Spinal instrumentation in infants, children, and adolescents: a review

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OBJECTIVE The evolution of pediatric spinal instrumentation has progressed in the last 70 years since the popularization of the Harrington rod showing the feasibility of placing spinal instrumentation into the pediatric spine. Although lacking in pediatric-specific spinal instrumentation, when possible, adult instrumentation techniques and tools have been adapted for the pediatric spine. A new generation of pediatric neurosurgeons with interest in complex spine disorder has pushed the field forward, while keeping the special nuances of the growing immature spine in mind. The authors sought to review their own experience with various types of spinal instrumentation in the pediatric spine and document the state of the art for pediatric spine surgery.

METHODS The authors retrospectively reviewed patients in their practice who underwent complex spine surgery. Patient demographics, operative data, and perioperative complications were recorded. At the same time, the authors surveyed the literature for spinal instrumentation techniques that have been utilized in the pediatric spine. The authors chronicle the past and present of pediatric spinal instrumentation, and speculate about its future.

RESULTS The medical records of the first 361 patients who underwent 384 procedures involving spinal instrumentation from July 1, 2007, to May 31, 2018, were analyzed. The mean age at surgery was 12 years and 6 months (range 3 months to 21 years and 4 months). The types of spinal instrumentation utilized included occipital screws (94 cases); C1 lateral mass screws (115 cases); C2 pars/translaminar screws (143 cases); subaxial cervical lateral mass screws (95 cases); thoracic and lumbar spine traditional-trajectory and cortical-trajectory pedicle screws (234 cases); thoracic and lumbar sublaminar, subtransverse, and subcostal polyester bands (65 cases); S1 pedicle screws (103 cases); and S2 alar-iliac/iliac screws (56 cases). Complications related to spinal instrumentation included hardware-related skin breakdown (1.8%), infection (1.8%), proximal junctional kyphosis (1.0%), pseudarthrosis (1.0%), screw malpositioning (0.5%), CSF leak (0.5%), hardware failure (0.5%), graft migration (0.3%), nerve root injury (0.3%), and vertebral artery injury (0.3%).

CONCLUSIONS Pediatric neurosurgeons with an interest in complex spine disorders in children should develop a comprehensive armamentarium of safe techniques for placing rigid and nonrigid spinal instrumentation even in the smallest of children, with low complication rates. The authors' review provides some benchmarks and outcomes for comparison, and furnishes a historical perspective of the past and future of pediatric spine surgery.

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KEYWORDS pediatric spine; spinal instrumentation; review; history

THE pediatric spine may be affected by various pathologies, which can be categorized as congenital, developmental, and acquired. These etiologies of pediatric spine disease represent an important distinction from those in adults. The inherent properties of the pedi-

atric spine, such as diminutive anatomy, absence of pediatric-specific instrumentation, and inability to extrapolate adult techniques to a child, make the insertion of pediatric instrumentation challenging. A singular problem in the pediatric age group is the restrictive, unwanted effects of

ABBREVIATIONS BMP = bone morphogenetic protein; PEEK = polyetheretherketone.

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spinal instrumentation on the skeletally immature spine. Fusing the skeletally immature spine may lead to far more serious issues beyond growth retardation. These issues may include restrictive lung disease, pulmonary hypertension, right heart failure, and death.

This review of our experience and series of pediatric patients describes seldom-used anterior and more often used posterior approaches for the placement of spinal instrumentation in the pediatric spine. It surveys the history of spinal instrumentation in children, beginning with Paul Harrington and his revolutionary treatment for scoliosis in children with polio. Various biomaterials and other surgical adjuncts, such as intraoperative navigation, are considered. Lastly, we briefly survey future directions for pediatric spinal instrumentation.

Methods

Our experience with the first 384 spinal fusions with instrumentation in children (age ≤ 21 years) was reviewed from July 1, 2007, to May 31, 2018. Up until July 31, 2016, surgeries were performed at Texas Children's Hospital in Houston, Texas (299 cases); thereafter, procedures were performed at Riley Hospital for Children in Indianapolis, Indiana (85 cases).

