_{\mathrm{C}x+\mathrm{C}x+1}$ and $\mathrm{DrsIP}_{\mathrm{C}x+\mathrm{C}x+1}$; Table 6). Significant differences between the interlevel distances of sagittal intersection points from cephalad to caudad C2–T1 existed between the levels C2–C3 and C3–C4 for both gender

Table 6 Interlevel distances of sagittal intersection points C2–T1 (in mm)

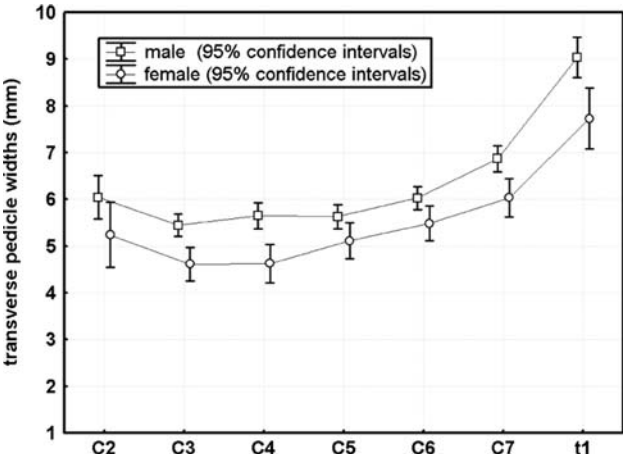
Level	Male Mean ± SD	Female Mean ± SD	All patients Mean ± SD
DsIPC2–C3	15.73 ± 1.56	15.15 ± 1.57	15.55 ± 1.57
DsIPC3–C4	19.73 ± 1.94	18.32 ± 2.35	19.29 ± 2.16
DsIPC4–C5	19.57 ± 2.91	19.54 ± 3.95	19.56 ± 3.23
DsIPC5–C6	19.12 ± 2.64	17.86 ± 2.19	18.73 ± 2.56
DsIPC6–C7	18.88 ± 2.46	18.62 ± 2.89	18.80 ± 2.57
DsIPC7–T1	20.14 ± 2.03	19.69 ± 3.15	20.00 ± 2.42

Mean data and SD integrate calculation of left and right measurements

Table 7 Distances of sagittal and transverse intersection points C3–T1 (in mm)

Level	DlsIP Mean ± SD (range)	DrsIP Mean ± SD (range)	DltIP Mean ± SD (range)	DrtIP Mean ± SD (range)
C3	3.02 ± 1.13 (0.0–5.36)	3.11 ± 1.10 (0.50–5.41)	2.29 ± 1.53 (−1.95–5.24)	2.20 ± 1.43 (−0.98–4.47)
C4	3.58 ± 1.35 (0.61–5.86)	3.75 ± 1.50 (0.39–5.91)	2.77 ± 2.25 (−2.52–8.19)	2.67 ± 2.24 (−2.6–5.77)
C5	4.97 ± 1.76 (1.11–9.20)	4.98 ± 1.88 (1.17–9.25)	2.24 ± 2.07 (−2.6–5.77)	2.53 ± 2.17 (−1.95–7.17)
C6	6.73 ± 1.92 (3.88–10.51)	6.27 ± 1.71 (3.45–9.78)	1.18 ± 2.95 (−10.4–5.65)	1.14 ± 2.52 (−6.49–4.77)
C7	6.69 ± 1.71 (3.28.10.51)	6.86 ± 1.67 (4.01–11.41)	−0.67 ± 3.55 (−9.76–5.21)	−1.21 ± 3.16 (−10.38–4.32)
T1	7.11 ± 1.33 (4.63–10.3)	7.11 ± 1.62 (4.63–10.3)	−1.18 ± 2.94 (−9.11–5.46)	−1.19 ± 3.07 (−9.08–6.30)

Merged data for male and female patients



Graph 1 Mean OPW in males and females with 95% confidence intervals

($P < 0.00001$, Table 6) which was a factor of the determined starting point for measurements at C2. Statistically significant differences in males existed also between C6–C7 and C7–T1 ($P = 0.0026$), and in females between C4–C5 and C5–C6 ($P = 0.006$).

