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THE HISTORY AND EVOLUTION OF SURGICAL DEFORMITY CORRECTION IN ADOLESCENT IDIOPATHIC SCOLIOSIS

Burak Abay[1], Hamisi Mraja[2], İlyas Dolaş[3], Selhan Karadereler[2], Meriç Enercan[1], Azmi Hamzaoğlu[2], Emin Alıcı[4]

[1]*Demiroğlu Bilim University Faculty of Medicine, Department of Orthopedics and Traumatology, İstanbul, Türkiye*

[2]*İstanbul Florence Nightingale Hospital, İstanbul Scoliosis and Spine Center, Clinic of Orthopedics and Traumatology, İstanbul, Türkiye*

[3]*Demiroğlu Bilim University Faculty of Medicine, Department of Neurosurgery, İstanbul, Türkiye*

[4]*Dokuz Eylül University Faculty of Medicine, Department of Orthopedics and Traumatology, İzmir, Türkiye*

ABSTRACT

The surgical correction of adolescent idiopathic scoliosis (AIS) has transitioned from long, coronal-focused distraction constructs to more sophisticated three-dimensional (3D) strategies that prioritize physiologic alignment, shorter fusions, and reliable recovery. The Harrington era demonstrated that internal fixation could safely control deformity on a large scale, yet experience with thoracic hypokyphosis and limited axial control exposed the need for constructs that address rotation and the sagittal profile. Cotrel-Dubousset instrumentation reframed AIS as a rotational deformity and introduced deliberate 3D correction; comparative series subsequently documented improved sagittal restoration and reduced reliance on postoperative external immobilization compared with earlier systems. The widespread adoption of thoracic pedicle-screw constructs-and later, direct vertebral rotation-made strong multiplanar correction routine while allowing more selective, shorter fusions guided by the Lenke classification. Current decision-making fine-tunes implant strategy and perioperative care, rather than seeking a single “best” construct. Enhanced recovery pathways consistently shorten hospital stays and reduce blood loss without increasing complications, supporting broader implementation alongside modern anesthetic and analgesic techniques. Posterior minimally invasive scoliosis surgery can decrease blood loss and length of stay compared with open posterior spinal fusion, though operative time may be longer and radiographic outcomes may be similar, underscoring the role of case selection and surgeon experience. Image guidance and robotics may improve pedicle-screw accuracy, but large contemporary datasets warn of higher radiation exposure and modeled lifetime cancer risk with routine navigation in AIS, supporting selective use rather than default adoption. Recently, for skeletally immature patients who fail bracing, vertebral body tethering offers a motion-preserving, non-fusion alternative with meaningful correction but a non-trivial risk of reoperation, requiring careful counseling and follow-up.

Keywords: Adolescent idiopathic surgery, deformity correction, posterior surgery

INTRODUCTION

What surgeons mean by a “good” scoliosis correction has changed with each generation of implants. Early internal fixation proved that large curves could be controlled safely and reproducibly, but it also taught hard lessons about what happens when we straighten the coronal plane without safeguarding rotation and thoracic kyphosis.

The field then pivoted from “making it straight” to “making it balanced.” A common language-the Lenke classification-helped surgeons decide which curves truly require fusion and how far to extend it[(1)]. At the same time, thoracic pedicle-screw constructs offered us reliable control over three columns, making multiplanar correction a standard practice rather than a goal to strive for. In practice, this combination of classification and segmental screws enabled shorter, more selective fusions while maintaining alignment[(2)].

Today the central question is not whether to correct in three planes, but how to individualize that correction for a specific teenager in front of us. Perioperative bundles such as enhanced recovery after surgery (ERAS) can shorten hospital stay and reduce blood loss without worsening complications[(3)]. While guidance technologies can enhance the precision of screw

Address for Correspondence: Meriç Enercan, Demiroğlu Bilim University Faculty of Medicine, Department of Orthopedics and Traumatology, İstanbul, Türkiye
E-mail: enercan@yahoo.com
ORCID ID: orcid.org/0000-0003-3263-9290
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placement, recent data indicate that routine navigation in adolescent idiopathic scoliosis (AIS) may lead to increased radiation exposure. Therefore, it is often more sensible to employ these technologies selectively rather than universally. For patients who are still growing and do not respond to bracing, vertebral body tethering offers a renewed chance to maintain spinal motion, though it comes with a reoperation risk that requires meticulous planning[4]. This review presents a journey from historical milestones to present-day choices-to offer pragmatic, classification-aligned guidance for individualized AIS correction.

