Eur Spine J (2016) 25:532–548
DOI 10.1007/s00586-015-3898-x

ORIGINAL ARTICLE

Factors influencing radiographic and clinical outcomes in adult scoliosis surgery: a study of 448 European patients

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Received: 27 September 2014 / Revised: 19 March 2015 / Accepted: 19 March 2015 / Published online: 28 April 2015
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Abstract

Introduction/purpose In adult scoliosis surgery (AS) delineation of risk factors contributing to failure is important to improve patient care. Treatment goals include deformity correction resulting in a balanced spine and horizontal lowest instrumented vertebra (LIV) in fusions not ending at S1. Therefore, the study objectives were to determine predictors for deformity correction, complications, revision surgery, and outcomes as well as to determine predictors of postoperative evolution of the LIV-take-off angle (LIV-TO) and symptomatic adjacent segment disease (ASD).

Methods The authors performed a retrospective analysis of 448 patients who had AS surgery. Patients' age averaged 51 years, BMI 26, and follow-up of 40 months. According to the SRS adult scoliosis classification, 51 % of patients had major lumbar curves, 24 % each with single thoracic or double major curves. 54 % of patients had stable vertebra at L5 and 34 % of patients had fusion to S1. The mean number of posterior fusion levels was eight and implant density 73 %. Among standard radiographic measures of deformity the LIV-TO was assessed on neutral and bending/traction-films (bLIV-TO). Clinical outcomes were assessed in 145 patients with degenerative-type AS using validated measures (ODI, COMI and SF-36). Prediction analysis was conducted with stepwise multiple regression analyses.

Results Preoperative thoracic curve (TC) was 53° and 33° at follow-up. Preoperative lumbar curve (LC) was 43° and 24° at follow-up. Curve flexibility was low (TC 34 %/LC 38 %). TC-correction (38 %) was predicted by preoperative TC ($r = 0.9$) and TC-flexibility ($r = 0.8$). LC-correction (50 %) was predicted by preoperative LC ($r = 0.8$), LC-flexibility ($r = 0.8$) and screw density ($r = 0.7$). Preoperative LIV-TO was 18.2° and at follow-up 9.4° ($p < 0.01$). 20 % of patients had a non-union (18 % at L5-S1). The risk for non-union at L5-S1 increased with age ($p = 0.04$), low screw density ($p = 0.03$), and postoperative sagittal imbalance [(T9-tilt ($p = 0.01$), C7-SVA ($p = 0.01$), LL ($p = 0.01$) and PI-LL mismatch ($p = 0.01$)]. 32 % of patients had revision surgery. Risk for revision was increased in fusions to S1 ($p < 0.01$), increased BMI ($p < 0.01$), sagittal imbalance (C7-SVA, $p < 0.01$), age ($p = 0.02$), and disc wedging distal to the LIV ($p < 0.01$). To a varying extent, clinical outcomes negatively correlated ($p < 0.05$) with revision, ASD, perioperative complications, age, low postoperative TC- and LC-correction, and sagittal and coronal imbalance at follow-up (C7-SVA, PT, and C7-CSVL). 59 patients had ASD, which correlated with preoperative and postoperative sagittal and coronal parameters of deformity. In a multivariate model, preoperative bLIV-TO ($p < 0.01$) and preoperative LIV-TO ($p < 0.01$) demonstrated the highest predictive strength for follow-up LIV-TO.

Electronic supplementary material The online version of this article (doi:10.1007/s00586-015-3898-x) contains supplementary material, which is available to authorized users.

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Conclusion In the current study, the magnitude of deformity correction in the sagittal and coronal planes was shown to have significant impact on radiographic and clinical outcomes as well as revision rates. Findings indicate that risks for complications might be reduced by restoration of sagittal balance, appropriate deformity correction and advanced lumbosacral fixation. The use of preoperative LIV-TO and LIV-TO on bending/traction-films were shown to be useful for surgical planning, selection of the LIV and prediction of follow-up-TO, respectively. Parameters of sagittal balance rather than coronal deformity predicted ASD.

Keywords Adult scoliosis · Surgery · Correction · Adult deformity · Complication · Outcome

Introduction

The surgical goals with adult scoliosis surgery are decompression of stenosis, restoring spinal balance, and improving clinical deformity, pain and disability. Achievement of these goals can be difficult. Also, adult deformity surgery is accompanied by high rates of major complications (32 % [3, 4], 30–50 % [6], 28–32 % [7], 54 % [8]), readmission (11–17 % [9]), and need for revision surgery (11–20 % [6], 17 % [10], 33 % [11], 35 % [12], 42 % [8]). Compared to adult deformities in general, risk factors for complications and revision surgery in adult scoliosis patients are less studied and usually the data is derived from multicenter analysis. Though valuable, these analyses can be biased with respect to applied techniques and complication reporting. Most adult deformity studies focus on clinical and demographic variables as risk factors for complications and reoperation [7, 9–16]. In contrast, the influence demographic, clinical and radiographical indices of sagittal and coronal balance have on complication, non-union and revision surgery in adult scoliosis is less studied [17–21]. Therefore, in an effort to advance our understanding of the risk factors for adult scoliosis surgery, our first objective was to determine predictors for complications and revision surgery as well as to assess radiographic and clinical outcomes in a European single-center series. Ultimately this information can assist patients and surgeons with decision making relevant to adult scoliosis surgery.

With increasing literature on adult deformity, the issue that seems increasingly neglected is that for many adult scoliosis patients, fusion to the sacrum is not required. Compared to adolescent patients, adult scoliosis with intended fusion stopping in the lumbar spine is characterized by increased rigidity and lower rates of spontaneous correction of the unfused fractional curves [22]. Residual wedging of the lowest instrumented vertebra (LIV) can increase the risk of and accelerate adjacent segment degeneration, adding-on, and revision surgery due to mechanical degenerative decompensation of the mobile lumbar segments [23, 24]. Therefore, the second purpose of this study was to identify parameters that are most valuable for planning the appropriate LIV and prediction of the postoperative LIV-TO (=take-off angle of the LIV).

Materials and methods

An adult scoliosis database was reviewed from 2001 to 2010 and patients fulfilling the following criteria were included: minimum age ≥30 years, scoliosis ≥20°, follow-up of ≥1 year, and anterior or posterior scoliosis surgery spanning ≥4 spinal levels. Patients with significant prior surgery defined as surgery >1 level, neurologic condition such as Parkinson's or neuromuscular scoliosis or a history of Halo traction were excluded.

Surgical technique

In the period studied, adult scoliosis patients were operated on using consistent techniques: for lumbar curves (LC), the strategy included segmental release, either combined antero-posterior or posterior-only in terms of discectomies and Ponte-type decompressions. No patient had a PSO. Thoracic curves (TC) were addressed using facetectomies and distractive/compressive maneouvers. Most patients had posterior screw-rod instrumentation (Xia 2, Stryker, Monterreux, France) and a minority had anterior correction and fusion (ASF) using 3rd generation systems. All patients had fusion with posterior iliac crest or rib bone grafts. No patient received bone substitutes.

Implant density (%) for posterior fusions was calculated based on the number of fused levels, anticipating a maximum of two pedicle screws/hooks per level, divided by screws used per vertebra.

In lumbosacral fusions, a staged ALIF operation was performed unless autofusion of L5-S1 or a collapsed disc space with large syndesmophytes was present. Patients were braced postoperatively for 4 months.

In posterior fusions, the upper instrumented level (UIV) or UIV + 1 was the end vertebra (EV) of the curve. For the LIV, the following criteria were appreciated: LIV at least EV + 1, ≤2 levels cephalad to the stable vertebra (SV), at the lumbar level that corrects parallel to the sacrum in the reversed bending film, and not adjacent to a severely degenerated disc or facet joint.

Radiographic parameters

A total of 41 radiographic parameters were studied using preoperative, postoperative and follow-up biplanar full-spine standing radiographs. Parameters selected defined severity of scoliotic deformity, shoulder and pelvic tilting, end-level alignment, and global sagittal and coronal balance using Cobb measurements. All abbreviations and main radiographic parameters are explained in Table 1 and Figs. 1 and 2. Curve flexibility and radiographic parameters that determine mobility of the LIV were studied on preoperative full-standing (LIV-TO) and on reverse bending and traction radiographs (Fig. 2). Beforehand, analysis did not reveal significant differences between LIV-TO on bending and on traction radiographs (median 13° vs 13.5°, $p = 0.44$, $n = 230$ comparisons). Thus, the best value was taken as the bending/traction-LIV-TO (bLIV-TO).

