SPINOPELVIC FIXATION: MODERN TECHNICAL SOLUTIONS

M.S. Vetrile, A.A. Kuleshov, S.N. Makarov, I.N. Lisyansky, N.A. Aganesov, V.R. Zakharin
N.N. Priorov National Medical Research Center of Traumatology and Orthopaedics, Moscow, Russia

The paper presents the second part of literature review devoted to modern techniques of spinopelvic fixation for various pathologies of the spine and injuries to the spine and pelvis. The review is non-systematic and was conducted using PubMed and eLibrary databases of medical literature. Modern techniques of spinopelvic fixation using screws installed in the ilium are highlighted, including anatomical and biomechanical features, clinical results of application, as well as the implementation of spinopelvic fixation for tumor lesions of the sacrum, including the use of customized implants and additive technologies. The features of classical installation of iliac screws and installation by the S2AIS technique are considered, and their advantages and disadvantages and possible complications are evaluated.

Key Words: spinopelvic fixation, lumbosacral region, spinal deformity, iliac screws, S2AIS technique, additive technologies.

Please cite this paper as: *Vetrile MS, Kuleshov AA, Makarov SN, Lisyansky IN, Aganesov NA, Zakharin VR. Spinopelvic fixation: modern technical solutions. Hir. Pozvonoc. 2021;18(4):101–110. In Russian.*

DOI: http://dx.doi.org/10.14531/ss2021.4.101-110.

Spinopelvic fixation is becoming increasingly topical in spine surgery. If previously the main indications for it were deformities accompanied by twisted pelvis (neuromuscular scoliosis), then with the expansion of surgeries, an increase in spinal osteotomies, correction of sagittal balance, the issue of performing spinopelvic fixation has become of particular significance. The anatomical features of lumbosacral region as a junctional zone, complex biomechanical interactions as well as its key role for the entire axial skeleton define the importance of spinopelvic fixation. The urgency of this issue also reflects the growing number of publications: in 2019 PubMed offered 40 articles on “spinopelvic fixation”, in 2020 – 50, in 2021 – 60.

We present a continuation of a non-systematic literature overview concerning spinopelvic fixation under the papers from PubMed and eLibrary databases. We used the following keywords: “spinopelvic fixation”, “iliac screws”, “S2AIS”, “spinopelvic reconstruction”, and “sacrectomy”.

The objective is to highlight modern techniques of spinopelvic fixation with the use of iliac screws, including anatomical and biomechanical features and clinical outcomes of its application. It is also essential to consider performing spinopelvic fixation in tumor involvement of sacrum, including with the use of customized implants.

Spinopelvic Fixation with Iliac Screws

The introduction of iliac screws into operational practice was a logical extension and development of the Galveston technique (Fig. 1).

A number of morphometric and experimental studies have been performed to define the optimal insertion trajectory of screws and their dimensions. In 1990, Miller et al. [1] published a study of the anatomy of 72 cadaveric models of pelvic. They noted constant anatomical features of iliac bones and confirmed the opinion of Allen and Ferguson that an iliac bone is the best fixing point for rods to the pelvis when performing spinopelvic fixation. Meanwhile, the authors pointed out that drilling a hole 110 mm long in the iliac bone, starting from the posterior superior iliac spine, will lead to penetration of the acetabulum in 25 % of cases. In this regard, the authors recommended using screws no longer than 90 mm.

According to anatomical and radiological studies of the pelvis, Schildhauer et al. [2] and Berry et al. [3] identified significant anatomical features concerning the possibility of using iliac screws. The authors considered two directions of screw insertion: from the posterior superior iliac spine to the upper edge of the acetabulum and the anterior inferior iliac spine, respectively (trajectories A and B in Fig. 2a). Key points of their procedure:

– the absolute minimum safe length of the screws when they are inserted in the iliac bones above the sciatic notch is 80 mm in adults and adolescent boys, 70 mm in adolescent girls;

– if the screws are directed towards the anterior superior iliac spine, it is permissible in most cases to use screws with a length of 100 mm;

– the average diameter of the iliac bone along the insertion trajectory at the narrowest point is 13.2 mm in adolescent girls and 17.3 mm in adult men, which is much larger than the diameter of the implants usually used.

The two narrowest places in the screw trajectory have been identified (at sacroiliac joint level and at sciatic notch level), during the passage of which the screws are fixed for the cortical layer of bone (Fig. 2b). Zhang et al. [4] performed anatomical and biomechanical research and studied the dependence of the insertion depth of the iliac screws (in fact, their length) and the fixation strength. Biomechanical research on cadaveric models included series of three studies: on the intact lumbosacral region, after resection of the sacrum and fixation with short iliac screws and long ones, respectively. In all cases the screw diameter was 7.5 mm. The length of the screws was chosen as follows: in the short fixation group, the screw end was located 2 mm ventral to the large sciatic notch, and in the long fixation group, it went 2 mm beyond the bone tissue at anterior superior iliac spine level. If the screws in both groups were arranged in this way, they passed through both narrow-width places of the iliac fixation.

As a result, the length of the inserted short screws averaged 70 ± 2 mm versus 138 ± 4 mm long ones with difference of almost 2 times. The obtained results showed comparable mechanical fixation strength with short and long screws under compression and torsion loads. A significant difference was in advantage of longer screws only in the pullout test. Therefore, it is observed that the use of shorter screws for spinopelvic fixation does not have a substantial effect on stability. Meanwhile, the complication risk associated with a possible screw malposition is reduced.

Numerous clinical observations prove the effectiveness of iliac screws. Peelle et al. [5] analyzed the treatment outcomes of 40 patients with neuromuscular scoliosis. Moreover, the authors compared a long-term use of the Galveston technique and the iliac screws. Good results and a relatively minimal number of complications when using screws were observed. Also, Tumialan et al. [6] note the advantage of iliac screws in spinopelvic fixation in deformities. Tsuchiya et al. [7] have traced long-term (from 5 to 10 years) results of iliac screw insertion in 67 patients with scoliosis and spondylolisthesis. There were no cases of abnormal fixation of screws in S1 vertebra. In five cases, fractures of screws in L5 or L4 vertebra and a fracture of the rod were observed. Moreover, in three out of five cases, interbody fusion was not initially performed. There were fractures of the iliac screws in 7 (10.5 %) cases. Signs of bone resorption around the iliac screws were recorded on X-rays in 43.3 % of cases. Two years after surgery, the iliac screws had to be removed from one or both sides due to their subcutaneous protrusion. It was done in 23 (34.3 %) patients. There was no pronounced instability effect of the iliac screws on the clinical outcomes. There were no signs of osteoarthritis and changes in sacroiliac joints in any case. Cho et al. [8] also note that the long-term results after 2 years in patients with signs of bone resorption around the iliac screws and without it do not substantially differ.