The sagittal intersection points resemble the projection of the center of the cervical pedicles onto the anterior vertebral cortex marking the theoretical entry points for 3.5 or 4.0 mm diameter cannulated ATPS (Fig. 2). Mean distances from adjacent disc spaces and cephalad endplates, respectively, to the sagittal intersection points are compiled in Table 7. In general, to ensure safe screw placement 0.5 mm of bone around each screw was determined as the critical value, and a safe entry point for placement of a 3.5 mm screw was assumed to be 2.25 mm (1.75 + 0.5 mm) [47] off. Accordingly, to select an entry point and to place a 3.5 or 4.0 mm ATPS with its head and the proximal outer rim of a plate (1 mm) close to, but beneath an adjacent disc space, at least an error margin of 3.25 and 3.5 mm, respectively, must be ensured. Using anatomical trajectories of pedicles axis for measuring the lsIP and rsIP, the frequency of those lsIP and rsIP with a distance below 4 mm to its adjacent cephalad disc space was 79.7% at C3, 58.6% at C4, 24.1% at C5, 5.2% at C7, and 1.7% at T1. These data has to be put into perspective to increased OPH compared to OPW. E.g., mean OPH of all C3- and C4-pedicles was both 7.3 mm. Mean sagittal angle of pedicle axis was 94.3° and 103.9° at C3 and C4, respectively. Hence, clinically there is a wider corridor in the sagittal plane to place a 3.5 or 4.0 mm pedicle screw inside the pedicles and sufficiently beneath adjacent disc spaces, as done with pCPS insertion [1].

Our calculations showed that measurements of DlsIP and DrsIP were not significantly different between male and female patients (Table 7). Therefore, we used the average data of all of our patients for designing the 'Standard Spine Models' (Table 8). Calculation of the 'Standard Spine Models' ±1 and 2 SD (five 'Standard Spine Models') according to the interlevel distances between sagittal intersection points in all 29 patients revealed that for, e.g., a static ATPS–plate system with fixed plate hole perforations, at least 105 different plates sizes would have to be designed. Derived from our data, in a conceivable ATPS–plate set (one- to six-level plates) designed according to the distances between the center of plate holes of the five calculated 'Standard Spine Models' for each conceivable plate length in between the levels C2–T1 to be instrumented, the remaining gap between two plate sizes next to each other (see Table 8, maximum of values in brackets) would be 3.2 mm in one-level plates, 5.8 mm in two-level plates, 8.4 mm in three-level plates, 10.8 mm in four-level plates, 12.9 mm in five-level plates, and 14.5 mm in six-level plates. But, using a screw–plate-

Table 8 Standard Spine Models ±1 and 2 SD calculated from distances of sagittal intersection points C2–T1 (in mm)

Level	C2	C3	C4	C5	C6	C7	T1
C2	-	-	-	-	-	-	-
C3	13.41 14.98 16.55 18.12 19.69 (1.57)	-	-	-	-	-	-
C4	29.38 33.11 36.84 40.57 44.30 (3.73)	15.97 18.13 20.29 22.45 24.61 (2.16)	-	-	-	-	-
C5	43.48 50.44 57.40 64.36 71.32 (6.96)	30.07 35.46 40.85 46.24 51.63 (5.39)	14.10 17.33 20.56 23.79 27.02 **(3.23)**	-	-	-	-
C6	58.09 67.61 77.13 86.65 96.17 (9.52)	44.68 52.63 60.58 68.53 76.48 (7.95)	28.71 34.50 40.29 46.08 51.87 **(5.79)**	14.61 17.17 19.73 22.29 24.85 (2.56)		-	-
C7	72.75 84.84 96.93 109.02 121.11 (12.09)	59.34 69.86 80.38 90.90 101.42 (10.52)	43.37 51.73 60.09 68.45 76.81 **(8.36)**	29.27 34.40 39.53 44.66 49.79 (5.13)	14.66 17.23 19.80 22.37 24.94 (2.57)	-	-
T1	88.91 103.42 117,93 132.44 146.95 **(14.51)**	75.55 88.44 101.38 114.32 127.26 **(12.94)**	59.53 70.31 81.09 91.87 102.65 **(10.78)**	45.43 52.98 60.53 68.08 75.63 (7.55)	30.82 35.81 40.80 45.79 50.78 (4.99)	16.16 18.58 21.00 23.42 25.84 (2.42)	-