On preoperative MRI scans, the degree of disc degeneration was classified according to Pfirmann (types 1–5). For statistical purposes, types 1–3 were defined as 'non-degenerated' and types 4 and 5 as 'degenerated'.

Scolioses and modifiers were classified according to the Schwab SRS adult scoliosis classification [25, 26]. LC were also defined according to Lenke into modifier A-C.

Clinical parameters

Standard demographic information was recorded. Medical records, surgical summaries, office charts and radiographs were studied and parameters of interest regarding diagnosis, indication, fusion levels, surgical technique, approach, instrumentation type, complications, and revision surgery were recorded. Analysis included the subjective degree of patients' satisfaction at follow-up. Clinical outcomes using validated measures were evaluated in patients with degenerative-type adult scoliosis, including the SF-36, ODI (Oswestry disability index), and COMI (central outcome measures index [27]).

Adverse events and surgical complications

Major perioperative medical and surgical complications were graded according to Glassmann [15]. Reoperation was defined as any unplanned return to the operating room as a result of the original surgery. Non-union was defined based on radiographs with evidence of screw loosening, implant failure or lucencies. A CT-scan was performed if there was doubt based on the radiographs. Surgical exploration was done in difficult cases.

A definition of symptomatic adjacent segment disease (ASD) was applied when a patient's symptoms related to adjacent segment degeneration required treatment and revision was either recommended or performed [28].

Statistical analysis

Data consistency was verified and data were screened for outliers and normality using quantile plots. Cross-tabulation tables were analyzed using Fisher's exact and Pearson's Chi squared tests. Paired t tests, multivariate linear as well as logistic regression models (with corresponding odds ratio and 95 % confidence intervals) were used to analyze the data. A coefficient of determination was used to estimate the predictive power of the regression analysis. All tests were two-sided and a p value less than 5 % indicated a statistically significant result. All statistical analyses were performed using NCSS 8 (NCSS, Kaysville, UT, USA) and STATISTICA 10 (StatSoft, Kaysville, UT, USA).

A multivariate analysis of risk factors for complications, ASD, and revision surgery was performed factoring in all radiographic and clinical parameters. Subset analyses were done for patients with lumbosacral fusion surgery (=LS-group), fusions to L5 (=L5-group), and fusions to L4 or L5 (=L4-L5-group). To enable benchmarking with previous studies, subset analysis was also done for patients with adult or degenerative-type scoliosis, ≥5 fusion levels, LIV at L4, L5 or S1, and minimum screw density >40 % (=L4-S1-group).In patients with any mobile lumbar segment below their fusion (LM-group), stepwise multivariate regression analysis was performed to identify predictors for postoperative LIV-TO.

Results

Sample characteristics

Mean patients' age was 51 ± 12 years, body mass index (BMI) averaged 26 ± 4 kg/m^2, and ASA-grade was 2.1 ± 0.6. Mean follow-up duration was 40 ± 23 months. Main sample characteristics including description of deformity characteristics for all patients are summarized in Table 2.

Radiographic results

Deformity correction

The main radiographic results for all patients are summarized in Table 3. Subset analyses of radiographic results for L5-, LS-, L4-S1-, and LM-groups are summarized in Table 4.

Statistical analysis showed that TC-correction was significantly correlated with preoperative TC ($r = 0.9$) and TC-flexibility ($r = 0.8$). LC-correction was significantly correlated with preoperative LC ($r = 0.9$) and LC-flexibility ($r = 0.8$). In patients with an instrumented lumbar spine, LC-correction was additionally influenced by screw density ($r = -0.8$) and patients that underwent an anterior release had improved LC-correction ($p < 0.01$).

Table 1 Abbreviations, radiographic parameters, and measurement techniques

Abbreviation	Radiographic parameter (dimension)	Radiographic measurement technique
ASA-grade	American Society of Anaesthesiologists physical status classification	Types 1 (normal healthy patients) to type 5 (moribund and not expected to survive without surgery)
AVR	Apical vertebral rotation of MTC (AVR-MTC) or LC (AVR-LC)	Vertebral rotation at the apex of deformity according to the method of Nash and Moe stratified into four grades (0–4)
C7-SVA	Sagittal vertical axis of C7 (cm)	Plumb line through the center of C7 in reference to the posterior endplate corner of S1
CSVL	Deviation of central sacral vertical line (CSVL) off C7 plumb line (cm)	Offset distance in centimeters of the C7 coronar plumb line off the CSVL; a negative value denotes deviation of the C7 plumb line to the left of the CSVL, while a positive value denotes deviation to the right
Deep-seated L5	Vertical level of L5 endplate is seated below iliac crests	On coronal radiographs deep-seated L5 vertebra is determined based on the L5 cephalad endplate position below the iliac crest. A L5 vertebra is supposed to provide intrinsic lumbosacral stability
Lateral translation	Degree of maximum lateral subluxation/listhesis	Description of severity of maximum lateral subluxation of one vertebra relative to the adjacent stratified into <1, 1–6, and >6 mm
LC	Cobb angle of the thoracolumber/lumbar Lumbar curve (°)	Standard Cobb angle measurement
LIV	Lowest instrumented vertebra	Defined per the vertebral level instrumented
LIVDA	LIV subjacent disc angle (°)	Coronal/sagittal disc angle made by the lower and superior endplates of the adjacent segment to the LIV, reported in absolute values; angles measured in coronal and sagittal plane
LIV-TO	LIV-take-off angle	Angle formed by endplate of LIV and horizontal line
bLIV-TO	LIV-TO on bending or traction radiographs	See LIV-TO
LL	Lumbar lordosis of L1 to S1 (°)	Angle formed by the upper endplate of L1 and the lower endplate of S1
PI-LL mismatch	Discrepancy between actual and ideal LL	Ideal LL is calculated as follows: LL = PI + 9°
TC	Thoracic curve (°)	Standard Cobb angle measurement
TC-/LC-bending	Cobb angle of TC or LC on bending radiographs	Standard Cobb angle measurement
TC-/LC-correction	Curve correction (in ° and %) at any given point, TC-correction equals spontaneous thoracic curve correction (SLCC)	Defined as the difference in the Cobb angle after surgery vs before surgery: Postoperative correction (%) = [(preop Cobb − postop Cobb)/preop Cobb] × 100 Follow-up correction (%) = [(preop Cobb − follow-up Cobb)/preop Cobb] × 100
TC-/LC-flexibility	Flexibility of thoracic curve or lumbar curve calculated by preoperative bending radiographs (in ° and %)	Defined as the difference in the Cobb angle in neutral vs bending radiographs: Bending-flexibility (%) = [(preop Cobb − bending Cobb)/preop Cobb] × 100
PI	Pelvic incidence (°)	Previously defined in other reports [1]
PJK-angle	Proximal junctional kyphosis angle (°)	The PJK-angle is defined as the angle obtained by the lower endplate tangent of the upper instrumented vertebra and the upper endplate tangent of the vertebra two levels cephalad to the upper instrumented vertebra
PJK	Proximal junctional kyphosis	PJK-angle ≥10° and at least 10° greater than preoperative measure [2]
PT	Pelvic tilt (°)	Previously defined in other reports [1]
Shoulder tilt	Shoulder tilt in the coronal plane (°)	As defined and validated by Kuklo [5].
SS	Sacral slope (°)	Previously defined in other reports [1]
Sagittal plane translation	Analysis of listhesis	The maximum anterior translation was graded according to the Meyerding classification of types 1–4 for each 25 % increase of translation
TK	Thoracic kyphosis of T4-T12 (°)	Angle formed by upper endplate of T4 and lower endplate of T12

Table 1 continued

Abbreviation	Radiographic parameter (dimension)	Radiographic measurement technique
TLA	Thoracolumbar angle T10-L2 in sagittal plane	Angle formed by upper endplate of T10 and lower endplate of L2
T9-tilt	T9-tilt	Angle between a line connecting the T9 center and hip axis and the vertical axis. T9-tilt is similar to PT [1]
UIV	Upper instrumented vertebra	Define per the vertebral level instrumented
UIVDA	UIV cephalad-adjacent disc angle (°)	Coronal/sagittal disc angle made by the lower and superior endplates of the adjacent segment to the LIV, reported in absolute values; angles measured in coronal and sagittal plane