Early Concepts and the Harrington Era

Recognition of spinal deformity dates to antiquity. Hippocratic descriptions emphasized forceful traction and suspension, while Renaissance and early-modern care remained largely mechanical-splints, corsets (e.g., Ambroise Paré's steel corset), and prolonged traction-aimed at containment rather than durable correction In the 19th century, Jules Guérin's myotomy marked the first purposeful surgical attempt at deformity release, and by 1911 Albee and Hibbs had introduced spinal fusion as a means to stabilize progressive curves; however, early fusion attempts were plagued by high nonunion rates and lengthy immobilization[5]. Mid-20th-century work on controlled spinal osteotomy clarified technique, dangers, and safeguards, framing the risk-benefit calculus that still informs corrective surgery[6].

The step-change came with Harrington's rod-and-hook system. His 1962 report established internal distraction/compression as a reproducible method to control deformity at scale, and the subsequent 1973 series of 578 cases cemented its feasibility and safety in routine practice[7]. Yet the lessons were equally formative: distraction constructs prioritized coronal straightening at the expense of axial derotation and physiologic sagittal contour. Loss of thoracic kyphosis and lumbar lordosis-the "flat-back" tendency-along with the need for prolonged postoperative immobilization (often months in a cast or brace) highlighted the limits of first-generation systems and set the stage for segmental, three-dimensional (3D) solutions.

The First-generation: The Reign of Distraction

The first widely adopted internal fixation for AIS arrived in 1962 with Paul Harrington's rod-and-hook construct, which applied distraction/compression across the curve and rapidly became the global standard for two decades[7,8]. Contemporary series documented substantial immediate coronal straightening, but limited control of axial rotation and thoracic kyphosis, with some loss of correction over time-limitations that would shape the next-generation of systems[5].

Standard postoperative care in the Harrington era commonly included prolonged external immobilization to protect fusion-often a body cast for weeks followed by bracing for a total of roughly 6-9 months-reflecting the biomechanics of single-rod distraction and fusion techniques of the time[9,10]. With longer follow-up, the characteristic complication profile of distraction constructs also emerged; most notably, flat-back sagittal imbalance from loss of lumbar lordosis frequently required later revision surgery[11].

Experience during this period likewise sharpened awareness of neurological risk from over-distraction. Surgeons adopted "wake-up test" as an intraoperative safeguard, a practice that later gave way to multimodal neurophysiologic monitoring as technology matured[12,13].

Segmental Constructs and Anterior Systems

By the 1970s, the field recognized the need for greater segmental control; Eduardo Luque's segmental spinal instrumentation used sublaminar wires at each level to anchor pre-bent rods and formalized translation of the spine toward the rod, enhancing coronal control while better preserving sagittal contour[14]. These constructs frequently reduced or eliminated the need for postoperative plaster immobilization compared with Harrington-era protocols[2]. Nevertheless, neurologic risk inherent to passing sublaminar wires limited universal adoption; a British Scoliosis Society survey reported neurologic complications of roughly 4% with sublaminar wiring[15]. In parallel, anterior approaches targeted thoracolumbar and lumbar curves: Dwyer's et al.[16] system used vertebral body screws linked by a cable to compress the convexity and shorten fusion spans. Zielke's 1976 ventral derotation spondylodesis stiffened the construct and deliberately addressed apical rotation, providing improved axial control and selective fusion options[17]. Comparative series and reviews indicate that these anterior systems often achieved stronger rotational correction and shorter fusion segments than distraction-based posterior instrumentation, with trade-offs including kyphogenic effects and approach-related cardiopulmonary and vascular risks[18].

The Third-generation: 3D Correction: Cotrel-Dubousset (CD) Achieving 3D Mastery

The decisive shift came with the field's embrace of scoliosis as a 3D deformity-coronal deviation, axial rotation, and sagittal malalignment-embodied by the mid-1980s introduction of CD instrumentation[5,19]. The CD system used multiple hooks, transverse connectors, and deliberate rod rotation/derotation to build a rigid frame; critically, construct stability meant external bracing could often be abandoned[20]. Subsequent "third-generation" systems built on this platform: the Texas Scottish Rite Hospital system paralleled CD concepts with double-rod constructs and cross-links that enhanced frame rigidity and facilitated 3D correction[4,5], while the ISOLA system leveraged translation via a cantilever technique (with optional sublaminar augmentation) to improve coronal and rotational correction in clinical series[4-7,21,22]. In this context, Alici and Pinar[23] described the Alici spinal system, a modular anterior-posterior instrumentation allowing three-plane correction and stable fixation in scoliosis, reporting a 92-patient series (58 idiopathic, 20 congenital, 12 paralytic, 2 neurofibromatosis) in which 24 patients underwent staged combined anterior-posterior fusion and 68 posterior-only fusion[24].