Rows in each block:(1) Mean distance of intersections points minus 2 SD plus 1 mm for each level instrumented.(2) Mean distance of intersections points minus 1 SD plus 1 mm for each level instrumented.(3) Mean distance of intersections points plus 1 mm for each level instrumented.(4) Mean distance of intersections points plus 1 SD plus 1 mm for each level instrumented.(5) Mean distance of intersections points plus 2 SD plus 1 mm for each level instrumented.In brackets: Distances of each of five calculated 'Standard Spine Models' from one to the next size. A translation mechanism must allow this distance to translate in order to accomodate ATPS in each individual.Same colors, from right above to left down, corresponding to one-, two-, three-, four-, five-, and six-level 'Standard Spine Models'

and not a screw–rod-system, the holes of the plate would have to fit always exactly the given location of a placed k-wire and the following cannulated ATPS in transverse and sagittal plane in all individuals. Hence, only by using a translation mechanism could these these gaps be approximated. A plate design with a translation mechanism would have to compensate for the individual variations in interlevel distances.

If the axis vertebra is excluded from calculating the 'Standard Spine Models' ±1 and 2 SD, the differences between calculated distances of plate hole perforations for one-, two-, three-, four-, and five-level plates at C3–T1 vary only by 2 mm. Thus, the total number of anatomically shaped plates could be reduced. From this point of view, with a translation mechanism allowing for shifting of the ends of a plate towards each other and allowing for some overlap between different plate sizes, as well as including those individuals with smallest and largest distances between sagittal intersection points, a translation mechanism would have to enable translation of about 3 mm in one-level, 5.5 mm in two-level, 8 mm in three-level, 11 mm in four-level, and 13 mm in five-level plates for instrumentation between C3 and T1. Due to this, the number of plates need to accommodate ATPS fixation in all individuals would be 25 for instrumentations C3–T1, and 30 for C2–T1. When designing the length adjusted plates about 1–2 mm will need to be added at either end of a plate to accommodate the screw holes at the projected intersection points. Total plate length $C_x - C_{x+(1-6)}$ is the calculated distances between intersection points, plus 1 mm added to each vertebral disc as a factor for the height restoration caused by using an inter-body fusion cage device or graft, plus the 1–2 mm either end required for production of a stable plate, plus half the diameter of an ATPS plate hole perforation.

Measurement of distances between ltIP and rtIP referred to mid-sagittal line (DltIP and DrtIP, Table 7) demonstrated that the +95% confidence interval was highest at C4 with 3.63 mm and the −95% confidence interval lowest at C7 with −2.41 mm. Only three individuals showed their transverse intersection points more than 5 mm lateral to one side of the mid-sagittal line. For better understanding, means and SD for ltIP/rtIP and lsIP/rsIP are visualized in Fig. 2. The pedicle axes do not necessarily intersect each other in the anterior part of the vertebral body. Accordingly our data for DltIP and DrtIP (Table 7) showed averages of −0.67 to +2.77 mm, with a maximum ranging from −10.38 to +8.19 mm concerning all patients, and with a maximum ranging between −7.01 to +8.19 mm excluding one large individual. Although ranges tended to be large, there were no significant interlevel, male versus female, or left versus right differences detected. The mean distances measured between mid-sagittal line and ltIP/rtIP shifted slightly from contralateral to mid-sagittal line of the measured pedicle axis at C3–C6 and towards the ipsilateral side at C7–T1 (Fig. 2). Most often pedicle axes not crossing the mid-sagittal line at the anterior vertebral body wall were observed at the caudal levels C7–T1, whereas at C6 and C7 the maximum distances of ltIP and rtIP to mid-sagittal line were observed. Due to midline crossing of the pedicle axis, insertion of ATPS is possible (mainly) unilaterally. As ltIP and rtIP resemble the varying entry points for ATPS in transverse plane, a static or translational plate design, as well as a platform–rod-system [9], will have to respect the individual variations of entry points in transverse and sagittal plane, by adjustment of the hole geometry, as well as the distances between the center of plate hole perforations. Concerning the differences of DltIP and DrtIP in designing an anatomical shaped ATPS–plate system, its screw holes have to respect the aforementioned facts. This process of adaptation results in an asymmetrical location of oval holes in the horizontal plane at the cephalad and caudal ends (Fig. 3) according to the DltIP/DrtIP at each cervical level. Hence, one side of an ATPS-plate (the left or right one) will show a cephalad oval hole in transverse plane of about 10 mm lenght and a round plate hole perforation to accommodate an adjacent vertebral body screw.