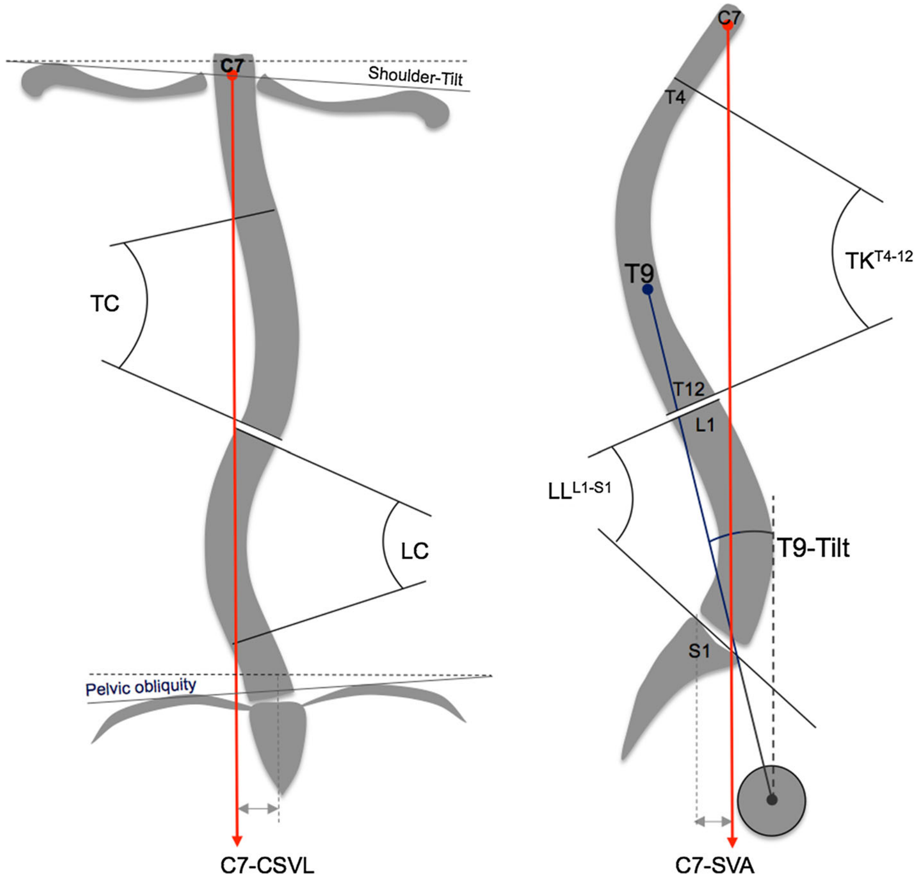

Fig. 1 Illustration of main radiographic measurements for coronal (*left*) and sagittal spinal deformity. For abbreviations see Table 1

Correction of deformity did not differ between idiopathic and degenerative-type adult scoliosis, but for both, correction was significantly better compared to congenital adult scoliosis (true for TC-correction, LC-correction, C7-SVA, C7-CSVL). The scoliosis correction index for major curves was 1.5 ± 3.3, indicating that, on average, scolioses parameters were corrected to better than their preoperative bending value. For example, the instrumented LC was 2.4 ± 4.1.

Concerning sagittal plane analysis, the typical significant interdependencies ($p < 0.05$, $r = 0.4$–0.8) between spino-pelvic (PI, SS, PT) and spinal parameters (LL, TK, PJK-angle, C7-SVA) existed. From preoperation to follow-up we noted a steady increase in the TK, PJK-angle, and C7-SVA, with the difference in PJK-angle reaching significance ($p < 0.0001$), indicating increased positive sagittal balance postoperatively. Multivariate analysis did not identify a single predictor for an increase in TK, C7-SVA, and PJK-angle, while a significant correlation existed for preoperative and postoperative PJK-angle ($r = 0.7$, $p < 0.05$).

Resolution of preoperative LIV-take-off angle (LIV-TO)

The LM-group included 295 patients with fusion stopping in the lumbar spine (Table 4). 35 % of these patients

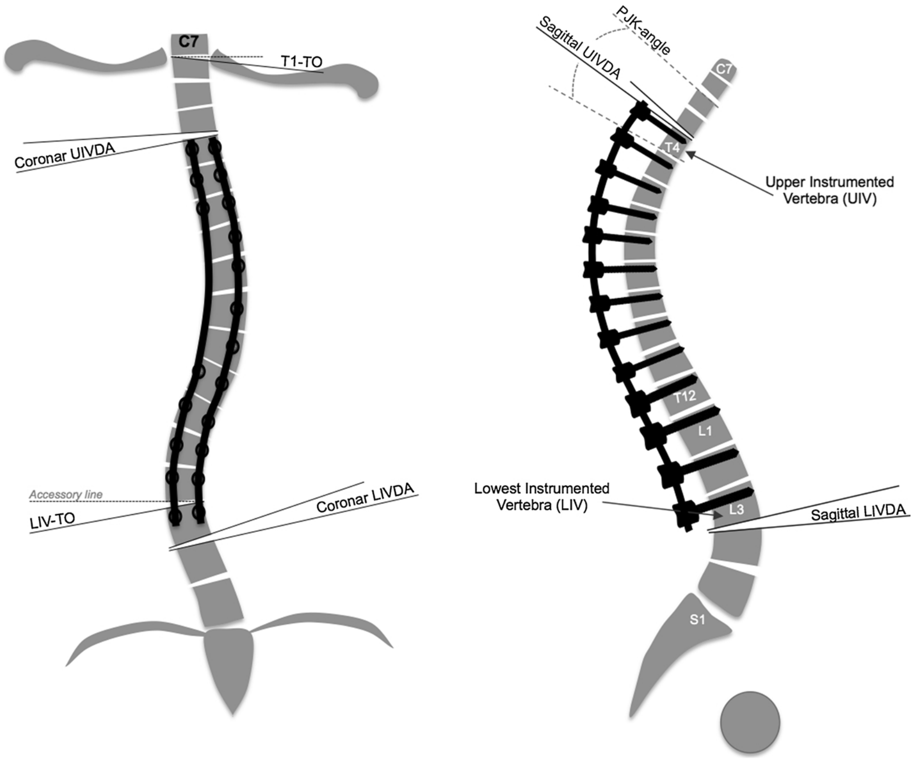

Fig. 2 Illustration of main radiographic measurements for segmental analysis of wedging angles adjacent to upper and lower instrumented vertebra in coronal (*left*) and sagittal (*right*) plane. For abbreviations see Table 1

had single TC, 33 % LC, and 32 % double major curves. 161 patients (55 %) had fusion ending at L4 or L5. 198 patients (67 %) had all pedicle screw constructs. Revision surgery was indicated in 85 patients (28 %), 55 patients (19 %) had a non-union. A total of 27 patients (9 %) had distal ASD.

Preoperative LIV-TO was 18.8 ± 9.4°, postoperative 9.5 ± 6.7°, and at follow-up 9.6 ± 6.4°. Preoperative to postoperative changes were significant ($p < 0.001$) and remained stable thereafter. Predictive models were developed for resolution of postoperative LIV-TO. In the predictive model, bLIV-TO ($p < 0.001$) and preoperative LIV-TO ($p < 0.001$) were identified as the best input variables. The prediction equation was as follows: postoperative LIV-TO = 0.95 + 0.32 × (preoperative bLIV-TO) + 0.22 × (preoperative LIV-TO). The model achieved a high level of accuracy ($R^2 = 0.64$). For prediction of LIV-TO at follow-up, the model remained significant (input variable bLIV-TO, $p = 0.00001$; preoperative LIV-TO, $p = 0.0016$) with a high level of accuracy ($R^2 = 0.59$). Further analyses with removal of data from bending/traction-films revealed that using preoperative LIV-TO alone, the model still accounted for 62 % of the variance observed [$R^2 = 0.62$; equation: postop LIV-TO = 1.26 + 0.443 × (preop LIV-TO); $p < 0.0000001$].

Adverse events and surgical complications

Adjacent level complication

The LM-group included 295 patients. 59 patients (13 %) had a symptomatic ASD. Proximal ASD accounted for 54 % of patients and distal ASD accounted for 46 %.The risk for ASD was increased with greater sagittal and coronal plane deformity.

Patients with proximal ASD had significantly increased preoperative coronal UIVDA ($p = 0.01$), postoperative C7-SVA ($p < 0.05$, OR = 0.98, 95 % CI 0.79–1.0, $p = 0.049$), postoperative pelvic obliquity ($p = 0.04$), preoperative PT ($p = 0.03$, OR = 0.95, 95 % CI 0.9–1.0) and PT at follow-up ($p = 0.048$). Specifically, an increase of PT by 14° doubled the risk for cranial ASD.

Patients with distal ASD were shown to have increased preoperative sagittal LIVDA ($p = 0.02$, OR = 1.03, 95 % CI 1.0–1.05) postoperative sagittal LIVDA ($p = 0.01$), bLIV-TO ($p = 0.02$), postoperative-instrumented LC ($p = 0.04$), and more frequent ASF ($p = 0.02$). Stratification of patients with sagittal LIVDA of −10° to 10°, <−10°, and >10° showed that patients with a LIVDA >10° (22 %) and <−10° (11 %) had increased rates of distal ASD ($p = 0.01$) compared to patients with LIVDA −10° to 10° (6 %).

