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ORIGINAL ARTICLE

Intraoperative imaging and navigated spinopelvic instrumentation: S2-alar-iliac screws combined with tricortical S1 pedicle screw fixation

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Abstract

Purpose The present study aimed to assess the feasibility, safety and accuracy of navigated spinopelvic fixation with focus on S2-alar-iliac screws (S2AIS) and tricortical S1 pedicle screw implantation with the use of high-resolution three-dimensional intraoperative imaging and real-time spinal navigation.

Methods Patients undergoing navigated intraoperative CT-based spinopelvic stabilization between January 2016 and September 2019 were included. Pelvic fixation was achieved by implantation of S2AIS or iliac screws (IS). S1 screws were implanted with the goal of achieving tricortical purchase. In all cases, instrumentation was performed with real-time spinal navigation and intraoperative screw positioning was assessed using intraoperative computed tomography (iCT), cone-beam CT (CBCT) and robotic cone-beam CT (rCBCT). Screw accuracy was evaluated based on radiographic criteria. To identify predictors of complications, univariate analysis was performed.

Results Overall, 52 patients (85%) received S2AIS and nine patients (15%) received IS instrumentation. Intraoperative imaging and spinal navigation were performed with iCT in 34 patients, CBCT in 21 patients and rCBCT in six patients. A total number of 10/128 (7.8%) iliac screws underwent successful intraoperative correction due to misalignment. Tricortical purchase was successfully accomplished in 58/110 (53%) of the S1 screws with a clear learning curve in the course of time. S2AIS implantation was associated with significantly fewer surgical side infection-associated surgeries.

Conclusions Real-time navigation facilitated spinopelvic instrumentation with increasing accuracy of S2AIS and tricortical S1 screws. Intraoperative imaging by iCT, CBCT or rCBCT permitted screw assessment with the chance of direct navigated revision of misplaced iliac screws to avoid secondary screw revision surgery.

Keywords Spinopelvic fixation · S2-alar-iliac screw · Tricortical S1 screw · Navigated spinopelvic fixation · Intraoperative navigation

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Introduction

Spinopelvic fixation plays an important role in the treatment of adult and pediatric spinal deformities, degenerative spine conditions, tumors, traumatic fractures and infections [1, 2]. However, multi-segmental instrumentation and fusion attempts to the sacrum remain a clinical challenge due to high biomechanical requirements, which may be associated with high rates of pseudarthrosis, instrumentation failure and sacroiliac joint pain [3, 4]. To overcome these limitations, different sacropelvic fixation techniques have been developed under the hypothesis that incorporation of the ilium into the instrumentation construct can offload biomechanical stress from the sacrum and lower the rates of instrumentation failure and pseudarthrosis [5–8]. At present, the most commonly used procedures for iliac fixation are the implantation of S2-alar-iliac screws (S2AIS) or classic iliac screws (IS) [9], which have been demonstrated to be superior compared to other pelvic fixation techniques in biomechanical and clinical studies [10–12]. For ideal sacral screw purchase, a tricortical pedicle screw implantation technique with purchase of the posterior cortex as well as the anterior and superior cortex of the promontory has recently been reported [13–15]. However, spinopelvic fixation with the combination of S2AIS and tricortical S1 screws is anatomically more challenging than classic instrumentation with the use of IS and bicortical S1 screws. Against this background, high-resolution three-dimensional intraoperative imaging and real-time spinal navigation offer a unique opportunity to appreciate the complex spinopelvic anatomy and target tricortical S1 purchase, but clinical data on the feasibility and accuracy of navigated spinopelvic fixation is currently still lacking. Therefore, the purpose of the present study was to assess the feasibility, safety and accuracy of navigated spinopelvic fixation with focus on S2AIS and tricortical S1 pedicle screw implantation with the use of high-resolution intraoperative computed tomography (iCT), cone-beam CT (CBCT) and robotic cone-beam CT (rCBCT)-based spinal navigation.

Materials and methods

Patient data

The study was approved by the ethics committee (EA4/093/13) and included 61 consecutive patients (37 women, 24 men) undergoing navigated intraoperative CT-based spinopelvic stabilization in our department between January 2016 and September 2019. Patients over 18 years of age who received at least one final intraoperative or postoperative CT scan were included. Indications for spinopelvic stabilization were multi-segmental instrumentation in adult spinal deformity correction, revision surgery due to material loosening and pseudarthrosis of the lumbosacral segment. From January 2016 to March 2017, pelvic fixation was achieved by IS implantation. From April 2017 to September 2019, pelvic fixation was preferably achieved by S2AIS implantation. All S1 screws were implanted with the goal of achieving tricortical purchase. In all cases, instrumentation was performed with real-time spinal navigation and intraoperative screw positioning was assessed using iCT, CBCT or rCBCT imaging.