Patient Demographics

There were 361 patients who underwent 384 operative procedures involving spinal instrumentation. Boys accounted for 48.2% of the population. The mean age at the time of surgery was 12 years and 6 months (range 3 months to 21 years and 4 months). The indications for spinal fusion can be divided into degenerative, congenital, trauma, and tumor (Table 1).

Operative Data

Among surgeries performed, spinal instrumentation was placed at the craniocervical junction (occiput–C2; 142 cases), subaxial cervical spine (C3–7; 99 cases), thoracic spine (T1–9; 129 cases), thoracolumbar junction (T10–L2; 142 cases), lumbar spine (L3–5; 165 cases), sacrum (105 cases), and pelvis (57 cases) (Table 1). Of the 384 cases, 360 were performed from a posterior-only approach, 14 cases were performed from combined anterior and posterior approaches, and 10 cases were performed from an anterior-only approach. It is important to note that anterior-only approaches were limited to cervical spine cases.

The types of spinal fixation devices and techniques used included occipital screws (94 cases); C1 lateral mass screws (115 cases); C2 pars/translaminar screws (143 cases); subaxial cervical lateral mass screws (95 cases); thoracic and lumbar spine traditional-trajectory and cortical-trajectory pedicle screws (234 cases); thoracic and lumbar sublaminar, subtransverse, and subcostal polyester bands (65 cases); S1 pedicle screws (103 cases); and S2 alar-iliac/iliac screws (56 cases) (Table 1). Based on our experience with spinal instrumentation in children, we describe our personal biases in selecting and placing anchor points in the spine of young children. Stepwise instruction and surgical indications for placement of spinal instrumentation in a child are included in our prior publications.³⁴

TABLE 1. Patient demographics and operative data

	Value
Patient demographics	
Patients, n	361
Spinal fusions, n	384
Mean age (range), yrs	12.5 (0.3–21.3)
Male, n (%)	185 (48)
Indications for spinal fusion	
Degenerative, n (%)	59 (15)
Congenital, n (%)	215 (56)
Trauma, n (%)	76 (20)
Tumor, n (%)	34 (9)
Location of spinal fusion	
Craniocervical junction (Oc–C2), n	142
Subaxial cervical spine (C3–7), n	99
Thoracic spine (T1–9), n	129
Thoracolumbar junction (T10–L2), n	142
Lumbar spine (L3–5), n	165
Sacrum, n	105
Pelvis, n	57
Approach to the spine	
Posterior, n (%)	360 (93)
Anterior, n (%)	10 (3)
Combined, n (%)	14 (4)
Spinal fixation devices & techniques	
Occipital screws, n	94
C1 lateral mass screws, n	115
C2 pars/translaminar screws, n	143
Subaxial cervical lateral mass screws, n	95
Thoracic/lumbar pedicle screws, n	234
Sublaminar polyester bands, n	65
S1 pedicle screws, n	103
S2 alar-iliac/iliac screws, n	56

Oc = occiput.

Description of Techniques

Posterior Spinal Instrumentation

Craniocervical Junction (occiput–C2)

Occipital Fixation. The zone of failure for occipito-cervical instrumentation is usually at the point of fixation to the occiput. A child's head is disproportionately large compared with that of adults, especially in the occipital region. Moreover, the necessity to keep the head and neck in a neutral position rather than flexed, or in a military tuck position, produces an acute angle between the slope of the occiput and the line of the cervical spine.^{106,112,123} These geometric constraints require extreme bends in the rods and subsequent notching of the rods that span occipito-cervical fusions. Additionally, the average skull thickness in the occipital region in children is 3.8 mm compared with 6.7 mm in adults.⁴ Because of poor screw purchase, thin bone stock, and rod notching, children may be more

FIG. 1. Occipital fixation. Tapping (A) and placement (B) of occipital screws. The stop-drill technique, which consists of triangulating toward the midline, performed slowly until penetration of the inner table of the skull, is routinely used to prevent dural and sinus laceration. Right- and left-sided screw trajectories are staggered to prevent screw paths from intersecting. Screws are typically placed between the inferior and superior nuchal lines. Screws may be placed in a unicortical fashion near the superior nuchal line to prevent penetration of the transverse sinus. Image created by Katherine Relyea, MS, CMI, and printed with permission from Baylor College of Medicine; first appeared in Chern JJ, et al: Instrumentation and stabilization of the pediatric spine: technical nuances and age-specific considerations, in Quinones-Hinojosa A (ed): *Schmidek & Sweet: Operative Neurosurgical Techniques: Indications, Methods, and Results*, ed 6. Philadelphia: Elsevier Saunders, 2012, Vol 1, pp 759–767. Figure is available in color online only.