Table 2 Main deformity characteristics of all adult scoliosis patients, $n = 448$

Characteristic	Distribution of parameter	Patients (%)
Adult scoliosis types	Adult idiopathic	236 (53 %)
	Degenerative type	185 (41 %)
	Congenital	27 (6 %)
SRS adult spinal deformity classification primary curve types	Double major	105 (23.5 %)
	Double thoracic	3 (0.7 %)
	Thoracolumbar/lumbar	229 (51 %)
	Single thoracic	109 (24 %)
Lenke classification lumbar modifier	Type A	58 (13 %)
	Type B	92 (21 %)
	Type C	296 (66 %)
Surgical approach	Antero-posterior	10 (2 %)
	Anterior released levels	5 ± 1 levels
	Posterior-only	264 (59 %)
	Fusion levels	8 ± 3 levels
	Postero-anterior	104 (23 %)
	Anterior ALIF-levels	3.3 ± 1 levels
	Anterior-only	70 (16 %)
	Fusion levels	5 ± 1 levels
Concave thoracoplasty (CTP—for rib hump deformity correction)		108 (24 %)
Age $\geq$ 50 years at surgery		238 (53 %)
Previous surgery	Any previous surgery (fusion and decompression)	46 (10 %)
	Spinal fusion max. 1 level	4 (9 %)
Posterior fusion length		7.4 ± 3 levels
Number of patients with $\geq$5 fusion levels		324 (72 %)
Implant density in posterior fusions		78 ± 25 %
Pedicle screw-only constructs		350 (78 %)
Lumbar/lumbosacral fusion to thoracic levels		244 (54 %)
Proximal junctional kyphosis (PJK-angle >10°)	New PJK postoperative (valid pairs, $n = 242$)	49 (20 %)
	New PJK at follow-up (valid pairs, $n = 235$)	84 (36 %)
	Revision rate in pts with new postop PJK	11 (22 %)
	Revision rate in pts w/o new postop PJK (valids, $n = 175$)	56 (31 %)
	Revision rate in pts with new follow-up PJK (valids, $n = 84$)	26 (31 %)
	Revision rate in pts w/o new follow-up PJK (valids, $n = 153$)	55 (36 %)
Degenerative listhesis or isthmic spondylolisthesis listhesis		98 (22 %)
	Meyerding grade 1	83 (85 %)
	Grade 2	12 (12 %)
	Grade 3	3 (3 %)
Subluxation modifier (lateral olisthesis)		410 (92 %)
	Maximum lateral subluxation <1 mm	121 (27 %)
	1–6 mm	189 (42 %)
	>6 mm	100 (22 %)
Most common apex of LL	L4	249 (56 %)
	L5	97 (22 %)
	L3	82 (19 %)

Table 2 continued

Characteristic	Distribution of parameter	Patients (%)
Most common apex of scoliosis in major thoracic curves	T8	69 (23 %)
	T9	69 (23 %)
	T10	48 (15 %)
	L1	39 (12 %)
Most common apex of scoliosis in major lumbar curves	L2	178 (40 %)
	L3	88 (20 %)
	L1	34 (10 %)
Deep-seated L5 vertebra		312 (70 %)
Fusion to the sacrum		55 (34 %)
	Use of S1 pedicle screws only	133 (87 %)
	Use of S1 pedicle and S2-ala screws	20 (13 %)
Most common location of stable vertebra (SV)	L5	243 (54 %)
	L4	107 (22 %)
	L3	23 (5 %)
Lowest instrumented vertebra (LIV)	Fusion to L4	113 (25 %)
	Fusion to L5	67 (15 %)
	Fusion L4, L5, or S1	242 (78 %)
	Fusion to L4, L5 or S1 to thoracic levels	181 (55 %)

Valids indicate absolute number of patients with radiographic visualization of PJK

Preoperatively, 23 (10 %) of 240 patients with valid MRI data had a preoperative degenerated disc below the LIV. This had no impact on the development of caudal ASD. Findings stressed that the LIV was less likely to be selected close to a degenerative disc. Patients with distal ASD had shorter follow-up compared to patients without ASD ($p < 0.001$, OR = 0.98, 95 % CI 0.97–0.99).

The L5-group included 67 patients (15 %). Revision surgery because of caudal ASD was indicated in 10 patients (15 %). Multivariate analysis showed that C7-SVA at follow-up was the only significant parameter indicating distal ASD (6.1 ± 4.2 vs 3.6 ± 3 cm, $p = 0.04$; OR = 1.3, 9 % CI 1.0–1.6, $p = 0.048$), as the differences for postoperative C7-SVA (5.5 ± 5.3 vs 3.1 ± 3.7) failed to reach significance.

In the L4-S1-group, 14 patients (7 %) had proximal ASD. These patients had larger preoperative PT (35.4° vs 25.4°, $p = 0.01$), postoperative PT (28.4° vs 24.9°, ns) and follow-up PT (38° vs 27.9°, $p = 0.005$). Also, these patients presented with higher postoperative T1-TO (8.1° vs 4.6°, $p = 0.02$) and smaller follow-up SS (24.8° vs 31.7°, $p = 0.02$). Patients with lumbar/lumbosacral fusion to the thoracic spine were less likely to develop proximal ASD compared to fusion stopping in the lumbar spine (6 vs 16 %, $p = 0.04$) as well as patients with fusion to S1 (10 vs 4 %, ns).

The results for PJK are summarized in Tables 3 and 4. The distributions of PJK and reoperation rates are shown in Table 2. The number of patients with newly developed postoperative PJK and a reoperation was 22 and 31 % in patients with and without preoperative PJK, respectively. At follow-up, these measures were 31 and 36 %, respectively. There were no significant correlations between PJK and a need for reoperation.

Early medical and surgical complications

Immediate postoperative major medical complications occured in 42 patients (9 %). Immediate surgical complications occurred in 32 patients (7 %), with reoperation indicated in 27 patients. Increased age was a risk factor for both medical complications (55 vs 51 years, $p = 0.04$) and early surgical complications ($p = 0.01$). Specifically, regression analysis revealed a doubled risk for surgical complications with an increase in age of 17 years (OR = 0.96, 95 % CI 0.92–0.99, $p = 0.01$). Also lumbosacral fusions increased the risk significantly (11 vs 2 %, $p < 0.01$; OR = 3.6, 95 % CI 1.4–9.3, $p < 0.01$). A total of 18 patients (4 %) had wound infections. Adult scoliosis surgery including ALIF did not influence revision rates ($p = 0.3$). A list of perioperative complications is shown in Table 5 (electronic supplement).

Non-union

In total, 90 patients (20 %) suffered a non-union. 26 patients (6 %) had a non-union and ASD. Risk factors for non-union included sagittal imbalance in terms of

Table 3 Summary of radiographic results for all adult scoliosis patients ($n = 448$)