In parallel, thoracic pedicle-screw fixation gained broad adoption in the mid-1990s, enabling powerful segmental three-column control and reliable multiplanar correction in AIS[2,25]. The addition of direct vertebral rotation (DVR) further improved apical derotation and coronal outcomes compared with simple rod derotation, and bilateral transpedicular screw constructs are now widely accepted as a reliable foundation for 3D correction in AIS (Figure 1)[26].

Thoracic Pedicle-Screw Era→DVR and Selective Fusion

With the transition to segmental three-column control, thoracic pedicle-screw constructs have become the cornerstone of AIS surgery, offering stronger multiplanar correction than hook-based systems and often enabling shorter fusions[2,27]. The introduction of DVR leveraged this screw purchase to address apical rotation more effectively than simple rod derotation, improving coronal and rotational correction in thoracic AIS[28,29]. Classification-guided planning matured in parallel: the Lenke system standardized curve typing and modifiers and underpins selective thoracic fusion (STF), in which only the structural thoracic curve is fused and the compensatory lumbar curve is left mobile[1]. Contemporary series report favorable spontaneous lumbar curve correction with STF when selection criteria are met, but also highlight risks-adding-on and coronal/lumbar decompensation-underscoring the need for careful indication and intraoperative alignment targets[30,31]. Although hybrid constructs remain in use, modern evidence and practice trends support all-screw constructs as a reliable foundation for 3D correction in AIS, with ongoing debate about rod characteristics and density tailored to pattern and goals (Figure 2)[32].

Advanced Techniques for Complex Deformity

For rigid or severe deformities, highly technical osteotomies are employed to achieve correction where flexibility is lost. The earliest such technique was the Smith-Petersen osteotomy (1945), a posterior column-shortening procedure that provides roughly 10° of correction per level in extension-based deformities[33]. More recently, the radical posterior-only vertebral column resection, popularized by Suk et al.[34], became the procedure of choice for fixed, severe deformities, although it is associated with a high risk of neurological and mechanical complications.

Growth Modulation

The drive to avoid the complications of definitive fusion, especially in very young patients, has spurred the development of fusionless techniques based on the Hueter-Volkmann principle, whereby increased compression inhibits physeal growth. Growth-modulation strategies include:

Anterior vertebral stapling: Shape-memory or metallic staples are placed on the convex side of the curve to temporarily modulate growth, with early and mid-term series showing feasibility in selected juvenile and adolescent patients with moderate curves[35].

Anterior vertebral tethering: A minimally invasive anterior approach using screws and a flexible tether to restrict growth on the convex side, indicated for skeletally immature patients with moderate, flexible curves. Early and mid-term results demonstrate progressive correction with preservation of motion but also report risks of over- or under-correction and need for revision or conversion to fusion (Figure 3)[36-38].