prone to instrumentation failure at its attachment to the skull.^{46,47,110}

Bicortical screw placement between the superior and inferior nuchal lines seems to be superior to unicortical placement in biomechanical studies.^{56,160} On the other hand, bicortical screw placement carries higher risk than unicortical screw placement. With bicortical screw placement, there are risks of durotomy, CSF leakage, dural venous sinus injury, and intracranial hemorrhage.^{63,127} CSF leakage and venous bleeding from an injured sinus may be stopped by working quickly to place the screw or plugging the hole in the skull with bone wax. Our occipital fixation technique is illustrated in Fig. 1.

C1 Lateral Mass Screws and C1–2 Transarticular Screws. The biomechanically sound Magerl technique⁶⁹ for C1–2 transarticular screw placement traverses 4 cortical surfaces and the C1–2 joint (Fig. 2). However, it is technically demanding and places the vertebral arteries

at risk. The rates of vertebral artery injury (2%–8%) are likely underreported in the literature.^{39,45,52,93} The use of this technique has been infrequently described in the pediatric spine.^{52,94,109,145}

Because of the prohibitive technical and anatomical requirements for the Magerl technique, C1–2 transarticular screws have given way to C1–2 screw-plate or screw-rod constructs as described by Goel and Laheri,^{53,55} and Harms and Melcher,⁵⁷ respectively. The Goel/Harms technique for C1–2 posterior instrumented fusion may be more applicable even in the smallest of children or those with anatomical variants (Fig. 3).

C1 lateral mass screw placement may itself carry the risks of vertebral artery injury, but our experience and that of others^{53,57,68,139} show that it can be performed safely and be an efficacious part of an atlantoaxial or occipitocervical construct in children.

C2 Pars/Pedicle and Translaminar Screws. C2 pars/

FIG. 2. C1–2 transarticular screw technique. Note the screw proximity to the vertebral arteries, making this a very challenging stabilization technique in children. Image created by Katherine Relyea, MS, CMI, and printed with permission from Baylor College of Medicine; first appeared in Chern JJ, et al: Instrumentation and stabilization of the pediatric spine: technical nuances and age-specific considerations, in Quinones-Hinojosa A (ed): *Schmidek & Sweet: Operative Neurosurgical Techniques: Indications, Methods, and Results*, ed 6. Philadelphia: Elsevier Saunders, 2012, Vol 1, pp 759–767. Figure is available in color online only.

pedicle screw placement carries a smaller risk of vertebral artery injury than C1–2 transarticular screw placement.⁶⁵ However, the risk to the vertebral arteries and spinal cord is still definable (Fig. 4).¹¹⁹

Wright^{160,161} described the translaminar screw technique (Fig. 5). Translaminar screw technique allows for safe, rigid fixation of C2 by circumventing the risk of vertebral artery injury. The literature demonstrates that this technique of crossing and noncrossing laminar screws is a safe and effective method of C2 fixation in children.^{32,87,136} Although a recent meta-analysis of cadaver studies brought concern with the lateral bending stability in C1 lateral mass–C2 translaminar screws, the difference was not statistically significant.⁴² Based on reports in the literature of the small series of children and slightly larger patient series of adults in which C2 translaminar screws are used, the follow-up and fusion rate are quite satisfactory.¹³⁸

Subaxial Cervical Spine (C3–7)

Lateral Mass Screws. Lateral mass screw fixation of the cervical spine has been shown to be effective in adult patients.^{36,124,134} There are 2 popular techniques for placing lateral mass screws. These are the Roy-Camille and Magerl techniques, both of which have been extrapolated

to pediatric patients. The youngest patient reported who underwent successful lateral mass screw placement was 8.2 years old.⁹ This corresponds with the age in which the pediatric spine is expected to transform into its adult configuration.¹²

Placing lateral mass screws in even younger children is feasible. However, surgery can be challenging because of proximity to the vertebral arteries, small bone volume in the lateral mass to safely accommodate a screw of sufficient width and length (3.5 × 14 mm),¹³⁴ and violation of the facet joint, which predisposes to untoward adjacent-level changes.^{9,12,25} Often, the spine surgeon is allowed only one opportunity to accurately place a screw, as the small size of the lateral mass does not allow for multiple attempts. Furthermore, a shorter screw may need to be placed (3.5 × 10 mm), compromising the strength of the construct. Our technique for placing subaxial lateral mass screws is illustrated in Fig. 6.