Radiographic parameter (unit)	Preop	Postop	Follow-up	p level (Δpreop to postop)	p level (Δpreop to follow-up)	p level (Δpostop to follow-up)
Sagittal parameter						
PJK-angle (°)	5.5 ± 10	6.3 ± 10	8.7 ± 11	$p = 0.02$	$p < 0.0001$	$p < 0.0001$
Sagittal UIVDA (°)	1.7 ± 4.4	1.8 ± 4.1	2.3 ± 5.5	ns	$p = 0.003$	ns
Sagittal LIVDA (°)[a]	−2.5 ± 15.7	−1.9 ± 15	−1.7 ± 13	ns	ns	ns
C7-SVA (mm)	29 ± 39	25 ± 35	35 ± 41	ns	$p = 0.001$	$p = 0.0001$
T9-tilt (°)	10.5 ± 5	10 ± 7	10 ± 7	ns	ns	ns
SS (°)	37 ± 11	36 ± 10	35 ± 11	$p = 0.01$	$p < 0.0001$	$p = 0.02$
PI (°)	59 ± 14	59 ± 15	60 ± 16	ns	ns	ns
PT (°)	24 ± 11	24 ± 11	26 ± 12	ns	$p = 0.01$	$p = 0.01$
LL L1-S1 (°)	45 ± 19	47 ± 15	46 ± 17	ns	ns	ns
Predicted LL (°)	–	–	68.2 ± 14.2	–	–	–
Mismatch predicted vs actual LL (°)		–	23.9 ± 15.8	–	–	–
TK T4–T12 (°)	30 ± 17	31 ± 14	34 ± 15	ns	ns	ns
Coronar parameter						
C7-CSVL (mm)	20 ± 21	20 ± 17	17 ± 14	ns	$p = 0.003$	$p = 0.0002$
Coronal LIVDA (°)	7.3 ± 4.6	4 ± 3.4	4.2 ± 4.3	$p < 0.0001$	$p < 0.0001$	ns
Coronal UIVDA (°)	4 ± 3.2	3.2 ± 2.9	3.6 ± 3.6	$p < 0.0001$	$p = 0.04$	ns
Shoulder tilt (°)	2.6 ± 2.1	2.3 ± 1.7	2.4 ± 2	$p = 0.01$	ns	$p = 0.049$
LIV-TO (°)	18 ± 10	9.5 ± 8	9.5 ± 7	$p < 0.0001$	$p < 0.0001$	ns
bLIV-TO (°)	13 ± 9	–	–	–	–	–
LIV-rotation[b]	0.7 ± 0.7	–	–	–	–	–
Thoracic curve—TC (°)	53 ± 26	32 ± 23	33 ± 18	$p < 0.0001$	$p < 0.0001$	ns
Instrumented TC (°)	53 ± 26	28 ± 19	29 ± 18	$p < 0.0001$	$p < 0.0001$	ns
T1–TO (°)	5.1 ± 4.8	5.4 ± 4.9	5.2 ± 4.9	ns	ns	ns
TC-bending (°)	38 ± 25	–	–	–	–	–
TC-flexibility (%)	34 ± 27	–	–	–	–	
TC-correction (%)	–	39 ± 28	38 ± 28	–	–	ns
Lumbar curve—LC (°)	43 ± 19	23 ± 15	23 ± 15	$p < 0.0001$	$p < 0.0001$	ns
LC-bending (°)	29 ± 17	–	–	–	–	–
LC-flexibility (%)	40 ± 23	–	–	–	–	–
LC-correction (%)	–	50 ± 25	47 ± 27	–	–	ns
Instrumented LC (°)	43 ± 19	20.3 ± 15	20.7 ± 15	$p < 0.0001$	$p < 0.0001$	ns
Instrumented LC-correction (%)	–	48 ± 24	47 ± 26	–	–	ns
Pelvic obliquity (°)	2.3 ± 1.9	2.1 ± 1.7	2.2 ± 2	$p = 0.01$	ns	ns
AVR major thoracic curves	2.2 ± 0.8	–	–	–	–	–
AVR major lumbar curves	2.2 ± 0.7	–	–	–	–	–

For abbreviations see Table 1

ns non significant, *T1-TO* T1 take-off angle, *AVR* apical vertebral rotation

[a] Negative value denotes lordosis

[b] Rotation according to Nash and Moe

increased postoperative C7-SVA (6 ± 4 vs 3 ± 4 cm, $p < 0.001$; OR = 0.93, 95 % CI 0.86–1.01, $p = 0.07$). Risk for non-union was also increased with smaller postoperative LL (OR = 1.02, 95 % CI 1.00–1.04, $p = 0.02$) and follow-up T9-tilt ($p = 0.03$). Specifically, an increase of LL by 35° reduced the risk for a non-union by half. BMI also had a significant impact (OR = 0.91, 95 % CI 0.86–0.96, $p < 0.001$) as the risk of non-union doubled if BMI increased by seven units. In contrast, coronal imbalance (C7-CSVL), the severity of sagittal or coronal vertebral slippage, and the presence of deep-seated L5 vertebra had no significant influence on non-union.

Table 4 Comparison of main radiographic and clinical characteristics of adult scoliosis patients with fusion to lumbar spine, L5 vertebra or S1

Parameter	LM-group LIV = cephald to S1 ($n = 295$)	LS-group LIV = S1 ($n = 153$)	L5-group LIV = L5 ($n = 67$)	L4-S1-group LIV = L4, L5 or S1 ($n = 181$)
Age	46 ± 11 years	61 ± 10 years	58.5 ± 10 years	59.1 ± 10.5
Follow-up (months)	41	40	36	35
Revision rate	$n = 85$ (29 %)	$n = 59$ (39 %)	$n = 24$ (36 %)	59 (33 %)
Screw density (%)	64	74	67	83
Fusion length	9.3 ± 3 levels	7.9 ± 3 levels	8.0 ± 3 levels	6.9 ± 2
LL preop (°)	48.2 ± 18.8	44.8 ± 19.3	38.9 ± 18.5	36.1 ± 18.3
LL postop (°)	50.4 ± 14.7	47.2 ± 14.7	46.8 ± 14.7	42.3 ± 12.3
LL follow-up (°)	50.3 ± 16.4	46 ± 17	41.6 ± 18.6	39 ± 14.2
TK preop (°)	31 ± 17.4	33.6 ± 1.6	27 ± 14.8	26.9 ± 14.1
TK postop (°)	31 ± 14.5	47.2 ± 14.7	31.2 ± 13.3	29.9 ± 11.8
TK follow-up (°)	34.1 ± 14.9	29.9 ± 16.5	34.3 ± 13.9	32.8 ± 13.3
Sagittal LIVDA preop (°)	−2.7 ± 15.3	−2.5 ± 15.7	−10.9 ± 16.3	−7.1 ± 17.9
Sagittal LIVDA postop (°)	−1.6 ± 14.7	−1.5 ± 14.7	−5.5 ± 16.9	−5 ± 14.5
Sagittal LIVDA follow-up (°)	−1.3 ± 13.7	−1.3 ± 13.7	−5.2 ± 17.3	−5.4 ± 15.4
C7-SVA preop (cm)	2.0 ± 3.6	2.9 ± 3.9	3 ± 3.9	3.9 ± 4.1
C7-SVA postop (cm)	1.8 ± 3.2	2.5 ± 3.5	3.4 ± 4	3.5 ± 3.8
C7-SVA follow-up (cm)	2.0 ± 3.6	3.3 ± 4.2	4.0 ± 3.3	5.2 ± 4.6
LC preop (°)	48.5 ± 18.3	43.2 ± 19.3	47.9 ± 20	40 ± 17.2
LC postop (°)	26.3 ± 14.4	22.7 ± 16.3	23.8 ± 17.7	17.8 ± 12.6
LC follow-up (°)	27.6 ± 14.7	23.6 ± 16.1	24.1 ± 17.5	17.9 ± 12.6
LC-flexibility (%)	36 ± 24.3	37.8 ± 23	33.6 ± 22.3	37.8 ± 21.1
LC-correction (%)	42.1 ± 24.8	46.7 ± 25.5	52.5 ± 26.4	57.5 ± 20.4
TC preop (°)	59.7 ± 23.7	52.5 ± 26.3	56.4 ± 25.1	40.8 ± 24.6
TC postop (°)	36 ± 21.8	31.8 ± 23	35.7 ± 24.6	16.9 ± 13.3
TC follow-up (°)	37.2 ± 20.1	33.2 ± 21.7	36.3 ± 23.3	24.2 ± 18.4
TC-flexibility (%)	32.8 ± 24.5	34.1 ± 25.9	20.7 ± 28.9	33.8 ± 31.2
TC-correction (%)	38.6 ± 18.9	37.9 ± 24.1	39.4 ± 20.5	42.9 ± 24.8
Coronal LIVDA preop (°)	7.4 ± 4.6	7.3 ± 4.6	6.8 ± 5.1	7.7 ± 5.3
Coronal LIVDA postop (°)	4.0 ± 3.4	4.0 ± 3.4	4.7 ± 6.1	3.9 ± 3.6
Coronal LIVDA follow-up (°)	4.2 ± 4.3	4.2 ± 4.3	3.5 ± 4.5	3.9 ± 3.7
C7-CSVL preop (cm)	1.9 ± 1.5	2.0 ± 1.9	2.2 ± 1.9	2.3 ± 2.3
C7-CSVL postop (cm)	1.9 ± 1.7	2.1 ± 1.7	2.5 ± 1.8	2.3 ± 1.7
C7-CSVL follow-up (cm)	1.5 ± 1.4	1.7 ± 1.5	1.8 ± 1.5	2.0 ± 1.5

For abbreviations see Table 1

In the L4-S1 group, 31 patients (17 %) had non-union. These patients had larger PI-LL mismatch (33° vs 24°, $p = 0.02$), smaller follow-up T9-tilt (5° vs 11°, $p = 0.008$), smaller follow-up LL (33° vs 40°, $p = 0.002$) and greater follow-up C7-SVA (9 vs 4.5 cm, $p < 0.0001$), while postoperative C7-SVA differences failed to reach significance (4.8 vs 3.2 cm, $p = 0.09$). These patients also had longer follow-up (50 vs 32 months, $p = 0.004$). For the subset analysis of patients with lumbosacral fusions, the differences related to non-union failed to reach significance (21 vs 11 %, $p = 0.08$).