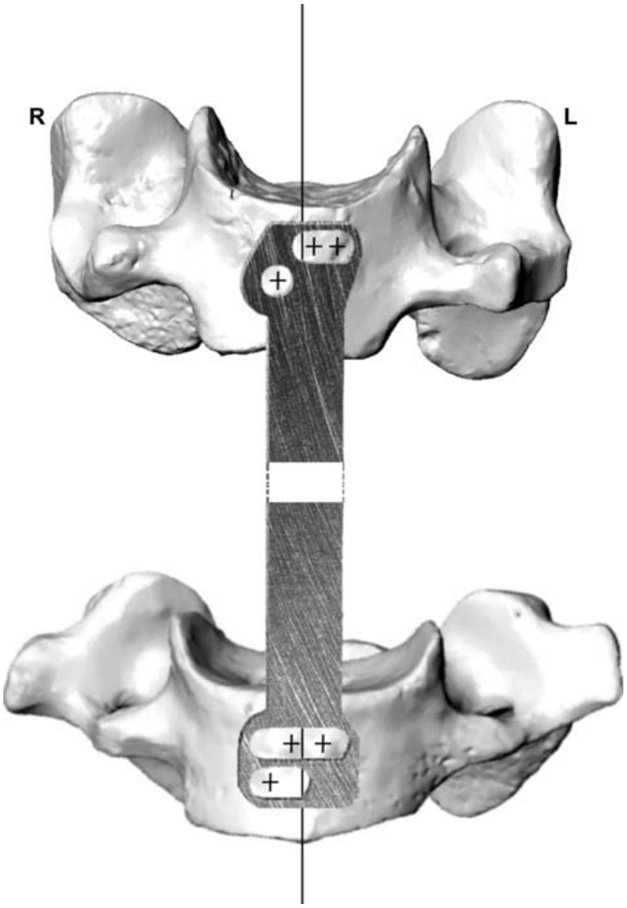


Fig. 3 Computer model depicts a conceivable design of an ATPS–plate system with asymmetrical plate holes proximally and distally, respecting asymmetric entry points for ATPS at C3–T1. Here, a conceivable design of a four-level instrumentation, e.g., C4–T1, is depicted. At the end-levels, proximal oval hole perforations are located, e.g., more left sided for an ATPS directing rightwards, and circular and slightly oval holes proximal and distal, respectively, directing leftwards for triangulated anterior vertebral body screws. Midsection of the plate marks space for a conceivable translation mechanism. With the plate enabled to translate the proximal towards the distal plate holes according to given entry points of the ATPS will support its clinical feasibility. The insertion of 3.5–4.5 mm ATPS will follow the insertion of a k-wire placed albeit parallel to the endplates to be instrumented. Afterwards, an ATPS-plate is chosen adjusted to the length of levels to be instrumented and translation is performed. Due to the oval holes, the differing entry points of the k-wires cranially and caudally in transverse plane can be compensated due to translation of the plate more medially or laterally along the longitudinal axis

To place the plate with its longitudinal axis close to mid-sagittal line, its caudal transverse counterpart hole, oval in shape, will be situated more closely to the mid-sagittal line in those plates designed for instrumentation at C6–T1.

As in the study by Ugur et al. [99], female individuals were underdistributed in our series with a male to female ratio of 1:0.45. However, significant gender related differences in creating ‘Standard Spine Models’ for ATPS, which were our most important calculations, did not exist. We derived data from a population of European origin. Differences in specimen from other continents have to be taken into account when comparing our results.