Sublaminar Wires. Sublaminar wires are considered “old school” but solid alternatives when lateral mass screws are not feasible.^{35,50,103,144,148} They are still frequently used in combination with contoured rods and/or lateral mass screws. It has been demonstrated that the wires confer immediate stability and help achieve solid fusion. In

FIG. 3. C1 lateral mass screw technique. The entry point of the C1 lateral mass screw is deep at the confluence of the C1 lamina and C1 lateral mass to avoid the vertebral artery in the more superficial sulcus arteriosus. The medial surface of the C1 lateral mass should be palpated as an important landmark. The entry point should be 2–3 mm from the medial aspect of the C1 lateral mass. The lateral aspect of the lateral mass should be avoided, as this is where the vertebral artery resides. Bicortical screw purchase is desired to increase pullout strength. To help with exposure of the bony landmarks for C1 lateral mass screw placement, we recommend sectioning the C2 nerve root. Judicious (and continuous) bipolar coagulation of the venous plexus surrounding the C2 nerve root should be performed. Stepwise division of the C2 nerve root proximal to the dorsal root ganglion. There is no reason to rush this portion of the procedure if acceptable blood loss is a goal of surgery. Image created by Katherine Relyea, MS, CMI, and printed with permission from Baylor College of Medicine; first appeared in Chern JJ, et al: *Instrumentation and stabilization of the pediatric spine: technical nuances and age-specific considerations*, in Quinones-Hinojosa A (ed): *Schmidek & Sweet: Operative Neurosurgical Techniques: Indications, Methods, and Results*, ed 6. Philadelphia: Elsevier Saunders, 2012, Vol 1, pp 759–767. Figure is available in color online only.

a biomechanical study¹³ and systematic review¹⁵⁵ comparing rigid constructs (screw-rod) and nonrigid constructs (screw-wire/wires only), screw-rod constructs outperform screw-wire/wire-only constructs in terms of instrumentation failure and fusion rates. Furthermore, our series of pediatric spine cases indicate that instrumentation of the cervical spine may carry a safer and more efficacious profile than a wire construct.⁶⁶ The sublaminar wire method, nevertheless, remains a salvage method to obtain internal support for fusion.^{76,97,116}

Pedicle Screws. Unlike in the thoracic and lumbar spine, subaxial cervical pedicle screws are not widely utilized because of the high risk to adjacent neurovascular structures involved in cannulating the cervical pedicles.²¹ Abumi et al.,^{1,2} alone advocate for cervical pedicle screws,

reported excellent clinical outcomes for use in the middle to lower cervical spine.

Translaminar Screws. Subaxial cervical translaminar screw placement is an option as a fixation point (Fig. 5). Theoretically, translaminar screws can be placed under direct vision, avoid important neurovascular structures, and attain a screw length much longer than a lateral mass screw. In reality, however, the laminar thickness of the subaxial cervical spine in a child can rarely accommodate a translaminar screw.³³

Thoracic and Lumbar Spine

Wires, Hooks, and Pedicle Screws. Posterior thoracolumbar instrumentation has been traditionally divided into

FIG. 4. C2 pars/pedicle screw technique. Note the proximity of the spinal canal and vertebral artery in comparison with the translaminar screw in Fig. 5. Image created by Katherine Relyea, MS, CMI, and printed with permission from Baylor College of Medicine; first appeared in Chern JJ, et al: Instrumentation and stabilization of the pediatric spine: technical nuances and age-specific considerations, in Quinones-Hinojosa A (ed): *Schmidek & Sweet: Operative Neurosurgical Techniques: Indications, Methods, and Results*, ed 6. Philadelphia: Elsevier Saunders, 2012, Vol 1, pp 759–767. Figure is available in color online only.

rigid and nonrigid constructs. The earliest arthrodesis constructs incorporated the spinous processes or other dorsal bony structures with structural autograft.²⁸ Although simple wiring techniques are no longer used today, Luque wiring, which employs sublaminar wires as anchor points, is still used occasionally. The Luque instrumentation system was a step toward more rigid segmental spinal instrumentation, avoiding mandatory postoperative external orthoses.⁹³ Wiring techniques are considered nonrigid because they allow “pistoning” of the spine in a craniocaudal direction.