Intraoperative imaging and spinal navigation

For iCT or rCBCT-based spinal navigation, the mobile AIRO iCT (Brainlab AG, Feldkirchen, Germany) or Artis Zeego II digital C-arm robot system (Siemens Healthcare, Forchheim, Germany) was used as previously described [16–18]. Spinal navigation was performed with an image-guidance system and infrared tracking camera (Brainlab Spinal Navigation Software Version 3.0 and Brainlab Curve, Brainlab AG, Munich, Germany) that permitted automatic patient/image co-registration [13, 16, 19]. For CBCT-based spinal navigation, the mobile O-arm system (Medtronic plc, Dublin, Ireland) was used. Similarly, spinal navigation was performed with an image-guidance platform and infrared tracking camera that permitted automatic patient/image co-registration (Stealth Station Navigation System, Medtronic plc, Dublin, Ireland). The type of intraoperative imaging was selected according to availability and logistical requirements. Figure 1 is illustrating the set-up of the three different imaging systems.

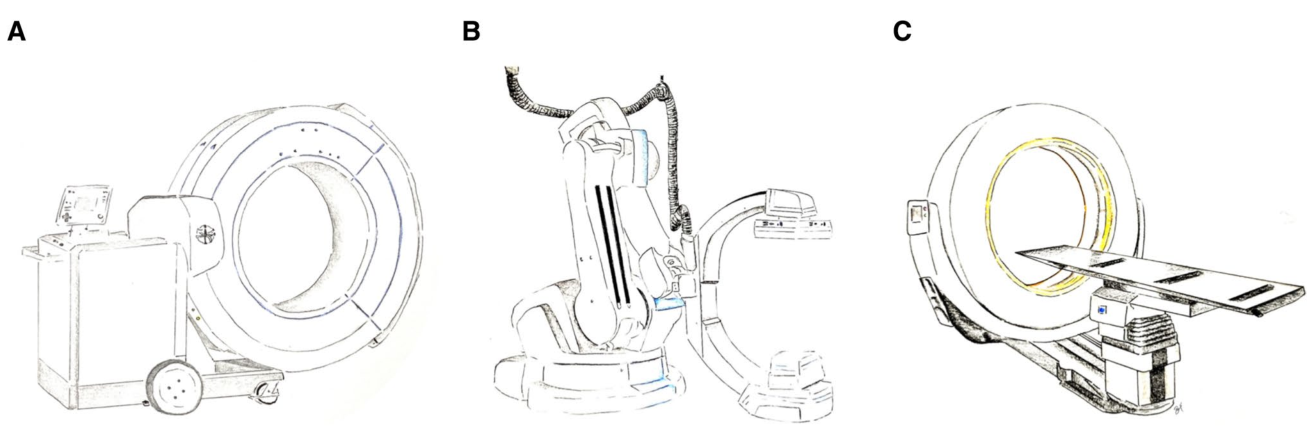

Fig. 1 Illustration of the different intraoperative imaging modalities. **a** CBCT with the mobile O-arm system (Medtronic plc, Dublin, Ireland). **b** rCBCT with the Artis Zeego II digital C-arm robot system (Siemens Healthcare, Forchheim, Germany). **c** iCT with the mobile AIRO iCT (Brainlab AG, Feldkirchen, Germany)