Installation of Iliac Screws through S2 Vertebra and Wings of Sacrum

The use of iliac screws is associated with a number of disadvantages. Firstly, the need for extensive skeletonization, which enhances the injury rate of the surgery. Secondly, the remotness to the spinal axis and the main fixing system axis requires the use of additional connecting nodes (connectors, plates), which raises the height of instrumentation system profile. Thirdly, the small volume of soft tissues in the area of screw insertion causes their subcutaneous protrusion, associated discomfort and an increased risk of seroma and infection. All this prompted the development of a new installation technique for screws in the iliac bones – through S2 vertebra and wings of sacrum at The Johns Hopkins Hospital of The Johns Hopkins University (USA). It was called S2 Alarm Iliac Screws (S2AIS technique). In 2009 O'Brien et al. [9] published the first data obtained under anatomical examination using cadaveric models. The authors identified the insertion point of the screws 1 mm

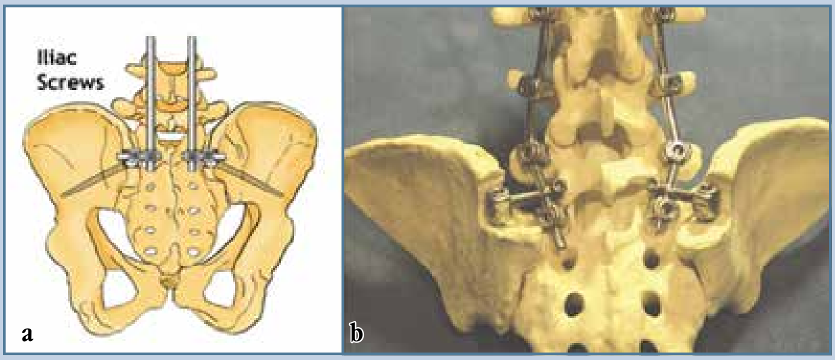

Fig 1
The arrangement of iliac screws [60] **(a)** and the design with iliac screws on the spinopelvic complex model [61] **(b)**

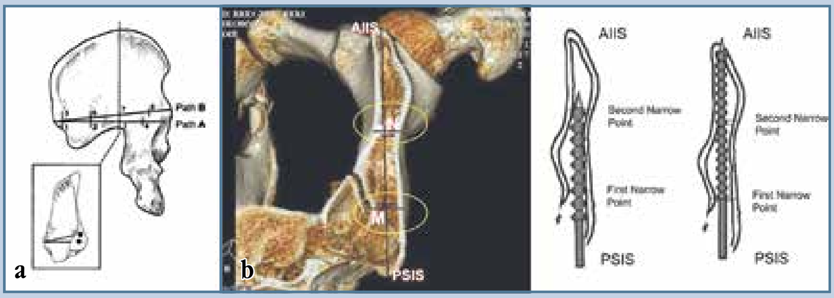

Fig 2
Possible insertion trajectories of screws into the iliac bones [3] **(a)** and narrow-width places along the screw trajectory in the iliac bones **(b)**: AIIS – anterior inferior iliac spine; PSIS – posterior superior iliac spine [4]

below and outward from the S1 dorsal intervertebral foramen, using screws from 70 to 100 mm. As a result, none of the screws passed inside the pelvis and did not constitute a risk of neurovascular complications. Three screws protruded from the posterior surface of the ilium. They also presented no threat of complications. All screw heads were located in line with the screw heads in S1 vertebra (Fig. 3). The authors note injury to the cartilaginous surface of sacroiliac joint in 60 % of cases.

CT data concerning the insertion of screws through the S2 into the iliac bone were also studied [10]. It is noted that this technique can provide a stable spinopelvic fixation in case of spinal deformities in adults. Starting with adolescents with complete bone growth, the optimal screw insertion point is 25 mm below S1 endplate and 22 mm laterally to the middle of S2 vertebra. The screw trajectory is on average 40° deflected caudally and laterally in the frontal and sagittal planes, respectively.

In the application of S2AIS technique, the screw heads are immersed on average 2 cm deeper from the surface of the skin, compared with the iliac screws [11]. Meanwhile, there is no need to use additional connectors to install the rod.

Biomechanical studies comparing the stability of S2AIS screws with iliac screws under various loads revealed a slight advantage in the fixation rigidity when using the S2AIS technique [12, 13]. These data are also verified by finite elements method [14].

Park et al. [15] performed a cadaveric study to determine the optimal method of free-hand installation of S2AIS screws and described the technique in detail. The insertion point is located in the middle of the distance between S1 and S2 intervertebral foramen by 2 mm medial to the lateral sacral crest (Fig. 3). The mini-invasive insertion of screws using S2AIS technique and application of robotics [16–18] are also described. The co-use of these technologies increases the accuracy of screw installation and reduce the injury rate of the operation.

Clinical outcomes of S2AIS technique application. Kebaish et al. [19, 20] described the treatment outcomes of 52 adult patients with spinal deformities; the average follow–up period was 2.5 years. Complications associated with the installation of screws were observed in three cases (2 screw fractures, 1 malposition), bone block at the L4–S1 level – in 92 % of cases.

Sponseller et al. [21] compared the treatment outcomes in children and adolescents with neurogenic scoliosis using the S2AIS screws technique and traditionally installed iliac screws. It was noticed that magnitude of Cobb angle correction in spinal deformity is comparable in both groups, whereas the correction of twisted pelvis is statistically significant in the S2AIS screw fixation groups (67 % vs. 60 %; $p = 0.002$). In both groups there were 2 cases of radiologically detected bone resorption around the pelvic screws. According to CT data, in 18 patients with S2AIS screws, there was no intrapelvic protrusion of the screws in any case; in a single case, the screw was outward by 5 mm. There were no cases of deep infection, subcutaneous implant protrusion, delayed skin trophic abnormalities above the implants and screw migration in group with S2AIS screws. In the group of patients with traditional iliac screws, deep wound infection was noted in three cases ($p = 0.09$); in three cases, there was a subcutaneous protrusion of implants with local skin manifestations. Therefore, the authors note a better correction of twisted pelvis and a smaller number of complications when using the S2AIS technique.