The first hook-based system was the Harrington rod, which was introduced in the 1960s.¹³⁷ These constructs were much more rigid than previous wiring techniques, leading to improved fusion rates that avoided the need for postoperative bracing.⁹³ The disadvantage of these constructs, as with pedicle screw fixation, is the effect of fusion on adjacent segments. In contrast to the 3D fixation of pedicle screw constructs, hooks anchor to the posterior elements alone and do not have the same ability to correct severe scoliosis curves.⁸⁵

Spinal instrumentation in the thoracic and lumbar spine has primarily been applied to the surgical reduction and fixation of spinal deformities. After the introduction of pedicle screws²² and advent of Harrington instrumentation,⁵⁹ spinal internal pedicle screw fixation gained popularity in the operative treatment of traumatic and non-traumatic spine disorders.^{20,78,125,126} Pedicle screw fixation offer 3-column control of the spinal column with powerful correction in the axial, sagittal, and coronal planes (Fig. 7). When compared with nonrigid methods, such as hook-

FIG. 5. Translaminar screw technique. C2 translaminar screw fixation is a safe technique for rigid fixation and avoids the vertebral arteries. A potential drawback to this technique is breach of the nonvisualized ventral lamina wall leading to dural laceration, CSF leak, or spinal cord injury. Wright's method for placing laminar screws can be modified with a small exit window in the dorsal cortex of the lamina at the laminofacet line. This exit window allows the surgeon to visualize the tip of the screw to ensure that it has not penetrated the ventral lamina cortex. Careful study of the preoperative CT scan can indicate screw length and width. Image created by Katherine Relyea, MS, CMI, and printed with permission from Baylor College of Medicine; first appeared in Chern JJ, et al: Instrumentation and stabilization of the pediatric spine: technical nuances and age-specific considerations, in Quinones-Hinojosa A (ed): *Schmidek & Sweet: Operative Neurosurgical Techniques: Indications, Methods, and Results*, ed 6. Philadelphia: Elsevier Saunders, 2012, Vol 1, pp 759–767. Figure is available in color online only.

and-wire constructs, pedicle screw constructs have higher fusion rates, lower implant failures, and obviate the need for postoperative bracing.^{14,90,91,143}

Polyester Bands. Polyester bands with a locking mechanism to the rod are a relatively new innovation. They serve as an alternative to traditional anchors, such as wire, hooks, and screws. Polyester is a biologically inert material with favorable mechanical properties, such as high tensile strength, high resistance to stretch, wet or dry, and resistance to degradation.¹³³ It represents an excellent candidate material for use in the spine. As an example, polyester has been incorporated in spinal constructs in Europe for more than 20 years (K. Mazda, personal communication, October 17, 2007).

The gentleness and flexibility of polyester seem to make it ideal for implantation in the pediatric spine. It is particularly useful when anatomy precludes safe placement of hooks or screws despite the availability of image guidance. Like other anchors to the spine, these polyester bands

FIG. 6. C3–7 lateral mass screw technique. The entire lateral mass of the subaxial cervical spine should be exposed at each level. On the dorsal square face of the lateral mass, an entry point 1 mm medial and 1 mm caudal from the midpoint (dot) should be selected. The drill and screw trajectory should be directed “up and out” toward the deep superior and ventral corner of the lateral mass box (about 20° lateral and 20° rostral) to avoid vertebral artery and nerve root injury, respectively. Image created by Katherine Relyea, MS, CMI, and printed with permission from Baylor College of Medicine; first appeared in Chern JJ, et al: Instrumentation and stabilization of the pediatric spine: technical nuances and age-specific considerations, in Quinones-Hinojosa A (ed): *Schmidek & Sweet: Operative Neurosurgical Techniques: Indications, Methods, and Results*, ed 6. Philadelphia: Elsevier Saunders, 2012, Vol 1, pp 759–767. Figure is available in color online only.