Discussion

Indications for ATPS

There are worthwhile reasons for attempting to invent an immediately rigid technique of anterior fixation in the cervical spine [12]. Despite adequate intraoperative construct stability, some series concerning ACPS in subaxial traumatic instabilities report the incidence of re-displacement or loss of alignment at 19% [38], or 50% in patients with ankylosing spondylitis [28], the incidence of redo surgeries with 11–20% [16, 38], and the need for posterior supplemental stabilization with 10–15% [16, 103]. Hence, increased stability with anterior-only instrumentations would be advantageous in highly unstable cervical spine injuries. In turn, reconstruction of the multilevel decompressed cervical spine is required in degenerative disorders, infections and deformities, and tumor related instabilities [6, 18, 54, 72, 90]. If multilevel ACDF is not feasible, corpectomy plus adjacent level discectomies and discontinous corpectomies with retention of an intervening body, respectively, has been successfully performed at three or more motion segments [5, 13, 29, 54]. But, some cases demand multilevel corpectomies. Unfortunately, long strut grafts or cages used for reconstruction are known to be biomechanically inferior [89] and vulnerable to failure requiring revision [18, 19, 37, 79, 97]. Surgical complications and construct failures encountered with plated long-segment strut grafts increase with the number of corpectomized levels [9, 13, 18, 30, 62, 71, 78, 81, 93, 97, 101] and the literature provides evidence that anterior-only constructs particularly in more than two-level corpectomies [12, 18, 37, 82, 92, 101] do show a cause for concern regarding failure rates. A review of literature [54] showed that the rate of non-unions in multilevel ACDF and failure rates for long-length decompressions/corpectomies is as high as 20–50%, and up to 30–100%, respectively. About 30–50% of complications in multilevel cases are due to graft/cage and instrumentation related causes and carry a significant reoperation rate, which is reported as being between 10–50% [12, 36, 54]. Therefore, biomechanical studies [21, 32, 41, 52, 59, 69, 84, 88, 89] and clinical series [6, 65, 79, 85, 102] support the addition of posterior stabilization in multilevel procedures improving the early and long-term stability. Besides multilevel fusions for degenerative diseases, a body of clinical situations, including tumor related three-column instability, severe osteoporosis or ankylosing spondylits, call for combined anterior–posterior stabilization [6, 28, 54, 91, 100]. From the point of view of measuring techniques, combined antero-posterior stabilization leaves no doubts, particularly in long corpectomy cases [20, 32, 46, 52, 58, 84, 88], yielding fusion rate of 100% without construct failures for three- and four-level surgeries [54, 79, 85, 87, 102]. However, with the biomechanical advantage of supplemental posterior stabilization comes the addition of a second approach, added surgical risks, and a higher rate of infection. Posterior procedures with cervical dissection can cause significant myofascial pain due to the stripping of the musculature from the posterior elements and can be associated with significant postoperative axial symptoms and neck pain [5, 54, 66, 72, 87]. Hence, further development of the ATPS technique with an anterior-only treatment strategy could overcome the aformentioned drawbacks while serving the benefit of transpedicular construct anchorage. Part 1 of this article obviously depicts the field of clinical settings in which an ATPS–plate sytem would be a valuable tool. The ATPS technique is not sought as a replacement of common techniques for daily cervical spine surgery, but a technical adjunct for select cases. Due to transpedicular three-column fixation, the ATPS-technique could merge the biomechanical merits of current pCPS fixations with the surgical benefits of anterior-only procedures.

Morphological feasibility of ATPS

Morphometric measurements based on CT scans compared to manual calliper measurements are proven efficient to determine pedicle dimensions [14, 47, 49, 86]. CT scans avoid possible deviations by post mortem changes such as dehydration and altered tonus of the soft tissue that might change the disc height [48]. In our study, measurements of sagittal and transverse intersection points defining the possible entry points for ATPS were recorded, which is not possible using direct calliper measurements. Nevertheless, to put our data in perspective, one has to accept that morphometric measurements between different observers [64], techniques, and populations from different continents vary to some extent (see Table 9), and that qualitative

Table 9 Comparison of mean pedicle outer width with other studies from literature (in mm)

Measurement technique		CT			Direct/CT					Direct		
Level	CS ($N = 29$)	Chazono [14] ($n = 63$)	Sakamoto [80] ($n = 30$)	Kareikovic [49] ($n = 53$)[a]	Datir [17] ($n = 18$)	Ludwig [64] ($n = 12$)	Ugur [98, 99] ($n = 20$)	Bozbuga [10, 31] ($n = 29$)	Jones [46] ($n = 56$)	Ebraheim [26, 53] ($n = 40$)[a]	Panjabi [68] ($n = 12$)[b]	Tan [95] ($n = 10$)[b]
C2	5.8			6.9/6.5					8.0		8.3/7.7	
C3	5.2	5.4	6.2	5.3/4.5		5.4	4.9	4.5	4.8	4.9/4.5	5.4/5.8	4.5/4.4
C4	5.3	5.5	6.3	5.4/4.5		6.1	5.2	4.4	5.2	4.7/4.6	5.1/5.7	4.6/4.5
C5	5.5	5.7	6.5	5.7/5.0		6.0	5.3	4.7	6.1	4.9/4.9	5.1/6.1	4.7/4.9
C6	5.9	5.9	6.7	5.9/5.0		6.2	5.7	4.7	6.5	5.2/5.0	5.6/6.3	5.1/5.4
C7	6.6	6.7	7.4	6.7/5.9		6.5	6.0	4.9	6.9		6.5/6.6	5.6/5.7
T1	8.6				7.3/5.8		6.5					7.4/7.5