Surgical procedure and screw insertion

Patients were positioned on radiolucent carbon-fiber operating tables and a midline exposure was performed. For acquisition of the spinal navigation scan with automatic patient / image co-registration, a spinal reference clamp (Brainlab AG, Munich, Germany or Medtronic plc, Dublin, Ireland) was attached to a spinous process or the iliac crest. All imaging was performed during apnea following 3–5 min of preoxygenation. After image acquisition, navigated iliac instrumentation was performed first: depending on the type of iliac screw, the screw entry point was identified at the posterior iliac crest (IS) or at the level of S2 between the S1 and S2 foramen (S2AIS) under consideration of axial, coronal and sagittal in-line views. A pilot hole was drilled with a navigated drill guide and a trajectory was planned targeting the anterior inferior iliac spine. For S2AIS instrumentation, the entry point was 2–4 mm lateral between the S1 and S2 dorsal foramen. After drilling to a depth across the cortical bone of the sacro-iliac (SI) joint, a guide-wire was inserted and the pilot hole was tapped to a desired depth across the SI joint. It is important to note that there is a very specific feel when penetrating through the cortex of the SI joint with a difference in tactile sensation when passing through the cancellous bone of the sacrum and going through the cortex of the SI joint and into the cancellous channel of the iliac bone. For IS insertion, the entry point was identified at the posterior superior iliac spine. Bone around the screw entry point was resected with a rongeur to better accommodate the screw head. A navigated pilot hole was drilled targeting the anterior inferior iliac spine and a guide-wire was inserted for tapping of the cancellous iliac bone. For S2AIS and IS insertion, the tapped hole was probed for breaches and a cannulated, measured iliac screw (CD Horizon® Solera™ Spinal System, Medtronic, Dublin, Ireland) with a length between 100 and 110 mm and diameter between 9.5 and 10.5 mm was inserted over the guide wire with the intention not to breach the iliac cortex. In S2AIS insertion, the screw entry point caudal and just slightly medial to the entry point of the S1 screw permitted a direct rod connection. In IS insertion, rod connection required the use of a separate connector.

Next, tricortical S1 instrumentation was performed. To permit sufficient convergence of the screw trajectory required for purchase at the anterior and superior promontory, S1 screws were inserted through a parafascial, transmuscular approach. After parafascial incision, an entry point slightly lateral and caudal to the posterior S1 pedicle cortex was identified with a navigated drill-guide and a pilot hole was drilled targeting the superior and anterior promontory. Identification of the entry point and trajectory was performed in axial, coronal and sagittal in-line views. After drilling of the pilot hole, the pedicle was tapped and screw measuring 7.5–9.5 mm in diameter and 50–55 mm length (CD Horizon® Solera™ Spinal System, Medtronic, Dublin, Ireland) was inserted with intention to breach the anterior and superior cortex of the promontory.

Intraoperative screw assessment

Screw positioning was intraoperatively assessed by a second iCT/CBCT or rCBCT scan. Criteria for correct positioning of an S2AIS were an entry point of the screw at the level of the S2 pedicle, course of the screw through the sacroiliac joint and course through the ilium without anterior, lateral or medial cortical breaches. Criteria for the correct positioning of an IS was a course through the ilium without anterior, lateral or medial cortical breaches. Criteria for correct tricortical positioning of an S1 screw were an entry point latero-caudal to the S1 pedicle and converging screw trajectory directed into the superior and anterior cortices of the sacral promontory [20]. Misalignment was judged by the primary surgeon and included: (a) lateral, medial or anterior breach of S2AIS or IS during passage through the cancellous iliac bone, (b) failure of SI joint passage in S2AIS, and c) lateral, medial, cranial or caudal breach of the S1 pedicle >4 mm, a direct intraoperative navigated screw revision was performed, followed by a final iCT/CBCT/rCBCT control scan to confirm repositioning. Importantly, failure to achieve tricortical S1 purchase with anterior and superior breach due to an insufficient convergence of the screw trajectory was not per se considered a reason for revision.

Statistical analysis

Continuous variables are presented as mean ± standard deviation and categorical variables as absolute and relative frequencies. Comparison of categorical variables was achieved using Chi^2-Test with Yates continuity correction. For continuous variables, the unpaired t-test was used. Univariate logistic regression was performed to identify predictors of complications. Odds ratios (ORs) were reported with 95% confidence intervals (CIs). All tests were 2-sided and $p<0.05$ was considered statistically significant. All statistical analyses were performed using SPSS (26.0; IBM®, Armonk, NY).

Results

Baseline patient characteristics and surgical data are presented in Tables 1 and 2. Overall, 52 patients (85%) received S2AIS and nine patients (15%) received IS instrumentation. The mean skin distance to the insertion point of the screw was significantly greater in S2AIS (56 mm) than in IS (42 mm; $*p=0.005$ versus S2AIS) (Fig. 2). There was no difference in age, gender and diagnosis between groups.