along with their rod-locking mechanism may be used to attain segmental control, reduction, and fusion (Fig. 8). Like other forms of sublaminar spinal instrumentation, such as sublaminar wire or laminar hooks, sublaminar polyester bands have a higher risk of spinal cord injury than pedicle screws.^{15,29,51,62,72,92,141} The intracanalicular space is violated with each pass of the sublaminar polyester band, whereas the intention of pedicle screws is to stay intraosseous and outside the spinal canal. The learning curve for placing sublaminar polyester bands is comparatively shorter than for placing pedicle screws; nonetheless, meticulous technique is necessary to reduce the risk of spinal cord injury, especially in the thoracic and thoracolumbar spine.

Complications may also occur with over-tensioning of the polyester bands, causing them to fracture through osteoporotic or partially cartilaginous bone, which was encountered in our early experience with these bands. Aggressive decortication of the lamina and subsequent decrease in laminar strength may also predispose it to fracture.¹¹ Promising results have been demonstrated with hybrid spinal constructs incorporating sublaminar polyester bands; however, long-term evaluations are still needed.^{38,142}

Complications and Complication-Avoidance Strategies

There were no deaths attributable to spinal instrumentation placement in our series of children. However, other

complications included hardware-related skin breakdown (1.8%), infection (1.8%), proximal junctional kyphosis (1.0%), pseudarthrosis (1.0%), screw malpositioning (0.5%), cerebrospinal fluid leak (0.5%), hardware failure (0.5%), graft migration (0.3%), nerve root injury (0.3%), and vertebral artery injury (0.3%). Our avoidance strategies for each of these complications are detailed in Table 2.

Discussion

History of Spinal Instrumentation in Children

The history of spinal instrumentation in children begins with the treatment of scoliosis by luminaries in spine surgery, including Dr. Russell A. Hibbs, Dr. Fred H. Albee, and Dr. H. P. H. Galloway.³⁷

The greatest breakthrough for the operative treatment of scoliosis came with the advent of the Harrington rod. Dr. Harrington started practice in Houston, Texas, in 1945 at Jefferson Hospital. During this time, he took a special interest in children with poliomyelitis and the high incidence of neuromuscular scoliosis in this patient population.^{37,58} Dr. Harrington quickly realized at the time that the therapies used to treat idiopathic scoliosis—physical therapy, bracing, casting, and early surgical techniques—were not appropriate for poliomyelitis patients. The Harrington rod was born out of his curiosity and compassion

FIG. 7. Thoracic and lumbar pedicle screw technique. Pedicle screw placement may start at the confluence of the pars interarticularis and transverse process. Rostral-caudal and mediolateral angulation of the pedicles should be studied prior to surgery at each vertebral level to help guide screw trajectory. There may be a role for intraoperative image guidance in the placement of pedicle screws. Image created by Katherine Relyea, MS, CMI, and printed with permission from Baylor College of Medicine; first appeared in Chern JJ, et al: Instrumentation and stabilization of the pediatric spine: technical nuances and age-specific considerations, in Quinones-Hinojosa A (ed): *Schmidek & Sweet: Operative Neurosurgical Techniques: Indications, Methods, and Results*, ed 6. Philadelphia: Elsevier Saunders, 2012, Vol 1, pp 759–767. Figure is available in color online only.

for patients; it was the first iteration of an implantable spinal instrumentation system.³⁷

After the Harrington rod system, many other notable systems, such as the Luque instrumentation system in 1977⁹³ and the Cotrel-Dubousset system in 1978, were created utilizing the contemporary spine surgery knowledge and techniques for deformity correction. This trend in development of spinal instrumentation represented a slow march toward 3D control and 3-column fixation of the spinal column, the standard for spinal instrumentation systems today.^{10,120,121,151}

Anterior Spinal Instrumentation

Anterior approaches to the spinal column for the placement of instrumentation are infrequent compared with posterior approaches. Anterior spinal instrumentation is most commonly confined to the cervical spine. Case series on anterior spine instrumentation have recently been reported.⁴⁸