Jain et al. [22] reported that out of 80 children who underwent sacroiliac fixation using the S2AIS technique, only three (3.8 %) cases required revision surgery. In their study, the technique of S2AIS fixation for spinal deformities in children and the use of screws with a diameter of less than 8 mm raised the risk of their breakdown.

In 2017, Elder et al. [23] published a study comparing the application results of S2AIS screws and iliac screws in adult patients with spinal deformities. According to their data, clinical and functional outcomes, the frequency of L5-S1 pseudoarthrosis, pain in sacroiliac joints and proximal kyphosis are comparable in both groups. Meanwhile, in the group of patients with S2AIS screws, the frequency of reoperations was lower (8.8 % vs. 48.0 %; $p < 0.001$); the frequency of infectious complications was also considerably lower (1.5 % vs. 44.0 %; $p < 0.001$); there was no subcutaneous protrusion of instrumentation when using the S2AIS technique (0.0 % vs. 12.0 %; $p = 0.02$).

Guler et al. [24] reported a higher stabilization rate of spinopelvic fixation using the S2AIS technique in comparison with iliac screws using connectors. The remaining analyzed papers of comparative studies on the use of iliac screws and screws installed according to the S2AIS technique show a smaller number of complications and reoperations when using the S2AIS technique [25–28].

In 2019, data from systematic and meta-analyses were published on comparing the number of complications and revision surgeries after performing spinopelvic fixation in children and adults with screws installed by the S2AIS technique. According to this analysis, the use of iliac screws is associated with a large number of postoperative complications and revision surgeries as well as a lower level of outpatient status in comparison with the use of the S2AIS technique [29].

Modification of Iliac Screw Installation

To reduce the height of the structure cross section and eliminate the need to use connecting parts, Sohn et al. [30] proposed an original modification of iliac screw installation. The installation point of the screw is located 1 cm caudal and 1 cm medial to the posterior superior iliac spine. Meanwhile, iliac spine resection is not performed (Fig. 4a). The authors' evaluation of this technique by applying the finite element method demonstrated the advantages of load distribution on screws compared to the S2AIS installation option [31]. Caddy-McCrea et al. [32] describe a similar technique. In this case, a partial resection of the medial part of posterior superior iliac spine is performed. The authors designate this technique as "DVIP –

Distal Ventral Iliac Pathway". Analyzing the long-term treatment outcomes in 128 patients, the authors point out the sufficient technical simplicity and safety of the method. It is also possible to install several screws. In addition, there is no need for connectors and injuring the sacroiliac joint.

Spinopelvic Fixation with the Installation of Dual Iliac Screws

Anatomical features of the iliac bones provide for the installation of a pair of screws on each side, respectively. Yu et al. [33] have demonstrated the biomechanical advantage of fixation with dual iliac screws compared to fixation with a single screw during sacrectomy. The authors also performed a study of possibility of iliac screws to be installed in different directions (Fig. 5). The obtained results of the biomechanical study indicate greater fixation stability with a double screw system. Meanwhile, it is insignificant to depend on the orientation of the iliac screws [33]. The main indications for the use of dual screw iliac fixation are: total resection of the sacrum [34], including sacroiliac joints; partial sacrectomy, including resection of more than 50 % of sacroiliac joints on both sides; partial sacrectomy with unilateral complete resection of the sacroiliac joint [33]. This technique is also applied when more rigid fixation is necessary for traumatic sacral injuries [35], extended deformities and performing corrective osteotomies of the sacrum [36–39]. A systematic literature review conducted by Bourghli et al. [40], confirms that dual screw fixation has an advantage over single-screw fixation in complex clinical situations.

Multi-rod Construct Arrangement in Spinopelvic Fixation

The installation of dual iliac screws enables the multi-rod arrangement of the surgical hardware. Shen et al. [41] described a new technique for the four-rod arrangement of a surgical hardware (Fig. 6), which was successfully applied in a patient with sacral chordoma. Mindea et al. [34] performed a cadaveric biomechanical study comparing various spinopelvic fixation techniques after total sacrectomy. The maximum fixation strength is achieved, according to the results obtained, when installing dual iliac screws and a four-rod arrangement of the surgical hardware. The next in terms of fixation strength was a design using dual iliac screws and dual rod arrangement.

Anterior Support Column Fixation during Spinopelvic Fixation

The value of interbody fusion during fixation at the L5–S1 level, especially when extended in the cranial direction, is beyond doubt. If it is not performed or if the bone block fails, the risk of fracture of the surgical hardware increases many times. In the case when the caudal fixation ends at the level of S1 vertebra, the fracture of the screws in S1 vertebra is likely to occur. Performing additional fixation with iliac screws considerably reduces the load on the screws in S1 vertebra and prevents their fracture. This is proven by biomechanical studies and the finite element method [42, 43]. It was also discovered that when the load on the screws in S1 vertebra decreases, the load on the rod increases above the screws in S1 vertebra [43]. Analysis of fractures of the surgical hardware above S1 vertebra revealed its correlation with the absence or failure of the anterior bone block at the L5--S1 level [44]. Meanwhile, the failure of fixation below S1 vertebra (fracture or instability of the pelvic screws) relates to a greater length of fixation and sagittal imbalance.