Table 1 Baseline characteristics

	S2AIS (*n* = 52)	IS (*n* = 9)	*p*
Age (mean ± SD)	65.89 ± 13.79	71.62 ± 8.11	0.086
Sex			0.148
Female	34 (65.4%)	3 (33.3%)	
Male	18 (34.6%)	6 (66.7%)	
Diagnosis			
Degenerative			
Primary deformity correction	27 (17.3%)	7 (77.8%)	
Secondary revision surgery	12 (23.1%)	1 (11.1%)	
Spinal stenosis	3 (5.8%)	0 (0%)	
Trauma	3 (5.8%)	1 (11.1%)	
Infection	4 (7.7%)	0 (0%)	
Tumor	3 (5.8%)	0 (0%)	
Prior history of lumbosacral surgery	37 (71.2%)	8 (88.9%)	0.480
Prior history of lumbosacral stabilization	28 (53.8%)	6 (66.7%)	

Table 2 Surgical characteristics

	S2AIS (*n* = 52)	IS (*n* = 9)	*p*
Operated levels (mean ± SD)	8.67 ± 3.45	10.67 ± 5.94	
Operation time (min, mean ± SD)	358.75 ± 131.8	461.78 ± 168.57	
Early perioperative complications			
Death	1 (1.9%)	0 (0%)	
Hematoma	2 (3.8%)	0 (0%)	
Intraoperative major vessel injury	1 (19.2%)	0 (0%)	
Late perioperative complications			
CSF fistula	1 (1.9%)	0 (0%)	
Surgical site infection	5 (9.6%)	4 (44.4%)	**0.027**
Total reoperation during hospitalization	8 (15.4%)	4 (44.4%)	
Navigation system			
iCT	27 (51.9%)	7 (77.8%)	
CBCT	19 (36.5%)	2 (22.2%)	
rCBCT	6 (11.5%)	0 (0%)	
Intraoperative correction of iliac screw	9 (17.3%)	0 (0%)	
Bicortical S1 screws	20 (38.5%)	6 (66.7%)	
Tricortical S1 screws	27 (51.9%)	2 (22.2%)	
No S1 screws	5 (9.6%)	1 (11.1%)	
Skin distance (mean ± SD)	55.88 ± 13.74	41.56 ± 12.70	**0.005**

p values in bold illustrates statistical significance at $p < 0.05$

In both groups, the majority of patients had a history of lumbosacral surgery or fusion, respectively (71 and 54% for S2AIS; 89 and 67% for IS). Twenty-three out of 61 patients (38%) underwent correction of kyphotic deformity and sagittal imbalance with pedicle subtraction osteotomy.

Screw accuracy and revision rates

Intraoperative imaging and spinal navigation were performed with iCT in 34 patients, CBCT in 21 patients and rCBCT in six patients (Fig. 3). A total of nine patients with S2AIS underwent intraoperative correction of iliac screws due to misalignment according to the criteria described above. In one case bilateral misalignment was observed, resulting in a total number of 10/128 (7.8%) iliac screws undergoing successful direct revision. In all cases, navigated correction of misplaced iliac screws was possible with each of the three imaging modalities (Fig. 4). There was no difference in accuracy of screw placement due to imaging modalities applied. There was no misalignment in the IS group.

In 55/61 patients, a total of 110 S1 screws were implanted with the goal of tricortical purchase, which was successfully

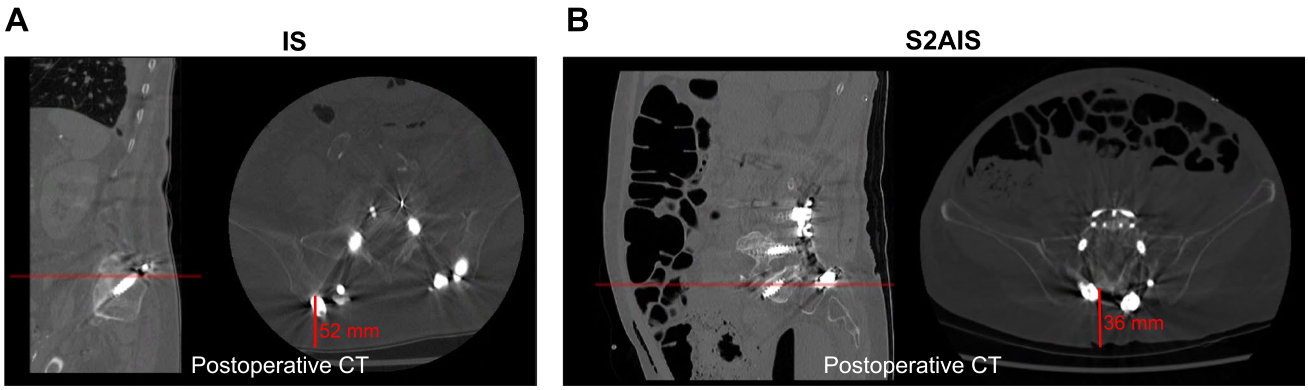

Fig. 2 Difference in skin distance of IS (**a**) and S2AIS (**b**) in two different patients. Note that S2AIS had significant deeper screw entry points. Both patients had matching BMI