CS current study

[a] Mean *x*/*x* resembles data reported in respect to male/female gender

[b] Mean *x*/*x* resembles data reported in respect to left/right side

Fig. 4 Photo model depicts the principles of ATPS fixation. *Left* one depicts sagittal plane of C6 vertebra; *right* one depicts transverse plane of C6 vertebra from cryosections. Note transverse intersection point of ATPS with anterior vertebral body close to mid-sagittal line, insertion of ATPS albeit parallel to upper vertebral endplate in sagittal plane, and crossing configuration of ATPS and vertebral body screw in transverse plane, respectively. *Asterisk* marks vertebral artery. Cryosections with kindly permission from A. Kathrein, M.D., University of Innsbruck/Austria

inter- and intralevel changes in pedicle morphology, even along their axes, can alter results of measurements [70].

The anatomic feasibility of ATPS at C3–T1 is based on the multitude of studies considering the quantitative morphology of human cervical spine. The VBD determines the antero-posterior diameter for a vertebral body screw. In our study VBD of C2–T1 showed a mean of 16.8 mm in males and 16.2 mm in females (Table 2). Concerning in- and exclusion of C2 or T1 into calculations, the results are similar to those of Kwon et al. [60] for C3–C7 (17.1 and 15.2 mm, respectively) and those of Ebraheim et al. [25] for C2–C7 (15.5 and 14.7 mm, respectively). According to our measurements, intendend to enable designing an ATPS–plate system, unicortical vertebral body screws could be inserted triangularly with lengths of 16–18 mm.

For ATPS, the midbody VBW determines the anterior work-space in coronal plane for screw placement and restricts the width of a plate. Average VBW at C2–T1 in horizontal plane was 25.3 mm for males and 23.3 mm for females (Table 2). Data for C3–C7 were similar to those of Kwon et al. [60] (24.6 and 23.0 mm, respectively). To allow for plate positioning even lateral to the mid-sagittal line, the width of an ATPS-plate could be 16–18 mm. In our study mean aVBH at C3–T1 was 15.8 mm for males and 14.9 mm for females (Table 2), similar to data of Oh et al. [67]. The data depict sufficient work-space for insertion of an ATPS and an adjacent vertebral body screw into each vertebra to be instrumented at C3–T1 (Fig. 4).

Our means for OPW that based on CT-scan measurements are comparable to data previously published [14, 49, 80] using similar techniques. Excluding data from Ludwig et al. [64], direct measurements reported in literature are smaller. But, our mean OPW at C2 was smaller than in other studies reviewed [56] which refers to the varying definitions of the ‘surgical C2-pedicle’ used. As in the current study, there were no significant differences between left and right OPW and OPH, as reported in literature [10, 64, 70, 73] and the OPW was found to be larger in males than in females [14, 49, 70, 80]. But, the OPH was not consistently larger in males than in females. Panjabi et al. [68] noted that pedicle height was greater than its width for both left and right pedicles of each vertebra, resembling similar observations compared to our study and that of Kareikovic et al. [49]. The OPW was shown to slightly increase in males and females from cephalad (C3) to caudad (C7) [10, 26], whereas the most significant difference was found between OPW of C6- to T1-levels (5.8–8.6 mm) in our study. In addition to the overall mean of OPW, the frequency of the limiting transverse diameter of cervical pedicles for a pedicle screw insertion deserves attention: In a study of Chazono et al. [14] and Kareikovic et al. [49] the frequency of the OPW below 5 mm was 32.2 and 75.5% at C3, 30.1 and 35.8% at C4, 25.4 and 13.2% at C5, 15.9 and 13.2% at C6, and 1.6 and 6.6% at C7, respectively. Data of Chazono were roughly similar to our measurements, as it was the incidence of OPW with 3–4 mm in their study and that of Panjabi et al. [68]. Taking into account the means and calculating the frequencies depicts that ATPS fixation using 3.5–4.5 mm diameter screws would be appropriate at all levels only in selected patients, but feasible in most of the biomechanically challenged end-levels (C6–T1) of multilevel cervical constructs.