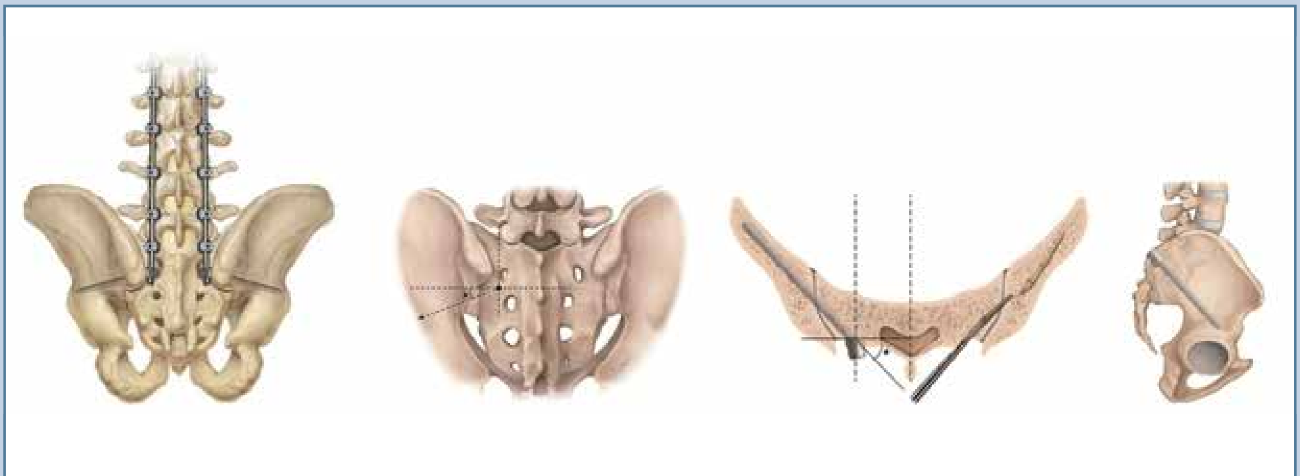

Fig 3
Installation of screws according to the S2AIS technique [15]

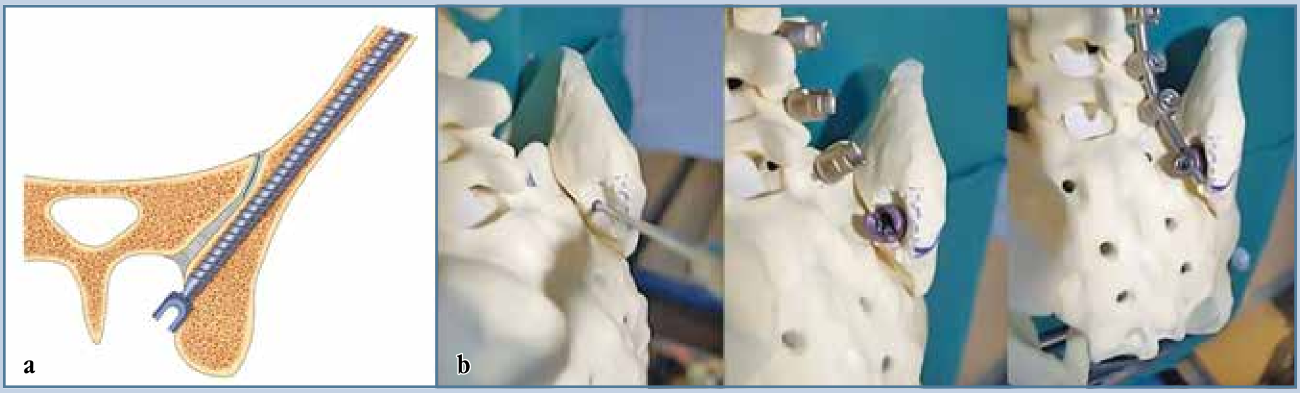

Fig 4
Installation of iliac screws according to modified techniques: **a** – according to Sohn et al. [31]; **b** – according to the DVIP (Distal Ventral Iliac Pathway) method [32]

Spinopelvic Fixation during Sacral Resection

The difficulty of supporting function restoration of spinopelvic complex in the sacral tumor resection is due to the use of various reconstructive techniques of spinopelvic fixation. The latter combines both dual iliac screws and multi-rod structures, as well as various trans-iliac fixation techniques using additional support in the pelvic bone with cortical grafts, expandable cages and cylindrical meshes (Fig. 7) [45–51].

Spinopelvic Fixation with Customized Implants

Modern technologies allow designing customized implants for spinopelvic fixation and replacement of resected bone structures. Customized implants made with the help of additive technologies are used for spinopelvic fixation and reconstructive and corrective surgeries in difficult clinical cases when the use of standard techniques is difficult or impossible.

Wuisman et al. [52] used a customized implant to perform spinopelvic reconstruction in a patient with osteosarcoma of the sacrum involving the sacroiliac joints. After resection of the sacrum and part of the iliac bones, reconstruction was performed with a customized implant (Fig. 8a).

Dalbayrak et al. [53] described 4 cases, including sacrectomy and destabilization of the previous spinopelvic fixation. Reconstruction was performed by U-shaped original plates resting on the iliac crests and connecting with the standard transpedicular instrumentation system in the lumbar spine (Fig. 8b).

A.A. Kuleshov et al. [54, 55] reported on the successful use of customized plates supported by the iliac crests, anatomically repeating the shape of the iliac bones, and connecting in the cranial direction with standard transpedicular fixators (Fig. 8b). Joukar et al. [56] conducted a biomechanical evaluation by the finite element method of spinopelvic fixation using an original tuning fork plate. According to the data obtained by them, the fixation is comparable in stability with the use of dual iliac screws. However, the load on surgical hardware is rather lower when using a tuning fork

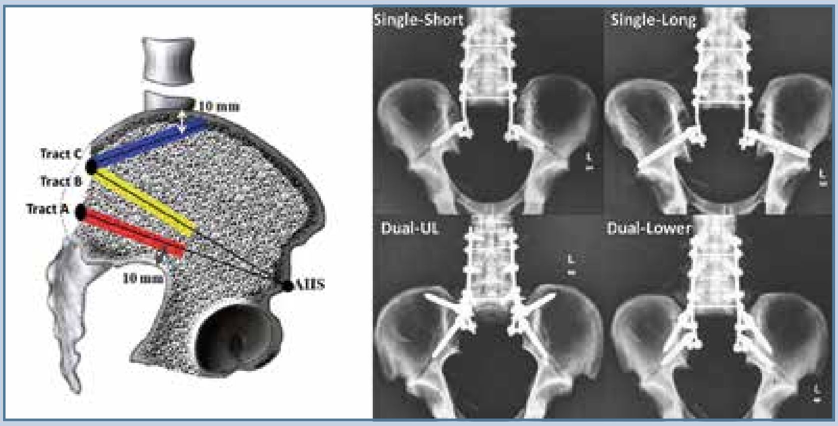

Fig 5
Possible trajectories of installing dual screws simultaneously into the iliac bones [33] and X-ray images of experimental study of various options for iliac screws to be installed [33]

plate. This may help to avoid breakage of metal fixators.