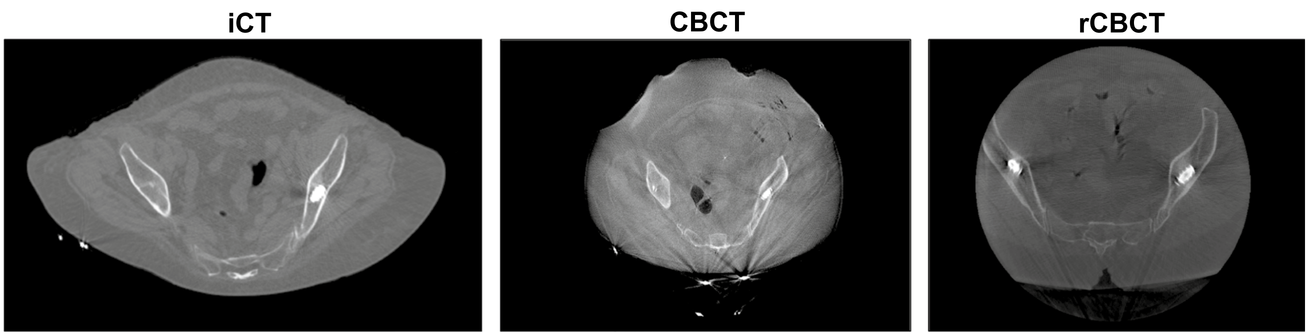

Fig. 3 Intraoperative imaging of S2AIS insertion with iCT, CBCT and rCBCT in three different patients. Note that screw placement was successful in all patients, despite greater hardware artifacts following assessment with CBCT and rCBCT

accomplished in 58/110 (53%) of the screws (Fig. 5). In six patients, no S1 screws were implanted. Only one patient required intraoperative correction of an S1 screw due to a lateral pedicle breach > 4 mm. Regarding our success rate of navigated, tricortical S1 implantation a clear learning curve was noted, beginning at 39% and reaching 91% at the end of our observation period (Fig. 6).

Surgical complications and predictors of reoperation

During the early perioperative course, a medially misplaced S2AIS resulted in vascular injury requiring endovascular intervention in one patient. A second patient suffered extensive pulmonary embolism and died. During hospitalization, overall 12/61 patients (20%) underwent reoperation (defined as an additional surgical procedure for surgical site infection (SSI), hematoma or CSF fistula) including 8/52 patients (15%) in the s2AIS group and 4/9 patients (44%) in the IS group. The most common cause for reoperation was SSI including 9/61 patients (15%) (Table 2). The frequency of SSI was significantly lower in S2AIS patients including 5/52 patients (10%) than in the IS group including 4/9 patients (44%; *$p=0.027$ versus S2AIS). Further, univariate analysis did not show a significant predictor for reoperation (Table 3). Regarding SSI, S2AIS implantation was associated with significantly fewer SSI-associated surgeries. (Odds ratio = 0.13, $p=0.014$).

Discussion

In this study, we show the feasibility and benefit of intraoperative imaging and real-time spinal navigation for spinopelvic fixation with S2AIS and tricortical S1 pedicle screws. Importantly, real-time navigation facilitated tricortical S1 pedicle screw insertion with increasing accuracy and intraoperative imaging by iCT, CBCT or rCBCT permitted direct screw assessment in all cases with the chance of direct navigated revision of misplaced iliac screws to avoid secondary screw revision surgery.

Previous studies on spinopelvic fixation have mainly focused on fluoroscopic guidance or freehand technique for screw insertion [9, 11, 12, 20, 21] but both show a