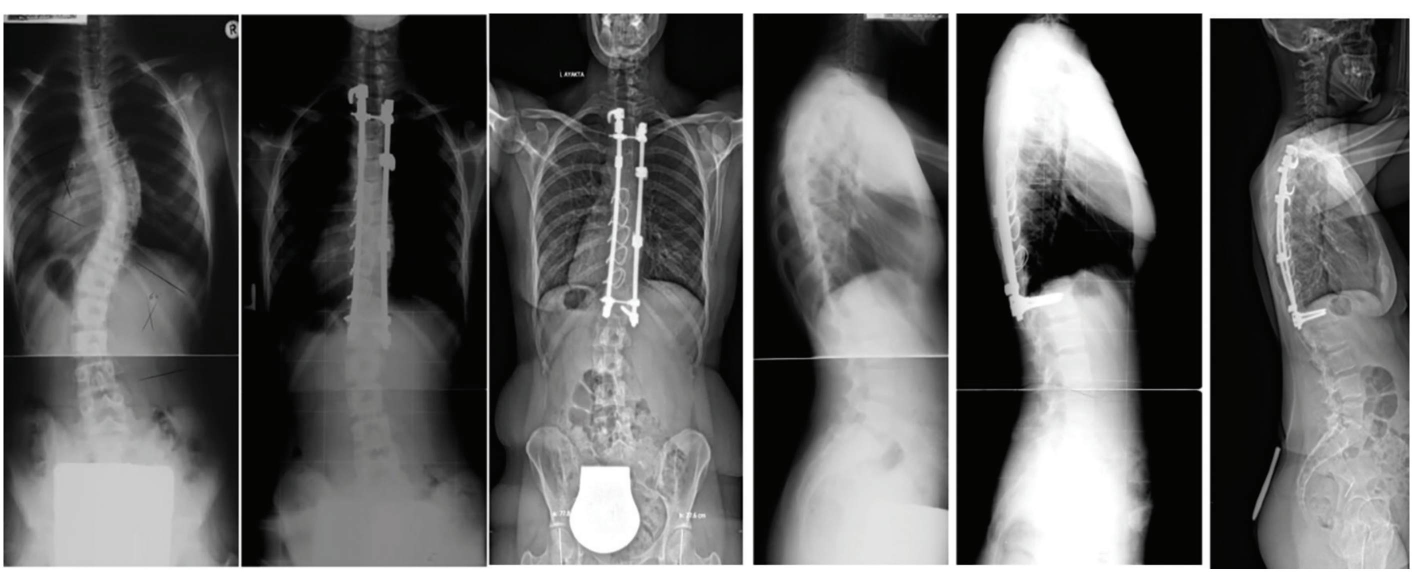

Figure 1. Standing whole-spine anteroposterior and lateral radiographs of a 12-year-old girl treated with posterior hook-screw instrumentation for adolescent idiopathic scoliosis. At 29-year follow-up, coronal and sagittal alignment remain well balanced with maintained deformity correction