Wei et al. [57, 58] report a good long-term outcome of the use of 3D-printed sacral prostheses (Fig. 9) after total sacrectomy. The authors describe 10 cases and report fewer complications compared to screw fixation.

A systematic literature review published in 2020 on the use of customized implants in spinal surgery showed that an individualized approach and the manufacture of implants by 3D printing in difficult clinical cases have advantages over standard techniques. Nevertheless, most of the available articles only describe a series of clinical cases. In this regard, it is essential to conduct more evidence-based clinical and biomechanical studies [59].

Conclusions

The use of iliac screws is currently the main technique for performing spinopelvic fixation. The installation of iliac screws is possible in various ways. Preference is given to techniques providing a lower profile of the instrumentation system and the absence of additional connecting elements. To prevent the destabilization of fixation, it is essential to perform a fusion of an anterior support column. In difficult clinical cases requiring more rigid fixation (for example, sacrectomy), it can be reached by installing several iliac screws on each side and a multi-rod arrangement of the surgical hardware. The use of customized implants gives an opportunity to restore the supporting function of the spinopelvic complex in complicated clinical cases.

The study had no sponsors. The authors declare that they have no conflict of interest.

Fig 6
Four-rod arrangement of a surgical hardware for performing spinopelvic fixation with the use of dual iliac screws [41]

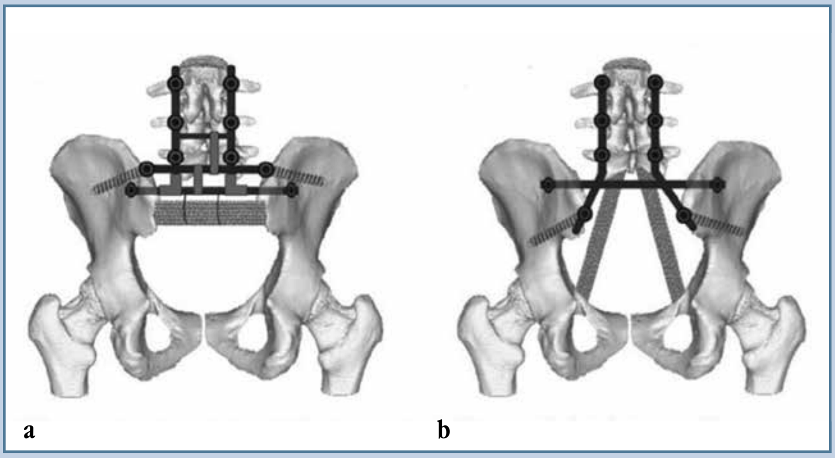

Fig 7
Several options for spinopelvic reconstruction after sacrectomy [46]: **a** – using the John Hopkins University technique; **b** – using cortical grafts and a trans-iliac rod

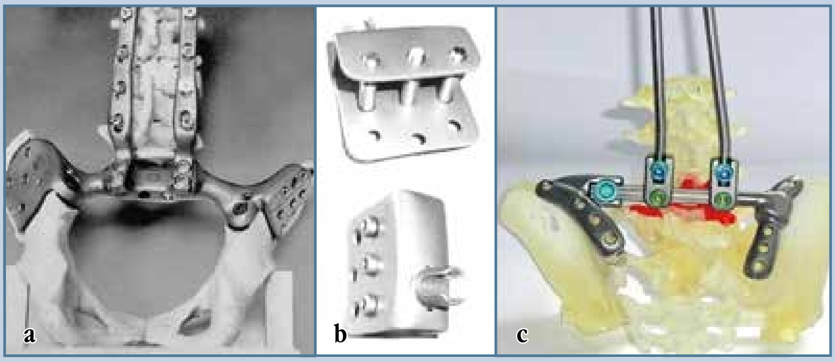

Fig 8
Several options of customized implants for spinopelvic fixation: **a** – individual design for spinopelvic fixation [52]; **b** – U-shaped plates to the iliac wings [53]; **c** – plates supported by the iliac wings [54, 55]

Fig 9
A prosthetic part of the sacrum made by 3D printing [58]