Lumbosacral non-union

Analysis of patients in the LS-group revealed non-union in 27 patients (18 %). L5-S1 non-union accounted for 30 % of all non-unions. The incidence of non-union in these patients was lowered if extended sacral instrumentation with screws in S1 and S2-ala was used compared to using only S1-pedicle screws (5 vs 16 %; $p = 0.04$). Patients with non-union at L5-S1 had increased age ($p = 0.04$), lower screw density ($p = 0.01$), and larger sagittal imbalance [T9-tilt ($p = 0.03$), C7-SVA ($p = 0.0001$), LL ($p < 0.001$), and PI-LL mismatch ($p = 0.01$)]. Subset analysis of patients with lumbosacral fusions identified smaller follow-up T9-tilt (2.7° vs 10°, $p = 0.006$) as the single risk factor for non-union at L5-S1, while differences for postoperative T9-tilt and C7-SVA existed, they did not achieve statistical significance.

Revision surgery

Revision surgery was indicated in 144 patients (32 %) who had 1.7 ± 2.5 revision surgeries. 94 % of these patients had late reoperation (>3 months postoperative) while 6 % had early reoperation ($\leq$3 months postoperative). Sagittal imbalance postoperatively ($p < 0.01$) and at follow-up in terms of C7-SVA ($p < 0.01$, OR = 0.92, 95 % CI 0.86–0.99, $p = 0.02$) were shown to be risk factors. Specifically, an increase of postoperative C7-SVA by 8 cm increased the risk for revision by 50 %. In addition, sagittal LIVDA ($p = 0.01$), increased BMI ($p = 0.03$), and higher residual deformity in terms of large postoperative TC ($p < 0.01$) and small postoperative LL ($p < 0.001$, OR = 1.02, 95 % CI 1.0–1.03, $p = 0.02$), follow-up LL ($p < 0.01$) and increased age ($p = 0.02$) also increased the risk for revision. Furthermore, patients with postoperative sagittal LIVDA >10° or −<10° had increased revision rates (43 and 35 %, respectively) compared to patients with LIVDA of −10° to +10° (23 %, $p = 0.006$).

Reduced risk for revision surgery existed in lumbar/lumbosacral fusions crossing the thoracolumbar junction (30 %) compared to those stopping at the lumbar spine (39 %, ns). Patients with a fusion to the sacrum had increased revision rates (39 vs 29 %, $p < 0.00001$; OR = 2.3, 95 % CI 1.6–3.5, $p < 0.01$), but, patients with LIV = L5 had comparable revision rates to patients with LIV = S1 (39 vs 36 %, ns). Surgery for implant removal was only performed in eight patients (2 %). In all others, reoperation was for non-union repair (63 %), extension of fusion (40 %), infection treatment (12 %), and decompression and haematoma removal.

In the L4-S1-group, patients with revision had smaller postoperative LL (39.2° vs 43.7°, $p < 0.04$) and follow-up LL (32.8° vs 41.2°, $p < 0.001$) and had larger follow-up C7-SVA (7.3 vs 4.3 cm, $p < 0.001$) with smaller follow-up SS (27.7° vs 32.6°, $p < 0.001$). Postoperative C7-SVA was also different, but did not reach significance (4.2 vs 3.2 cm, ns). Also, patients with revision had longer follow-up durations (45 vs 31 months, $p < 0.001$).

A newly developed PJK postoperatively (19 %) did not have a significant influence on revision rates (33 vs 29 %, ns), even if patients with only posterior fusion >5 levels in idiopathic and degenerative adult scoliosis were included.

Clinical outcomes

Clinical outcomes were available for 145 patients with degenerative adult scoliosis. There were no significant differences for these patients compared to the remaining sample with respect to baseline parameters and in particular for revision rates, non-union rates, and C7-SVA. Survey of these patients revealed that 79 % were 'satisfied' or 'very satisfied' with their results at their last visit. Outcomes in terms of the ODI was 19 ± 1 % (0–41 %), COMI was 5.2 ± 2.6 points (0–9.8), SF-36 PCS was 38.7 ± 24.6 (3–96), and SF-36 MCS was 44.5 ± 25.6 (3–93). Interrelations between the validated measures were strong (e.g., COMI &ODI: $r = 0.82$).

Poorer clinical outcomes were observed in association with sagittal (C7-SVA, PT, LL, sagittal LIVDA) and/or coronal imbalance (C7-CSVL, T1-TO, shoulder-tilt, pelvic obliquity). Results from correlation analyses are summarized in Table 6 (electronic supplement).Clinical outcomes were also negatively influenced by the need for revision surgery (SF-36-MCS, $p = 0.03$), proximal ASD (SF36-PCS, $p = 0.06$), distal ASD (SF-36 MCS, $p = 0.07$), perioperative surgical complications (SF36-MCS, $p = 0.01$), increased patient age (COMI, $r = 0.55$, $p < 0.05$; ODI, $r = 0.5$, $p < 0.05$), and previous surgery (COMI: $p = 0.01$; ODI: $p = 0.01$).

Discussion

Adult scoliosis patients include a heterogenous group with a variety of deformities, patients 40 years of age with a single TC as well as patients that are 70 years of age with major positive sagittal imbalance as a consequence of a decompensated LC. Regardless, stratification of risk factors relevant to all types of adult scoliosis remains of interest to help counsel patients and to compare treatment options. Hence, in the current study we analyzed risk factors for adverse events of surgery in all adult scoliosis types taking into account the impact of all potentially relevant radiographic and clinical risk factors. Our goal was to conduct a comprehensive analysis taking into account all aspects related to adult scoliosis surgery from a global perspective. We did not exclude subgroups which otherwise might mitigate selection bias if published in a separate study with not including all relevant clinical and radiographic variables outlined in the current study (e.g., issues related to PJK or ASD). A multivariate analysis was done and identified postoperative and follow-up positive sagittal imbalance as a risk factor for non-union, ASD, revision surgery, and inferior clinical outcomes in the entire patient population as well as in subset analyses with patients with more homogenous characteristics (LS-group, L4-S1-

group). Baseline parameters such as ASA-grade, age, lumbosacral fusions, curve distributions, follow-up, and correction of TC and LC were comparable to other studies [3, 13, 15, 17, 29].

Deformity correction

Data on coronal plane correction in adult scoliosis patients from larger samples are sparse. In the current study, TC-correction averaged 39 % and LC-correction 50 %. Review of the literature shows that TC-correction ranges from 30 to 68 % and about 45 % on average [6, 7, 19, 22, 30], LC-correction ranges from 30 to 55 % and about 45 % on average [7, 30–32], and major curve correction ranges from 43 to 55 % [29, 33]. Correction rates do not compare well with those achieved in adolescent scoliosis. Our findings stress that for LC-correction in particular, preoperative flexibility and implant density had a significant influence. The lack of a significant correlation observed between screw density and TC-correction might be due to the low thoracic implant density in general in the period studied.

A progressive global increase of TK > 10° was reported to occur in 41 % of 73 patients with adult scoliosis and with UIV ≤ T9 [34]. We noted a steady increase of TK by 4° postoperatively, which echo observations by Kim [19] who also noted a net increase of 4°. A single risk factor could not be identified but our observations suggest that TK increase should be expected in adult scoliosis surgery and has to be taken into account during index surgery.

Correction of LIV-take-off (LIV-TO)

Biomechanical, histological, and clinical studies have indicated that substantial disc pressure profile asymmetry is to be expected with extension of the fusion into the lumbar spine and with asymmetric LIV-TO. Asymmetric loading, as experienced by the mobile lumbar discs below long scoliosis constructs with oblique LIV-TO, might accelerate the natural course of ASD [18, 35]. Therefore, particularly in adult scoliosis, a postoperative level LIV and a balanced spine in the sagittal and coronal plane are valuable in accomplishing physiological stress profiles below the fusion mass [18, 23]. Our study targeted the prediction of postoperative evolution of the LIV in adult scoliosis with long fusions not ending at the S1. We succeeded in establishing a predictive model with a high level of accuracy (Fig. 3). For planning LIV-selection, the current study provides a rationale by showing that postoperative LIV-TO is best predicted by the net effect of preoperative LIV-TO and bending-LIV-TO. For clinical use, the single parameter of LIV-TO and the suggested formula seems appropriate to improve prediction of postoperative LIV.