For the mean PAL, ranges were reported between 22 and 33 mm at C3–C7 [10, 49, 80]. In comparison, our mean PAL at each level was larger (Table 3). Notably, in comparison to previous studies [10, 49], our software enabled adapting the plane of transverse pedicle axis with respect to the cervical lordosis, which might explain that our PAL were larger. According to our data, ATPS for C3–T1 could show lengths of 20–40 mm, comparable to customized pCPS in use [75].

Measuring the tPA remains a concern, since determination of the pedicle axis is difficult especially with direct techniques [10, 49]. The tPA measured for pCPS insertion varies between a minimum mean of 36° for the male C7 pedicle to a maximum mean of 49° for the male C4 pedicle [49]. Our means for ltPA and rtPA were 2°–4° larger compared to previous studies [46, 49, 73]. Surgical recommendations for the angulation to be used in pCPS insertion at the C3 to C6 levels show a range of 40°–45° [44, 46, 64, 98]. Based on an ex vivo study of Sakamoto et al. [80], 50° was recommeneded as screws of 4.5 mm diameter would fit in all 120 vertebrae C3–C6 at 50° without violating the transverse foramen or spinal canal. We measured the tPA perpendicular to the diameter between transverse foramen and medial border of the pedicle. Our mean OPW were similar to that reported previously (Table 9), and the mean tPA was 48°. Hence, Sakamoto's suggestion to choose a SAS-50° might be appropriate also for ATPS insertions.

We measured the lsPA and rsPA formed by the pedicle axis and a line drawn along the anterior vertebral body, as this angle would be that created between an ATPS and the anterior cervical plate. Our sagittal angulations measured are therefore not comparable to previous ones [10, 49, 68, 73], but correspond to those depicted in clinical practice with pCPS fixation [3, 75, 94]. Kareikovic et al. [49] found that C2 and C3 pedicles were directed superiorly compared with the inferior vertebral endplate, that C4 and C5 pedicles were parallel to it, and that C6 and C7 pedicles were inferiorly directed, sharing similar observations with other authors [14, 64, 68, 73]. However, clinically Abumi et al. [1] showed that paralleling the CPS according to the upper endplate in the sagittal plane is sufficient. In our study lsPA and rsPA were the lowest at the C3-level with a mean of 94°, that is an ATPS would to be directed slightly in cephalad direction in relation to the anterior vertebral cortex at C3. The associated lsIP and rIP showed a mean of 3 mm. As mentioned, the OPH height is mainly larger than the OPW. Therefore, a more steep cephalad directed trajectory for insertion of an ATPS is possible also at this level. Consecutively, the sagittal intersection points resembling the entry points of ATPS at these and other levels might be chosen more caudad in reference to the superior endplate of the instrumented vertebra if necessary. With the measurements of the distances of the sagittal and transverse intersections (lsIP and rsIP/ltIP and rtIP) the authors assessed the theoretical entry points for ATPS in to the vertebral bodies and pedicles, respectively. During insertion of ATPS using a manual, fluroroscipally assisted insertion technique, these data that can be derived from fine CT-scans to locate the starting points for a k-wire and cannulated screw, respectively.

The C2-morphology is not suitable for ATPS as mean lsPA and rsPA was 55.9° and 55.1° in an oral direction. An ATPS would have to be inserted transorally, which is not a realistic scenario when using an anterior retropharyngeal approach. We performed measurements including C2 to validate the whole data pool in comparison with data from literature (Table 9). Our results regarding the C2-pedicle dimensions (pars interarticularis of C2) are comparable to previous ones reviewed [56]. As with the use of common cervical plates, within a conceivable ATPS–plate-system the plate would accomodate vertebral body screws for insertion into C2 whilst allowing placement of ATPS at the caudad level. The reason why preferably one ATPS with an adjacent VBS at each level between C3 and T1 can be inserted with the ATPS technique is refered to the fact that in the horizontal plane and going from posterior to anterior the pedicles converge towards the midline with only the lower cervical levels (C6–T1) the pedicle axis intersecting anteriorly to the vertebral body or at its anterior edge [51, 55].