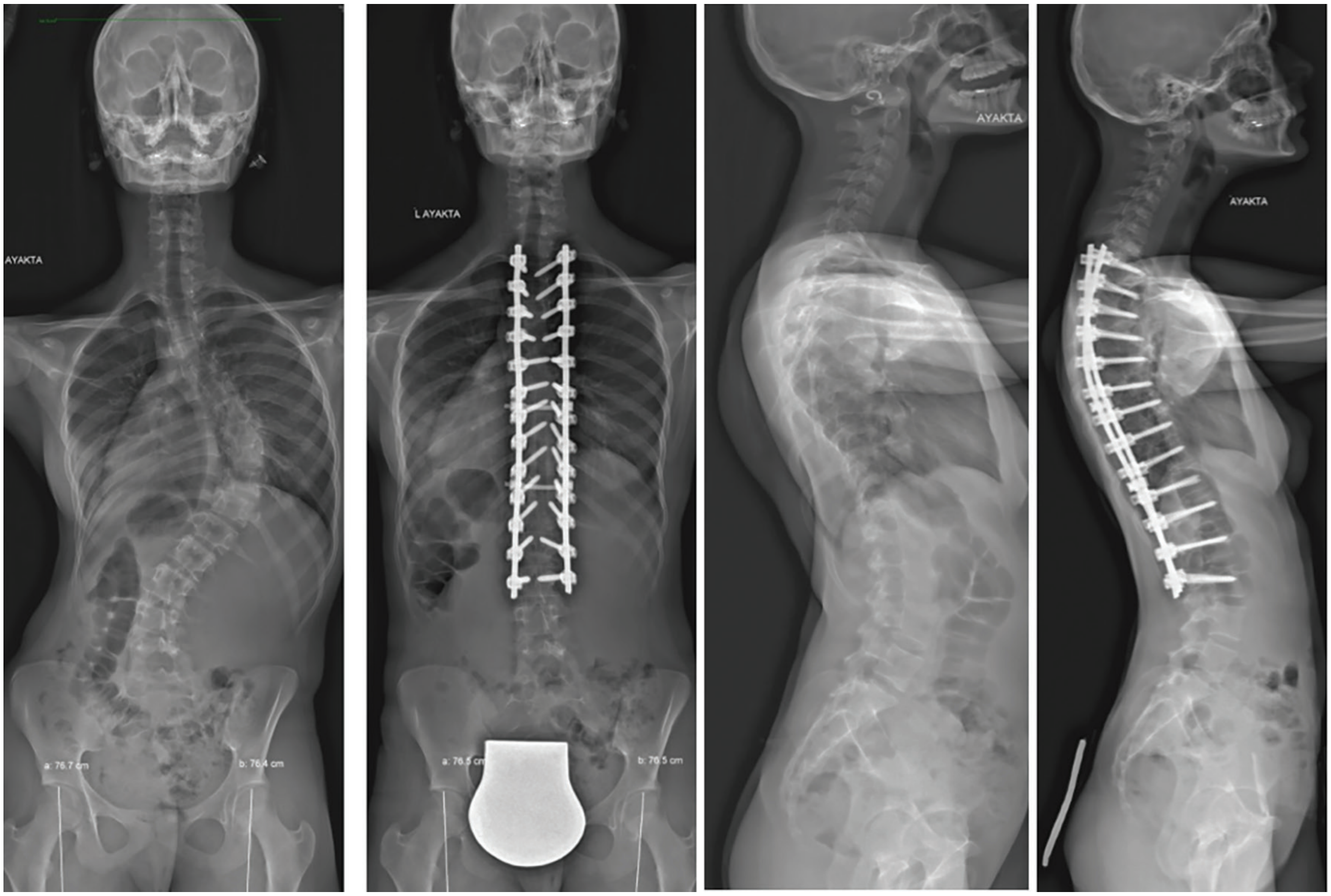

Figure 2. Pre- and postoperative standing whole-spine anteroposterior and lateral radiographs of a 15-year-old girl with adolescent idiopathic scoliosis treated with posterior pedicle-screw instrumentation

The Cutting Edge: Minimally Invasive and Digital Surgery

The latest evolution in AIS surgery focuses on minimizing the surgical footprint while maximizing precision. Minimally invasive surgery (MIS) for AIS, introduced around 2010-2011, aims to reduce muscle stripping, scarring, blood loss, and recovery time. Comparative studies and a recent meta-analysis suggest that MIS is associated with reduced estimated blood loss, lower transfusion rates, and less postoperative opioid use, although operative time is often longer and radiographic correction and functional scores may slightly favor conventional open posterior fusion[39].

Surgical precision is being enhanced by new technologies. Computed tomography (CT)-based navigation and O-arm-assisted systems improve pedicle-screw placement accuracy compared with traditional freehand techniques in deformity surgery, including AIS, albeit sometimes at the cost of increased operative time and higher radiation exposure to the patient and operating room staff. Robot-assisted systems have similarly demonstrated higher accuracy rates than freehand placement in complex spinal constructs, though their routine use in AIS remains center-dependent and cost-sensitive[39,40].

ERAS pathways have become an important adjunct to surgical technique in AIS. Protocols that integrate optimized analgesia, early mobilization, multimodal antiemesis, and standardized perioperative care consistently shorten hospital stay without increasing complications or readmissions[40].

Implant Strategy: Screw Density and Rod Characteristics

Current evidence does not support a single universally “optimal” pedicle-screw density in AIS correction. Lower-density constructs can achieve comparable radiographic correction and complication rates in appropriately selected patients, while offering potential advantages in cost, blood loss, and operative time compared with high-density patterns[41]. However, some series still associate higher screw density with slightly greater immediate Cobb angle correction, suggesting that implant strategy should be individualized rather than protocol-driven[42]. In parallel, rod material and diameter have emerged as key determinants of construct behavior. Stiffer, larger-diameter cobalt-chromium rods (e.g., 6.0-6.35 mm) may improve coronal and sagittal correction, especially kyphosis restoration, but at the expense of higher mechanical stress at the bone-implant interface and possibly increased reoperation risk, whereas titanium rods (often 5.5 mm) provide a more forgiving, biologically “friendlier” construct[42].

Image Guidance, Robotics, and Augmented Reality (AR)

Image-guided navigation, robotic assistance, and AR are increasingly used to refine implant placement and workflow.