References

1. **Miller F, Moseley C, Koreska J.** Pelvic anatomy relative to lumbosacral instrumentation. J Spinal Disord. 1990;3:169–173.
2. **Schildhauer TA, McCulloch P, Mann JR.** Anatomic and radiographic considerations for placement of transiliac screws in lumbopelvic fixations. J Spinal Disord Tech. 2002;15:199–205. DOI: 10.1097/00024720-200206000-00005.
3. **Berry JL, Stahurski T, Asher MA.** Morphometry of the supra sciatic notch intrailiac implant anchor passage. Spine. 2001;26:E143–E148. DOI: 10.1097/00007632-200104010-00002.
4. **Zheng ZM, Yu BS, Chen H, Aladin DMK, Zhang KB, Zhang JF, Liu H, Luk KDK, Lu WW.** Effect of iliac screw insertion depth on the stability and strength of lumbo-iliac fixation constructs: an anatomical and biomechanical study. Spine. 2009;34: E565–E572. DOI: 10.1097/BRS.0b013e3181ac8fc4.
5. **Peelle MW, Lenke LG, Bridwell KH, Sides B.** Comparison of pelvic fixation techniques in neuromuscular spinal deformity correction: Galveston rod versus iliac and lumbosacral screws. Spine. 2006;31:2392–2398. DOI: 10.1097/01.brs.0000238973.13294.16.
6. **Tumialan LM, Mummaneni PV.** Long-segment spinal fixation using pelvic screws. Neurosurgery. 2008;63(3 Suppl):183–190. DOI: 10.1227/01.NEU.0000320431.66632.D5.
7. **Tsuchiya K, Bridwell KH, Kuklo TR, Lenke LG, Baldus C.** Minimum 5-year analysis of L5–S1 fusion using sacropelvic fixation (bilateral S1 and iliac screws) for spinal deformity. Spine. 2006;31:303–308. DOI: 10.1097/01.brs.0000197193.81296.f1.
8. **Cho W, Mason JR, Smith JS, Shimer AL, Wilson AS, Shaffrey CI, Shen FH, Novicoff WM, Fu KMG, Heller JE, Arlet V.** Failure of lumbopelvic fixation after long construct fusions in patients with adult spinal deformity: clinical and radiographic risk factors: clinical article. J Neurosurg Spine. 2013;19:445–453. DOI: 10.3171/2013.6.SPINE121129.
9. **O'Brien JR, Yu WD, Bhatnagar R, Sponseller P, Kebaish KM.** An anatomic study of the S2 iliac technique for lumbopelvic screw placement. Spine. 2009;34:439–442. DOI: 10.1097/BRS.0b013e3181a4e3e4.
10. **Chang T-L, Sponseller PD, Kebaish KM, Fishman EK.** Low profile pelvic fixation: anatomic parameters for sacral alar-iliac fixation versus traditional iliac fixation. Spine. 2009;34:436–440. DOI: 10.1097/brs.0b013e318194128c.
11. **Matteini LE, Kebaish KM, Volk WR, Bergin PF, Yu WD, O'Brien JR.** An S2 alar iliac pelvic fixation: Technical note. Neurosurg Focus. 2010;28:E13. DOI: 10.3171/2010.1.FOCUS09268.
12. **O'Brien JR, Yu W, Kaufman BE, Bucklen B, Salloum K, Khalil S, Gudipally M.** Biomechanical evaluation of S2 alar-iliac screws: effect of length and quad-cortical purchase as compared with iliac fixation. Spine. 2013;38: E1250–E1255. DOI: 10.1097/BRS.0b013e31829e17ff.
13. **Hoernschemeyer DG, Pashuck TD, Pfeiffer FM.** Analysis of the S2 alar-iliac screw as compared with the traditional iliac screw: does it increase stability with sacroiliac fixation of the spine? Spine J. 2017;17:875–879. DOI: 10.1016/j.spinee.2017.02.001.
14. **Shin JK, Lim BY, Goh TS, Son SM, Kim HS, Lee JS, Lee CS.** Effect of the screw type (S2-alar-iliac and iliac), screw length, and screw head angle on the risk of screw and adjacent bone failures after a spinopelvic fixation technique: A finite element analysis. PLoS One. 2018;13:e0201801. DOI: 10.1371/journal.pone.0201801.
15. **Park JH, Hyun SJ, Kim KJ, Jahng TA.** Free hand insertion technique of S2 sacral alar-iliac screws for spino-pelvic fixation: Technical note, a cadaveric study. J Korean Neurosurg Soc. 2015;58:578–581. DOI: 10.3340/jkns.2015.58.6.578.
16. **Laratta JL, Shillingford JN, Meredith JS, Lenke LG, Lehman RA, Gum JL.** Robotic versus freehand S2 alar iliac fixation: in-depth technical considerations. J Spine Surg. 2018;4:638–644. DOI: 10.21037/jss.2018.06.13.
17. **Laratta JL, Shillingford JN, Lombardi JM, Allrabaa RG, Benkli B, Fischer C, Lenke LG, Lehman RA.** Accuracy of S2 alar-iliac screw placement under robotic guidance. Spine Deform. 2018;6:130–136. DOI: 10.1016/j.jspd.2017.08.009.
18. **Tanasansomboon T, Tejapongvorachai T, Yingsakmongkol W, Limthongkul W, Kotheeranurak V, Singhatanadgige W.** Minimally invasive percutaneous modified iliac screw placement using intraoperative navigation: a technical note. World Neurosurg. 2021;146:240–245. DOI: 10.1016/j.wneu.2020.11.112.
19. **Kebaish KM, Gunne AP, Mohamed AS, Zimmerman R, Ko PS, Skolasky RL, O'Brien JR, Sponseller PD.** A new low profile sacro-pelvic fixation using S2 alar iliac (S2AI) screws in adult deformity fusion to the sacrum: a prospective study with minimum two-year follow-up. In: SRS 44th Annual Meeting and Course. San Antonio, Texas, September 23–26, 2009. E-Poster #21. 2009:170.
20. **Kebaish KM, Pullter Gunne AF, Mohamed AS, Ko PS, Skolasky RL, O'Brien JR, Sponseller PD.** A new low profile sacro-pelvic fixation using S2 Alar Iliac (S2AI) screws in adult deformity fusion to the sacrum: a prospective study with minimum two-year follow-up. In: North American Spine Society Annual Meeting; November 10–14, 2009; San Francisco, CA; 2009.
21. **Sponseller PD, Zimmerman RM, Ko PS, Gunne AFP, Mohamed AS, Chang TL, Kebaish KM.** Low profile pelvic fixation with the sacral alar iliac technique in the pediatric population improves results at two-year minimum follow-up. Spine. 2010;35:1887–1892. DOI: 10.1097/BRS.0b013e3181e03881.
22. **Jain A, Kebaish KM, Sponseller PD.** Sacral-alar-iliac fixation in pediatric deformity: radiographic outcomes and complications. Spine Deform. 2016;4:225–229. DOI: 10.1016/j.jspd.2015.11.005.
23. **Elder BD, Ishida W, Lo SFL, Holmes C, Goodwin CR, Kosztowski TA, Bydon A, Gokaslan ZL, Wolinsky JP, Sciubba DM, Witham TF.** Use of S2-alar-iliac screws associated with less complications than iliac screws in adult lumbosacropelvic fixation. Spine. 2017;42:E142–E149. DOI: 10.1097/BRS.0000000000001722.
24. **Guler UO, Cetin E, Yaman O, Pellise F, Casademut AV, Sabat MD, Alanay A, Grueso FS, Acaroglu E.** Sacropelvic fixation in adult spinal deformity (ASD); a very high rate of mechanical failure. Eur Spine J. 2015;24:1085–1091. DOI: 10.1007/s00586-014-3615-1.
25. **Cottrill E, Margalit A, Brucker C, Sponseller PD.** Comparison of sacral-alar-iliac and iliac-only methods of pelvic fixation in early-onset scoliosis at 5.8 years' mean follow-up. Spine Deform. 2019;7:364–370. DOI: 10.1016/j.jspd.2018.08.007.
26. **Shillingford JN, Laratta JL, Tan LA, Sarpong NO, Lin JD, Fischer CR, Lehman RA Jr, Kim YJ, Lenke LG.** The free-hand technique for S2-alar-iliac screw placement. J Bone Joint Surg Am. 2018;100:334–342. DOI: 10.2106/JBJS.17.00052.
27. **Ishida W, Elder BD, Holmes C, Lo SL, Goodwin CR, Kosztowski TA, Bydon A, Gokaslan ZL, Wolinsky JP, Sciubba DM, Witham TF.** Comparison between S2-alar-iliac screw fixation and iliac screw fixation in adult deformity surgery: reoperation rates and spinopelvic parameters. Global Spine J. 2017;7:672–680. DOI: 10.1177/2192568217700111.
28. **Shabtai L, Andras LM, Portman M, Harris LR, Choi PD, Tolo VT, Skaggs DL.** Sacral alar iliac (SAI) screws fail 75% less frequently than iliac screws in neuromuscular scoliosis. J Pediatr Orthop. 2017;37:e470–e475. DOI: 10.1097/BPO.0000000000000720.
29. **Keorochana G, Arirachakaran A, Setrkraising K, Kongtharvonskul J.** Comparison of complications and revisions after sacral 2 alar iliac screw and iliac screw fixation for sacropelvic fixation in pediatric and adult populations: systematic review and meta-analysis. World Neurosurg. 2019;132:408–420.e1. DOI: 10.1016/j.wneu.2019.08.104.
30. **Sohn S, Chung CK, Kim YJ, Kim CH, Park SB, Kim H.** Modified iliac screw fixation: technique and clinical application. Acta Neurochir (Wien). 2016;158:975–980. DOI: 10.1007/s00701-016-2772-x.