The authors measured the distance between the sagittal intersection points of the pedicle axis at the anterior vertebral cortex. These data have to be taken into calculation if one considers preclinical release prototyping of an ATPS-plate to evaluate biomechanical characteristics.

Biomechanical considerations for ATPS

Fusion rates in the spine have been shown to have a direct correlation to the mechanical stability of the fusion construct [35, 54, 61] with construct failure particularly in multilevel constructs most often occuring early during postoperative course [18, 54, 71]. Early failure depends on the immediate stability conferred by the construct [41] and relies on the mobility of the fused segments, screw purchase, alignment and load sharing achieved, the bone quality, and stabilizing potential of the construct [8, 32, 74]. With the ATPS-technique, enhanced screw anchorage by transpedicular fixation [45, 46, 59] would be of benefit to resist the axial pull-out forces that can compromise the screw–bone interfaces even with constrained screw–plate systems [83]. Serving for three-column pedicle screw fixation [11, 21] the ATPS technique would provide posterior column support but with use of an anterior-only approach. The current study on the OPW and OPH showed that all cervical pedicles from C6 to T1 would have been amenable to incorporate 4.5 mm diameter ATPS. In this context it is of note that the failure in multilevel ACDF or corpectomies is mostly observed at the end-levels of the constructs (the caudal more than the cephalad), where graft/cage subsidence and telescoping occurs, hardware fractures or levers off [4, 33, 39, 54, 69, 83, 104]. Up to 78% of multilevel fusions end at the CTJ (C7–T1) [40]. Boockvaar et al. [8] observed construct failures in 18% in fusions ending at the CTJ and pseudoarthrosis in 12%. Similarly, Wang et al. [104] observed a higher rate of graft migration in corpectomies involving a fusion ending at the C7 vertebral body. Conclusively, fusions ending at the lower cervical spine would in particular benefit from increased construct anchorage that would yielded by use of ATPS. Concerning an ATPS–plate-system, it is the author's belief that two transpedicular constrained plate–screw fixations, proximally and distally, with two vertebral body screws will significantly increase construct stability in comparison to currently used screw–plate systems. This has the potentional of a *clinical stability* comparable to pCPS fixations, which in turn might reduce the incidence of postsurgical loss of alignment, construct failure, and diminish the need for postoperative orthotic wear in selected cases.

Surgical prerequisites for ATPS

The technique of CPS insertion was first described and further developed by Abumi et al. [1]. Since this time, increased usage and safety with cervical pedicle placement using manual and computer assisted techniques are documented in the spinal literature [105, 107]. The incidence of non-critical breaches was reported up to 100% and even though perforation of the transverse foramen occurs at times, the vertebral artery does not occupy the whole part of the foramen transversarium [56] with most pedicle wall perforations occurring non-critical [1, 50, 56, 94]. The cervical pedicles seem tolerant to some screw violations as many VA injuries go asymptomatic [2, 96, 106]. Nonetheless, with insertion of CPS and ATPS goes the risk of vertebral artery injury, which in turn can be fatal! But, as the use of CPS becomes more widespread with time and our knowledge base expands, the concerns regarding neurovascular injuries will be put into perspective. The issue of ATPS accuracy and savety will be further discussed in 'Part 2' of the ATPS-project.

Conclusion

The idea behind the ATPS–plate system lies in the desire to increase stability after reconstruction of highly unstable, particularly multilevel decompressed cervical spines in fractures, degenerative and neoplastic disorders. Before implementation of a new technique, the authors exposed and showed that the morphology of the cervical spine is feasible for ATPS insertion, suggesting that this technique is also clinically possible in selected vertebrae and patients. The authors also offered the anatomical template that enables preclinical release protoyping of an ATPS–plate system which in turn enables biomechancial testing of the whole construct prior to any clinical application. The surgical technique of ATPS and its accuracy will be evaluated with use of manual and computer-assisted insertion techniques. A three-column fixation device as with the ATPS–plate system could be a valuable tool with a biomechanical advantage in the surgeon's armamentarium. Surgeons will have to consider the trade-off between the potential benefit of increased construct stability and avoiding added posterior surgery and the potential of neurovascular injury risk that goes with any cervical pedicle screw insertion technique.

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