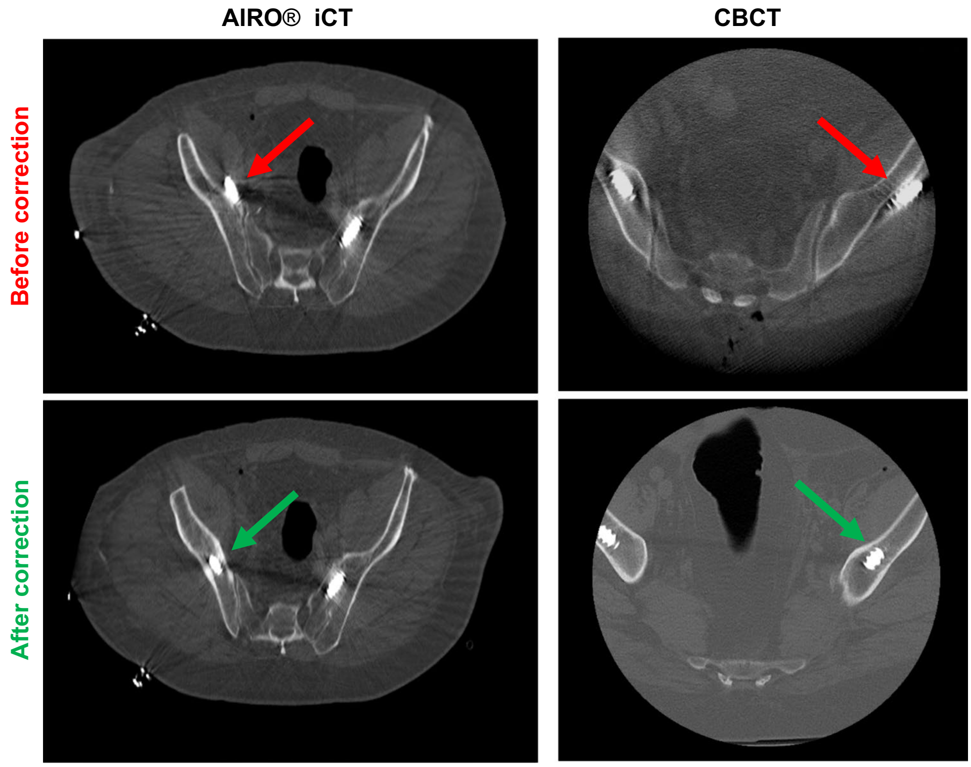

Fig. 4 Intraoperative revision of misplaced S2AIS following iCT or CBCT-based navigation in two patients: the (red and green) arrows point out the misplaced and corresponding intraoperatively corrected S2AIS. Note that intraoperative correction was successful in both patients

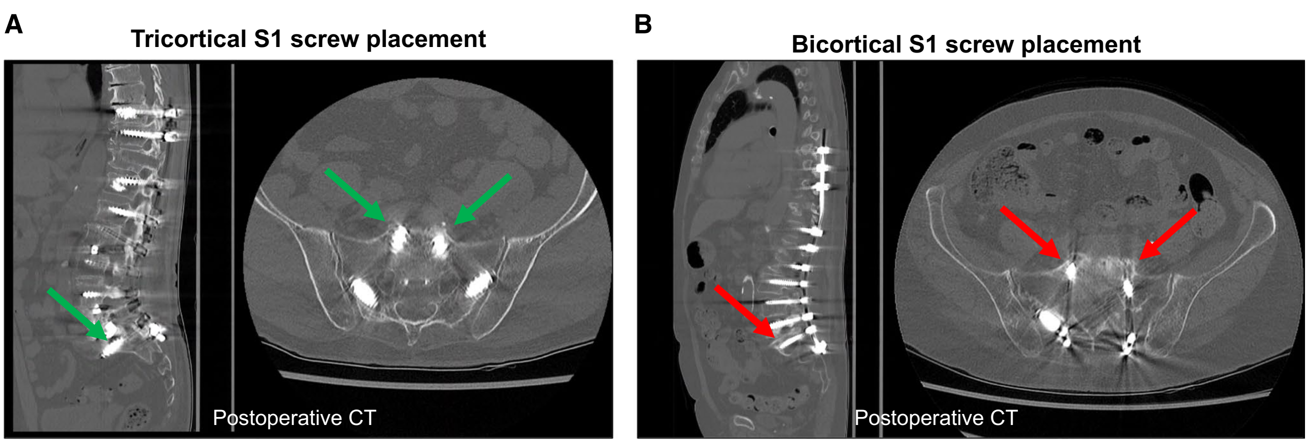

Fig. 5 Postoeprative CT imaging of S1 screw placement with the initial goal of tricortical purchase in two different patients. Successful tricortical S1 screw placement (**a**) is pointed out with green arrows. Note the screw trajectory directed into the superior and anterior cortices of the sacral promontory. Bicortical S1 screw placement (**b**) is pointed out with red arrows. Note that the S1 screws are parallel to the S1 endplate and not converging to the superior cortex

considerable rate of screw misplacement that potentially necessitates secondary screw revision surgery [22]. Here, intraoperative imaging and spinal navigation offer the possibility to improve accuracy and reduce radiation exposure for the OR team, together with the promise for better outcomes [19, 23–27]. Even though radiation dose received by patients was not documented in this study, radiation exposure for the surgical team was completely eliminated as all scans in this study were performed remotely from an adjacent, shielded room. In comparison, recent literature is showing an average surgeon radiation dose of $6.0 \pm 7.9 \times 10^{-3}$ mSv/screw for conventional fluoroscopy without navigation [28]. Comparing different imaging modalities, previous studies have shown higher overall mean radiation dose in iCT compared to CBCT [29].