31. **Sohn S, Park TH, Chung CK, Kim YJ, Jang JW, Han IB, Lee SJ.** Biomechanical characterization of three iliac screw fixation techniques: A finite element study. J Clin Neurosci. 2018;52:109–114. DOI: 10.1016/j.jocn.2018.03.002.
32. **Cady-McCrea CI, Visco ZR, Lavelle WF, Tallarico RA.** Distal ventral iliac pathway for spinopelvic fixation: technique description and case series. Int J Spine Surg. 2021;8116. DOI: 10.14444/8116.
33. **Yu BS, Zhuang XM, Zheng ZM, Li ZM, Wang TP, Lu WW.** Biomechanical advantages of dual over single iliac screws in lumbo-iliac fixation construct. Eur Spine J. 2010;19:1121–1128. DOI: 10.1007/s00586-010-1343-8.
34. **Mindea SA, Chinthakunta S, Moldavsky M, Gudipally M, Khalil S.** Biomechanical comparison of spinopelvic reconstruction techniques in the setting of total sacrectomy. Spine. 2012;37:E622–E627. DOI: 10.1097/BRS.0b013e31827619d3.
35. **Acharya NK, Bijukachhe B, Kumar RJ, Menon VK.** Ilio-lumbar fixation-The Amrita technique. J Spinal Disord Tech. 2008;21:493–499. DOI: 10.1097/BSD.0b013e31815b5cc4.
36. **Ebata S, Ohba T, Oba H, Haro H.** Bilateral dual iliac screws in spinal deformity correction surgery. J Orthop Surg Res. 2018;13:260. DOI: 10.1186/s13018-018-0969-9.
37. **Bodin A, Roussouly P.** Sacral and pelvic osteotomies for correction of spinal deformities. Eur Spine J. 2014;24(Suppl 1):72–82. DOI: 10.1007/s00586-014-3651-x.
38. **Ozturk AK, Sullivan PZ, Arlet V.** Sacral pedicle subtraction osteotomy for an extreme case of positive sagittal balance: case report. J Neurosurg Spine. 2018;28:532–535. DOI: 10.3171/2017.8.SPINE17550.
39. **Czyz M, Forster S, Holton J, Shariati B, Clarkson DJ, Boszczyk BM.** New method for correction of lumbo-sacral kyphosis deformity in patient with high pelvic incidence. Eur Spine J. 2017;26:2204–2210. DOI: 10.1007/s00586-017-5205-5.
40. **Bourghli A, Boissiere L, Obeid I.** Dual iliac screws in spinopelvic fixation: a systematic review. Eur Spine J. 2019;28:2053–2059. DOI: 10.1007/s00586-019-06065-3.
41. **Shen FH, Harper M, Foster WC, Marks I, Arlet V.** A novel “four-rod technique” for lumbo-pelvic reconstruction: theory and technical considerations. Spine. 2006;31:1395–1401. DOI: 10.1097/01.brs.0000219527.64180.95.
42. **Lebwohl NH, Cunningham BW, Dmitriev A, Shimamoto N, Gooch L, Devlin V, Boachie-Adjei O, Wagner TA.** Biomechanical comparison of lumbosacral fixation techniques in a calf spine model. Spine. 2002;27:2312–2320. DOI: 10.1097/00007632-200211010-00003.
43. **Galbusera F, Casaroli G, Chande R, Lindsey D, Villa T, Yerby S, Mesiwala A, Panico M, Gallazzi E, Brayda-Bruno M.** Biomechanics of sacropelvic fixation: a comprehensive finite element comparison of three techniques. Eur Spine J. 2020;29:295–305. DOI: 10.1007/s00586-019-06225-5.
44. **Park SJ, Park JS, Nam Y, Yum TH, Choi YT, Lee CS.** Failure types and related factors of spinopelvic fixation after long construct fusion for adult spinal deformity. Neurosurgery. 2021;88:603–611. DOI: 10.1093/neuros/nyaa469.
45. **Newman CB, Keshavarzi S, Aryan HE.** En bloc sacrectomy and reconstruction: technique modification for pelvic fixation. Surg Neurol. 2009;72:752–756. DOI: 10.1016/j.surneu.2009.02.008.
46. **Varga PP, Szoverfi Z, Lazary A.** Surgical resection and reconstruction after resection of tumors involving the sacropelvic region. Neurol Res. 2014;36:588–596. DOI: 10.1179/1743132814Y.0000000370.
47. **Gallia GL, Haque R, Garonzik I, Witham TF, Khavkin YA, Wolinsky JP, Suk I, Gokaslan ZL.** Spinal pelvic reconstruction after total sacrectomy for en bloc resection of a giant sacral chordoma. Technical note. J Neurosurg Spine. 2005;3:501–506. DOI: 10.3171/spi.2005.3.6.0501.
48. **Bederman SS, Shah KN, Hassan JM, Hoang BH, Kiester PD, Bhatia NN.** Surgical techniques for spinopelvic reconstruction following total sacrectomy: a systematic review. Eur Spine J. 2014;23:305–319. DOI: 10.1007/s00586-013-3075-z.
49. **Gallia GL, Suk I, Witham TF, Gearhart SL, Black JH 3rd, Redett RJ, Sciubba DM, Wolinsky JP, Gokaslan ZL.** Lumbopelvic reconstruction after combined L5 spondylectomy and total sacrectomy for en bloc resection of a malignant fibrous histiocytoma. Neurosurgery. 2010;67:E498–E502. DOI: 10.1227/01.NEU.0000382972.15422.10.
50. **Gillis CC, Street JT, Boyd MC, Fisher CG.** Pelvic reconstruction after subtotal sacrectomy for sacral chondrosarcoma using cadaveric and vascularized fibula autograft. J Neurosurg Spine. 2014;21:623–627. DOI: 10.3171/2014.6.SPINE13657.
51. **Choi MK, Jo DJ, Kim SB.** Pelvic reconstruction surgery using a dual-rod technique with diverse U-shaped rods after posterior en bloc partial sacrectomy for a sacral tumor: 2 case reports and a literature review. World Neurosurg. 2016;95:619.e11–619.e18. DOI: 10.1016/j.wneu.2016.08.022.
52. **Wuisman P, Lieshout O, van Dijk M, van Diest P.** Reconstruction after total en bloc sacrectomy for osteosarcoma using a custom-made prosthesis. Spine. 2001;26:431–439. DOI: 10.1097/00007632-200102150-00021.
53. **Dalbayrak S, Yilmaz M, Kaner T, Gokdag M, Yilmaz T, Sasani M, Oktenoglu T, Ozer AF.** Lumbosacral stabilization using iliac wings: A new surgical technique. Spine. 2011;36:E673–E677. DOI: 10.1097/BRS.0b013e3181f8fa7c.
54. **Kuleshov AA, Vetrile MS, Shkarubo AN, Docenko VV, Es’kin NA, Lisyanskiy IN, Makarov SN.** Additive technologies in surgical treatment of spinal deformities. N.N Priorov Journal of Traumatology and Orthopedics. 2018;(4):19–29. DOI: 10.17116/vto201803-04119.
55. **Vetrile MS, Kuleshov AA, Makarov SN, Lisyansy IN, Kokorev AI, Aganesov NA, Zakharin VR.** Peculiarities of spinopelvic fixation in deformations and traumatic injuries of the spine. NN Priorov Journal of Traumatology and Orthopedics. 2021;28(1):17–27. DOI: 10.17816/vto63954.
56. **Joukar A, Mehta J, Goel VK, Marks DS.** Biomechanical analysis of the tuning fork plate versus dual pelvic screws in a sacrectomy model: a finite element study. Global Spine J. Published online 2021:1–8. DOI: 10.1177/2192568220983792.
57. **Wei R, Guo W, Ji T, Zhang Y, Liang H.** One-step reconstruction with a 3D-printed, custom-made prosthesis after total en bloc sacrectomy: a technical note. Eur Spine J. 2017;26:1902–1909. DOI: 10.1007/s00586-016-4871-z.
58. **Wei R, Guo W, Yang R, Tang X, Yang Y, Ji T, Liang H.** Reconstruction of the pelvic ring after total en bloc sacrectomy using a 3D-printed sacral endoprosthesis with re-establishment of spinopelvic stability: a retrospective comparative study. Bone Joint J. 2019;101-B:880–888. DOI: 10.1302/0301-620X.101B7.BJJ-2018-1010.R2.
59. **Burnard JL, Parr WCH, Choy WJ, Walsh WR, Mobbs RJ.** 3D-printed spine surgery implants: a systematic review of the efficacy and clinical safety profile of patient-specific and off-the-shelf devices. Eur Spine J. 2020;29:1248–1260. DOI: 10.1007/s00586-019-06236-2.
60. **Dayer R, Ouellet JA, Saran N.** Pelvic fixation for neuromuscular scoliosis deformity correction. Curr Rev Musculoskelet Med. 2012;5:91–101. DOI: 10.1007/s12178-012-9122-2.
61. **Moshirfar A, Rand FF, Sponseller PD, Parazin SJ, Khanna AJ, Kebaish KM, Stinson JT, Riley LH 3rd**. Pelvic fixation in spine surgery. Historical overview, indications, biomechanical relevance, and current techniques. J Bone Joint Surg Am. 2005;87 Suppl 2:89–106. DOI: 10.2106/JBJS.E.00453.