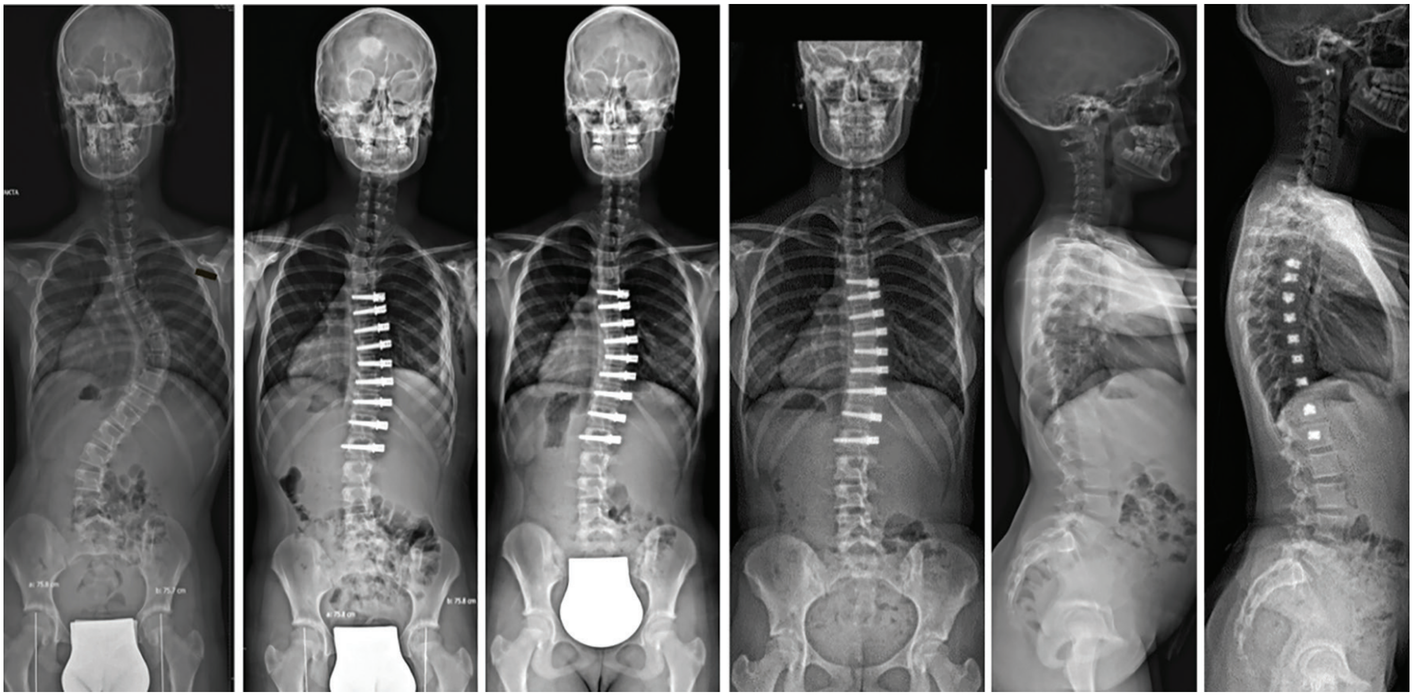

Figure 3. Standing whole-spine radiographs of a skeletally immature patient treated with VBT for a 70° main thoracic curve. Early postoperative AP radiograph shows residual deformity, which gradually remodels to 8° at 3-year follow-up. Lateral radiographs demonstrate improvement of thoracic kyphosis from 15° to 33° with preserved global sagittal alignment. VBT: Vertebral body tethering, AP: Anteroposterior

Systematic reviews and large database studies indicate that CT-based navigation and robotic systems can improve pedicle-screw accuracy compared with traditional freehand techniques; however, this often comes at the cost of longer operative times and increased radiation exposure[43]. In AIS, the cumulative ionizing dose is particularly relevant, with some models estimating a measurable increase in projected lifetime cancer risk when heavy intraoperative CT use is combined with preoperative imaging[44]. Experienced deformity surgeons may achieve comparable accuracy using freehand or fluoroscopy-assisted techniques with substantially less radiation, underscoring the importance of surgeon expertise and case selection[43-45]. AR-assisted navigation and next-generation robotics show promise for enhancing visualization, accuracy, and workflow, but high-quality, pediatric deformity-specific outcome data remain limited, and their role in routine AIS practice is still evolving[46].

CONCLUSION

Across seven decades, AIS correction has evolved from coronal distraction to subtle 3D strategies. Segmental pedicle-screws with DVR remain the gold-standard treatment; fusion levels are increasingly tailored using Lenke principles, implant strategy (density, rods) is individualized, and ERAS optimizes recovery. Guidance/robotics/AR assistance should be deployed cautiously-balancing accuracy gains against time, cost, and radiation-while VBT remains a specialized option for carefully selected, skeletally immature patients.

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Footnotes

Authorship Contributions

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