Perioperative complications

Fraughts in adult scoliosis surgery are related to major perioperative complications. Accurate incidence reporting is of importance to counsel patients and to determine individualized risk assessment. In our study, major medical (general) complications occurred in 9 %, perioperative

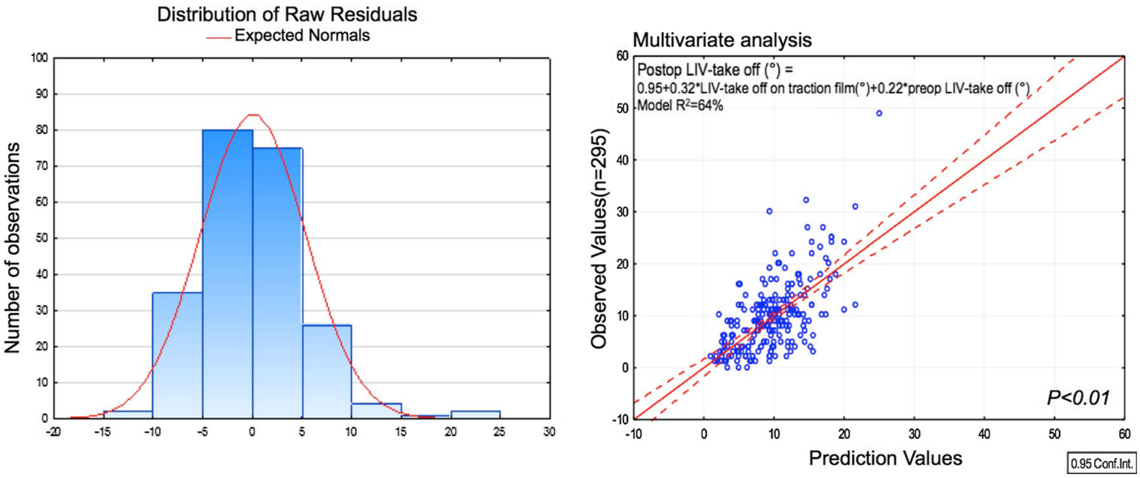

Fig. 3 Prediction models were developed regarding the resolution of the postoperative LIV-take-off angle (LIV-TO) including all adult scoliosis patients with fusion ending in the mobile lumbar spine ($n = 295$): multivariate analysis resulted in the following significant input variables: Preoperative LIV-TO on bending/traction-films ($p < 0.00001$) and preoperative LIV-TO on full-spine standing films ($p = 0.0001$). Prediction accuracy is illustrated in the *left graph* stressing the distribution of raw residuals (*x axis* Cobb angles, *y axis* number of cases) compared to expected distribution by the prediction equation. Small differences between predicted and observed values are illustrated in the *graph on the right*. Prediction equation was as follows: postoperative LIV-TO = 0.95 + 0.32 × (preop bLIV-TO) + 0.22 × (preop LIV-TO). Multiple square $R = 0.64$. The model accounted for 64 % of the variance observed

surgical complications in 7 %, and infections in 4 %. In comparison, Blamoutier [3] reported on multicenter results of 180 adult scoliosis patients (age $>$ 50 years, average ASA-grade of 2, and $\geq$12 months follow-up) and identified general complications in 16 %, and infections in 6 %. Charosky [17] reported general complications in 14 % of 306 adult scoliosis patients. Weistroffer [16] reported an infection rate requiring revision in 12 % [16], and Howe [12] reported 10 % medical complications, both in patients with mixed type adult deformity. Our rates are also comparable to the rate of acute perioperative complications (11 %) reported by the SRS mortality and morbidity database [36] as well as the rate of major perioperative complications reported in multicenter studies by Glassmann (10 %) [15] and Schwab (8 %) [14].

In a multicenter study of all types of adult deformity, early reoperation rates were 5 % [10] which is similar to our reported rate of 6 %. Those authors noted a 1-year reoperation rate of 17 %, which was not significantly altered in patients with three-column osteotomies (19 %). As in the SRS M&M study, in our study complications were not influenced by the type of adult scoliosis. In contrast to other studies [14, 36], we did not observe increased complication rates with combined antero-posterior surgeries. In Glassman's [15] multicenter study of 434 adult deformity patients also with $\geq$1-year follow-up, 14 % had a major surgical complication. Using the same criteria as Glassmann, Cho [7] reporting on 250 adult scoliosis patients from a single-center series and identified major complications in 28 and 32 % of primary and revision surgeries, respectively. An increased risk was shown with an increased age of patients particularly >60 years, which was similar to our findings of increased major surgical perioperative complications in patients of older age.

Non-union and revision surgery

The rate of non-unions in adult scoliosis surgery has been reported as 9 % [7], 12 % [17], 13 % [37], 15 % [7], 15 % [8], 19 % [3], and 32 % [13]. Kelly [13] reported a operation rate of 21 % in 455 adult deformity surgeries in a single-center series. The main causes of reoperation were non-union, ASD and PJK. Patients with non-union are more likely to undergo reoperation and these patients have poorer clinical outcomes compared to patients without reoperation [10, 38, 39] [19].

There is scant literature regarding comprehensive assessment of the associations of radiographic measures with risk of failure, non-union, and revision surgery. Most studies focus on the correlation of clinical variables and risk for complications in mixed groups of patients, with or without surgery, and include all adult deformity patients [29]. Only a few studies have tried to address this gap. In a single-center study of 132 patients with failed adult scoliosis surgery and non-union, a large postoperative SVA predicted an increased risk for persisting non-union in 10 % of patients [40]. Cho [7] reported on 250 adult scoliosis patients from a single-center series and identified an increased risk of non-union in revision vs primary adult scoliosis surgery cases (15 vs 9 %). However, radiographic measures were not correlated with non-union. In a multicenter study of 306 adult scoliosis patients [17], the preoperative PT (23° vs 26°) was identified as the only radiographic risk factor for revision surgery among lumbosacral fusions. In a smaller series of 45 patients [20] with adult scoliosis surgery for L5 or S1 sagittal decompensation, which frequently indicates reoperation, revision surgery occurred in 42 % of patients. Risk were increased with preoperative LL, preoperative SVA, and higher PI as well as hypolordotic fusion with postoperative LL $<$ 30° [20]. In long lumbosacral fusions, Kim [19] identified risk factors for non-union that included thoracolumbar kyphosis, osteoarthritis of the hip, postoperative SVA $\geq$ 5 cm, age $>$ 55 years, and inadequate sacropelvic fixation. In Blamoutier's study [3] the authors applied a stepwise risk analysis and identified fusion to sacrum, preoperative sagittal imbalance—particularly decompensated-fusion length, and comorbidities as major risk factors for revision. Risk for revision surgery was 25 % at 1 year and 50 % at 6 years.

Our review of the literature regarding the role of sagittal imbalance indicates that only a few studies offer some evidence that postoperative positive imbalance is actually a risk factor for non-union, sagittal decompensation at follow-up, construct failure and revision surgery. Results of our study indicate that preoperative, postoperative and follow-up positive sagittal imbalance is correlated with an increased rate of non-union and risk for revision surgery.

With respect to other parameters, while the study of Kim [41] did not reveal a significant difference regarding outcomes and revision prevalence whether fusion stopping at L1, T11 or T9, our study indicated less revisions in patients with fusion ending in the thoracic compared to the lumbar spine. Contrary to the results of a multicenter study by Schwab [14], in our study, BMI, had a significant negative influence on non-union and revision rate.

In our study, risk for non-union and revision surgery was also significantly increased in patients with fusions to the sacrum. Charosky [17] using iliac + S1 screws for $\geq$5 level fusions to the ilium in adult scoliosis patients reported a reoperation rate of 48 %. The risk increased in patients with PSO and higher preoperative PT (26° vs 23°). Non-union rates in adult deformity fusions to the sacrum range from 0 to 24 % [12, 16, 19, 38, 42]. With respect to postoperative imbalance (SVA $\geq$ 5 cm), insufficient sacropelvic fixation in patients with mixed type adult deformity was shown to increase risk for non-union in long fusions to the sacrum [19]. Likewise, the current study showed that sagittal balance and advanced lumbosacral fixation conferred improved fusion rates in patients with fusion to the sacrum when compared to fusions to S1 only. Evidence exists that with advanced lumbopelvic fixation (e.g., S1 + S2 screws, S1 + ilium screws, S1 + S2-ala-ilium screws) this rate might be further improved, while subsequent surgeries, for example, for removal of symptomatic iliac screws, might be indicated in 15–34 % [39]. Even though advanced lumbopelvic instrumentation has been utilized in several studies, the rate of non-union or 'mechanical failure' at L5-S1 remains 5–10 % [38, 42]. For example the use of BMP was shown to increase fusion rates in long adult deformity fusion by about 20 % [33, 43]. Thus, the appropriate method of lumbosacral stabilization for the range of severities of adult deformity has yet to be defined.