Address correspondence to:
Vetrile Marchel Stepanovich
N.N. Priorov National Medical Research Center
of Traumatology and Orthopaedics,
10 Priorova str., Moscow, 127299, Russia,
vetrilams@cito-priorov.ru

Received 27.10.2021
Review completed 17.11.2021
Passed for printing 19.12.2021

Marchel Stepanovich Vetrile, MD, PhD, traumatologist-orthopedist, senior researcher, N.N. Priorov National Medical Research Center of Traumatology and Orthopaedics, 10 Priorova str., Moscow, 127299, Russia, ORCID: 0000-0001-6689-5220, vetrilams@cito-priorov.ru;
Alexander Alekseyevich Kuleshov, DMSc, traumatologist-orthopedist, head of Vertebrology Department, N.N. Priorov National Medical Research Center of Traumatology and Orthopaedics, 10 Priorova str., Moscow, 127299, Russia, ORCID: 0000-0002-9526-8274, cito-spine@mail.ru;
Sergey Nikolayevich Makarov, MD, PhD, traumatologist-orthopedist, N.N. Priorov National Medical Research Center of Traumatology and Orthopaedics, 10 Priorova str., Moscow, 127299, Russia, ORCID: 0000-0003-0406-1997, moscow.makarov@gmail.com;
Igor Nikolayevich Lisyansky, MD, PhD, traumatologist-orthopedist, N.N. Priorov National Medical Research Center of Traumatology and Orthopaedics, 10 Priorova str., Moscow, 127299, Russia, ORCID: 0000-0002-2479-438, lisigornik@list.ru;
Nikolay Aleksandrovich Aganesov, traumatologist-orthopedist, N.N. Priorov National Medical Research Center of Traumatology and Orthopaedics, 10 Priorova str., Moscow, 127299, Russia, ORCID: 0000-0001-5383-6862, kolyanzer@yandex.ru;
Vitaly Romanovich Zakharin, traumatologist-orthopedist, N.N. Priorov National Medical Research Center of Traumatology and Orthopaedics, 10 Priorova str., Moscow, 127299, Russia, ORCID: 0000-0003-1553-2782, zakhvit@gmail.com.