Recent studies and meta-analysis have shown the superior accuracy of navigated, intraoperative spinal instrumentation compared to non-navigated techniques [30–36]. Particularly

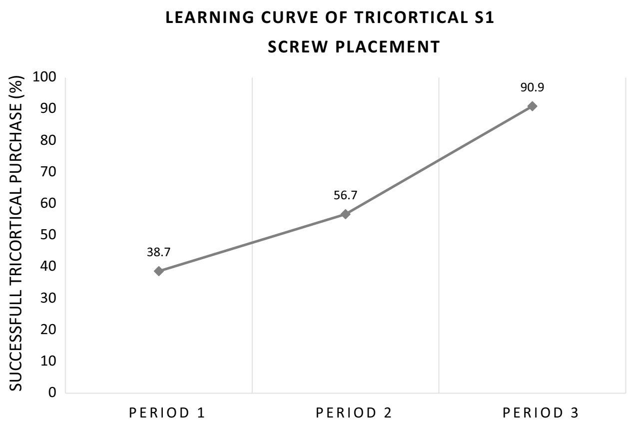

Fig. 6 Learning curve of tricortical S1 screw placement over three periods. Period 1 including patients operated between 2016 and 2018. Period 2 including patients operated between 01/2019 and 05/2019. Period 3 including patients operated since 06/2019. A clear learning curve was noted regarding the success rate of navigated, tricortical S1 implantation

Table 3 Univariate analyses on predictors of reoperation and SSI

	Reoperation (*n* = 24)		Surgical site infection (*n* = 9)	
	Univariate		Univariate	
	OR [95% CI]	*p*	OR [95% CI]	*p*
Age	1.00 [0.95, 1.07]	0.875	0.97 [0.91, 1.05]	0.438
Sex	0.64 [0.22, 1.83]	0.405	0.26 [0.05, 1.13]	0.082
Operation time	0.98 [0.80, 1.20]	0.868	1.10 [0.84, 1.45]	0.473
S2AIS	0.46 [0.10, 1.94]	0.288	0.13 [0.03, 0.68]	**0.014**
Skin distance	1.00 [0.96, 1.04]	0.939	0.97 [0.91, 1.03]	0.348

p values in bold illustrates statistical significance at $p < 0.05$

for safe and reliable S2AIS and tricortical S1 pedicle screw insertion, real-time spinal navigation is becoming increasingly attractive considering the complex anatomical considerations of biomechanically superior screw insertion across multiple cortices in the sacral and iliac bone. For S2AIS, the screw trajectory purposefully crosses the cortical surfaces of the sacro-iliac joint to involve the dense bone above the sciatic notch [5], which is associated with lower mechanical failure and complication rates than conventional IS implantation [9] and greater pullout strength [37]. Other advantages of S2AIS over IS include a deeper screw insertion point to the skin surface, direct connection to the proximal construct and less extensive soft tissue dissection [11, 20, 38]. Therefore, the medical team in the present study preferably implanted S2AIS in pelvic fixation over the course of time. The second essential component of spinopelvic fixation is biomechanically stable sacral fixation. For this purpose, different pedicle screw implantation techniques have been described. Most recently, a tricortical S1 pedicle screw implantation technique has been reported, which requires a lateral-caudal entry point into the pedicle with a medially converging trajectory targeting a purposeful breach of the anterior and superior cortex of the sacral promontory [13, 15]. In human specimens, such tricortical purchase has been reported to result in higher biomechanical stability and pull-out strength [14]. However, S2AIS and tricortical S1 instrumentation is technically more challenging than conventional iliac and sacral instrumentation and against this background, the use of intraoperative imaging and spinal navigation offers the advantage of anatomic real-time visualization and high precision targeting of a desired trajectory with the benefit of immediate implant control. Despite our efforts in the present study, however, iliac screw misplacement still occurred in approximately 8% of all screws. Although this number lies within the reported 5–16% misplacement rate of iliac screws inserted without image guidance [9, 11, 22], however, the use of intraoperative 3D imaging permitted direct implant assessment with successful navigated correction of all misplaced screws and most importantly helped to avoid secondary screw revision surgery in all cases. Lee et al. previously described 12.4% of misplaced iliac screws in non-navigated cases, resulting in 4% of all patients receiving secondary surgery [22].