Symptomatic adjacent segment disease (ASD) and proximal junctional kyphosis (PJK)

Fusion stopping in the mobile lumbar spine in adult scoliosis is associated with a risk for adjacent segment degeneration requiring surgery (ASD), particularly at the distal levels. Distal ASD accounts for up to 28 % of reoperation in long fusions for adult deformity [13]. In a study by Edwards [44] 33 % of 31 patients with long fusions to L5 suffered ASD after a mean of 5.6 years. In a study by Charosky [17], 9 % had ASD. In a study by Brown [45] of 16 patients with long adult scoliosis fusions to L5, 19 % had ASD at L5-S1 after a mean of 32 months. In a study by Cho [20] of 24 patients with fusions to L5, nine patients had complications. Risk factors identified were sagittal imbalance and lumbar hypolordosis. 58 % of patients had radiographic adjacent degeneration and 3 % had ASD. In a study by Kuhns [31], 23 % had and 19 % were considered for reoperation because of ASD. In a series of 85 adult scoliosis patients with long fusions to L4 or L5, 12 % had ASD after a mean of 9 years [35].

In our study, postoperative sagittal balance and L5-S1 angulation correlated with L4-L5 and L5-S1 degeneration. Subset analysis for the L4-5 disc alone showed a significant correlation between postoperative positive sagittal imbalance and risk for radiographic degeneration. Likewise, degeneration at the L5-S1 disc significantly correlated with postoperative higher lordotic disc wedging at L5-S1. Notably, the correlation between sagittal balance and disc degeneration at L4-S1 failed to reach significance and in general there were no significant correlations between degeneration, pain and ASD. Accordingly, a systematic review on distal ASD after long thoracolumbar fusions with sample size not exceeding $n = 95$ showed ASD in 18 % of patients at 2 years follow-up. Preoperative sagittal imbalance was shown to be related to the risk of distal radiographic ASD. Only a higher postoperative fractional curve was shown to be significant risk factor for ASD [24]. Notably, in our study, residual deformity in the sagittal *and* in the coronal plane had a negative impact on the ASD rate. Our data also indicated that better deformity correction and balance in the sagittal and coronal planes reduced the risk for revision surgery related to ASD and led to improved clinical outcomes. Furthermore, statistical analysis revealed that a sagittal LIVDA $> 10°$ and $< -10°$ confers an increased risk for ASD and revision surgery.

Proximal ASD frequently coincidences with what is currently summed up in PJK. In a series of Howe [12] on 103 thoracic-to-ilium fusions, revision was indicated in 13 % for proximal ASD. PJK was noted to occur in 12–39 % and about 20 % on average [4, 13, 34, 46]. In one multicenter study of 180 adult scoliosis patients [3], PJK occured in 7 % and 50 % of these required surgery. In a recent single-center study [47] of 206 adult scoliosis patients, the incidence of PJK requiring revision increased in older patients with large corrections in their LL and sagittal balance. In another study of 157 adult scoliosis patients [2], PJK occured in 20 and 12 % of these required revision. In our study, PJK developed in 20 %. Reoperation rates did not differ in association with PJK.

In adult scoliosis, the cause of PJK is multifactorial. It has been reported that large changes in LL and sagittal balance, age, ligamentous element injury, high PI, TK $> 30°$ pedicle screws compared to hooks, rigid vs tapered rods, low BMD, sacropelvic residual sagittal imbalance, failed normalization of global sagittal alignment, and long fusions to the sacrum can affect PJK in adult deformities [2, 4, 46]. Notably, in our adult scoliosis patients, PJK was found to not be an independent risk factor for revision. This might be associated with a reoperation rate of 20 % related to mainly lumbar and lumbosacral non-unions with the failure due to sagittal imbalance more likely occurring at the lower lumbar and lumbosacral spine where fixation of the long fusion construct was more challenged than at the proximal anchor side within the rigid TC.

Clinical outcomes

It is believed that in adult deformity patients postoperative sagittal imbalance adversely affects clinical outcomes. Several studies validated this concept [48–50], however, Sanchez-Mariscal in 2012 [29] and Blondel in 2013 [51] recognized that the evidence for this assumption is still modest for adult deformities and more often derived from non-operated [26, 50, 52, 53] or mixed operated/non-operated cohorts [53–55]. Correlation strengths between clinical and preoperative radiographic measures were moderate to good [54, 55]. In a multicenter study by Lafage [53] on non-operated results, SVA, PT and sagittal T1-tilt were most highly correlated with HRQOL measures. Postoperative parameters were not studied. In a multicenter study [56] of 177 adult deformities (average age 54 years), patients with an improvement of PT, SVA or PI-LL modifiers were significantly more likely to achieve a minimal clinically important difference in ODI, SF-36 PCS, and SRS-scores.

Sanchez-Mariscal [29] published the first study correlating follow-up radiographic parameters and clinical outcomes in 59 adult scoliosis patients (average age >21 years, >4 levels fusions, major curve >40°). Greater positive sagittal balance, PI, and PT correlated with poorer SRS-22-scores. With increased age, SRS-22 and SF36-outcomes decreased ($r = 0.3$–0.5). Multivariate analysis including PT, age, and SVA did identify significance for the PT and age but with a R^2 of only 29 %. In contrast, coronal parameters did not correlate with HRQOL measures, and it is thought that the clinical impact of deformity is determined and predicted primarily by the sagittal plane [54]. Notably, in a study by Daubs [57] of 85 adult scoliosis patients, preoperative CSVL > 4 cm, LC change, and sagittal imbalance (SVA) were shown to impact SRS-22 scores with the latter being the most significant predictor. In a multicenter study by Acaroglu [58] of 483 patients with adult deformity, follow-up coronal imbalance and LC magnitude were shown to influence SRS-22 values among the SVA, LL, BMI, gender and age. In another study by Ploumis [59] of 58 adult scoliosis patients, preoperative coronal imbalance >5 cm, LL, but not sagittal imbalance, significantly affected function and outcomes. In our study, significant interdependence was observed between several clinical outcome measures and postoperative and follow-up radiographic indices of sagittal and coronal balance (C7-SVA and CSVL) with an emphasis on sagittal balance parameters (see Table 6). Of note, increased C7-SVA and lower LL were predictors of reduced clinical outcomes in terms of disease specific measures (ODI and COMI), while increased coronal imbalance and CSVL, respectively, indicated poorer clinical outcomes in both disease specific and general functional outcome measures (SF-36, ODI, COMI).

It is of note that not all clinical outcomes measured correlated both with postoperative and with follow-up radiographic indices of sagittal and coronal imbalance. Postoperative standing position in some patients might be affected by postoperative pain, though a standardized strict method was used in our clinic for full-spine radiographs. The current study suggests that mechanical failure and sagittal decompensation postoperatively depends on multiple radiographic and clinical variables. This might mitigate that statistical analysis failed to provide significance for some of the corresponding clinical and radiographic variables. Likewise, in a multicenter study [60] of 276 patients, sagittal and coronal balance parameters (SVA) did not predict best vs worst outcome groups in terms of the ODI and the SRS-22, while patient-related factors (e.g., BMI) did. Our study adds evidence to the assumption that for a better understanding of predictors of radiographic and clinical outcomes, large scale studies are indicated that not only focus on a single parameter (e.g., PJK issue) but rather apply multivariate analysis to elucidate the most relevant variables. Limitations of our study include its retrospective design and mid-term follow-up averaging 40 months. Studies with even longer follow-up might stress our main findings and delineate some of the risk factors identified, respectively.

Conclusions

Our study analysed radiographic and clinical outcomes in a large sample of patients with adult scoliosis. Indices of sagittal and coronal imbalance were shown to impact reoperation rates and clinical outcomes. Risk of complications can be reduced by restoration of sagittal balance, appropriate balancing in the coronal plane and using extended lumbosacral fixation for fusions to S1. Future studies are indicated to provide external validity of the risk factors identified in our retrospective study using a prospective research strategy and to identify threshold parameters that predict poorer clinical outcomes in operated adult scoliosis patients as well as risks for mechanical failure, for example, non-union, PJK and ASD.

For long fusions into the mobile lumbar spine, our study provides a useful rationale for selection of the LIV based on a multivariate approach. Analysis of the preoperative LIV-TO and LIV-TO on bending/traction-films is recommended for surgical planning.

Acknowledgments The study was supported by a Stryker International research grant.

Conflict of interest None.

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