Further, intraoperative implant assessment was possible with each of the three investigated imaging modalities, although in our experience iCT offered an advantage in cases requiring an instrumentation length beyond 5 segments and in obese patients, due to the larger scan area and higher spatial detail resolution of iCT compared to CBCT or rCBCT imaging.

The biomechanical superiority of S2AIS over IS has previously demonstrated in several studies [9, 11, 12, 20] but in most of these, iliac and sacral screws were implanted using a fluoroscopic or freehand technique. In the present study, for the first time we report the successful application of the three most commonly available, state-of-the-art intraoperative imaging technologies. Despite the benefit regarding screw precision and revision possibilities, we still experienced an overall perioperative reoperation rate around 19.7%, which remains comparable to previous reports [9, 39]. Most likely, this is explained by the fact that the surgical reasons for reoperation that we defined in our present series did not include screw revision surgery but only complications that remain independent from intraoperative 3D imaging or spinal navigation. Nevertheless, the trend toward fewer reoperations following S2AIS (15.4%) compared to IS (44%) implantation could be explained by the less extensive soft tissue dissection required for S2AIS insertion, which in our study was also associated with significantly lower rate of SSI and falls in-line with the results from a recent meta-analysis [9]. However rates of SSI in S2AIS were slightly higher in this study with 9.6% compared to previous reports with SSI rates between 1.5 and 4.5% [9], potentially as a result of a high number of multilevel deformity correction surgeries. Further, the higher rate of SSI following conventional IS implantation could also be explained by the 26% lesser distance of the screw head to the surface of the skin surface in patients with IS, which is in agreement with a previous report [40] and bears the additional risk of a painful posterior iliac prominence [5]. Measures to minimize IS prominence include grafting of an osseous depression [41] and although we did in fact harvest bone at the screw entry point site to better seat the IS before implantation, we failed to achieve a skin distance of the screw head that was comparable to S2AIS, similar to previous reports [29, 40].

To date, tricortical S1 pedicle screws have not yet been described in the context of navigated spinopelvic fixation. Next to the clear biomechanical advantage of anterior and superior purchase of the promontory in addition to posterior purchase of the S1 pedicle [14], tricortical S1 screws also showed a lower risk of injuries to the sacral artery and vein, the common iliac artery and the L5 nerve root [15]. However, true tricortical placement remains technically challenging, which is mirrored by the fact that only 53% of our implanted S1 screws actually met tricortical criteria, despite deliberate attempts to achieve tricortical purchase with the help of image guidance and. Interestingly, failed tricortical purchase was mainly caused by failure to sufficiently converge the screw and a screw length limited to 55 mm for the selected pedicle screw diameters of 7.5 mm and above, despite a caudal-lateral screw entry point and a transmuscular approach. Nevertheless, the benefit of using image guidance for this technique can be noted in the steep learning curve that we experienced and that eventually helped raise our success rate above 90%, although all surgeons had a high level of experience with non-navigated S1 screw placement prior to this study.

Although our study inherently lacks power due to its limited number of patients, retrospective nature and single-center design, the investigated cohort is representative of patients requiring spinopelvic instrumentation across a typical spectrum of pathologies. Still, generalizability may be hampered due to our study design and center-specific standard operating procedures.On the other hand, spinopelvic fixation remains rare and our series of 61 patients is within the reported number of patients that were included in the largest five studies on spinopelvic fixation techniques [9]. The unequal distribution of 9 IS and 52 S2AIS procedures is another limitation and naturally, selection bias needs to be considered despite the fact that all procedures were performed by the same team of experienced spine surgeons. Finally, long-term follow-up was limited and future prospective studies are needed to confirm the potentially superior biomechanical properties of S2AIS plus tricortical S1 pedicle screw fixation, which may improve long-term outcome of patients requiring spinopelvic fixation.

Conclusion

Real-time navigation facilitated spinopelvic instrumentation with increasing accuracy and intraoperative imaging by iCT, CBCT or rCBCT permitted screw assessment with the chance of direct navigated revision of misplaced iliac screws to avoid secondary screw revision surgery.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical approval The study was approved by the ethics committee (EA4/093/13).

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