Advantages of Anterior Instrumentation

There are several important advantages to anterior ap-

proaches over posterior approaches. The patient does not need to be turned prone for positioning on the operating room table, which is important when the spinal column is unstable. Anterior spinal instrumentation may allow for less extensive fusion (i.e., motion segments spared), may require less soft-tissue dissection to expose the spine, may be associated with decreased blood loss, and may have higher fusion rates and lower infection rates.^{16,44,95,147,149,154} In the growing spine, addition of anterior instrumentation to a previous posterior fusion construct (circumferential fusion) may help prevent the occurrence of “crankshaft” deformity.^{41,82,140}

Disadvantages of Anterior Instrumentation

The most significant disadvantage of anterior spinal instrumentation is that it is rarely a stand-alone construct. A second procedure may be required to place supplemental posterior spinal instrumentation. Contemporary posterior or posterolateral approaches to the spine (e.g., costotransversectomy and lateral extracavitary) may allow simultaneous exposure of the anterior, middle, and posterior columns of the spine.¹¹⁸ In these approaches, anterior and posterior spinal instrumentation may be inserted through a single approach.

Biomaterials

Autograft, including iliac crest, tibia/fibula, and rib, remains the gold standard in pediatric spine surgery. However, the materials may also be primarily cartilaginous in young children, thereby limiting its use as structural autograft. Titanium and polyetheretherketone (PEEK) cages⁷⁹ have been used as vehicles to hold graft material while providing immediate load-bearing properties.^{6,30,31,86} Due to the favorable modulus of elasticity of PEEK in comparison with bone, it is preferred over titanium cages.¹⁵⁹ Titanium cage use is reserved for older children and adolescents with higher density bone;⁶ otherwise, titanium cages are prone to settle and telescope.

The off-label use of bone morphogenetic protein (BMP) has increased in both the adult and pediatric patient populations since its approval by the FDA in 2002.⁶⁷ Allograft, in combination with BMP, may provide high fusion rates that rival that of the autograft gold standard. In younger children where the quantity of autograft is limited, BMP offers a promising alternative. Other purported advantages of BMP include decreased operative time, lower blood loss, and elimination of donor site morbidity. The safety and efficacy of BMP has been documented in adult and pediatric case reports and case series.^{64,130–132} Reported complications of BMP include seroma formation, soft-tissue swelling, delayed wound healing, and heterotopic bone formation. The long-term effects of BMP, such as oncogenesis, are unknown. Therefore, full informed consent from patients and their parents for the cautious use of BMP should be obtained.

Intraoperative Spinal Navigation

The use of intraoperative spinal navigation for screw insertion has been shown to improve accuracy and decrease unexpected returns to the operating room for screw revi-

FIG. 8. Sublaminar wire/band technique. The ligamentum flavum is resected in the interlaminar spaces above and below the lamina of interest. We are careful not to resect too much of the lamina itself. A gentle curve for the malleable semirigid tip of the wire or polyester band is created. The tip is passed gently underneath the lamina from caudal to rostral. A hemostat or nerve hook is used to snare the tip of the wire or polyester band. Through use of a push-pull technique to avoid a loop of wire or band compressing the thecal sac and spinal cord, the wire or band is progressively passed underneath the lamina until the semirigid tip has fully traversed the lamina. Once all sublaminar wires or bands have been passed, each wire or band is secured to the rod. Sequential tensioning may then be applied to produce a translation of the spine toward the rod. Image created by Katherine Relyea, MS, CMI, and printed with permission from Baylor College of Medicine; first appeared in Chern JJ, et al: *Instrumentation and stabilization of the pediatric spine: technical nuances and age-specific considerations*, in Quinones-Hinojosa A (ed): *Schmidek & Sweet: Operative Neurosurgical Techniques: Indications, Methods, and Results*, ed 6. Philadelphia: Elsevier Saunders, 2012, Vol 1, pp 759–767. Figure is available in color online only.

sion.^{7,73,96,102,104,115,150} The use of computerized image guidance in the pediatric spine seems even more opportune as there is a smaller margin for error in placing spinal instrumentation. Most of the pediatric spine literature^{82,83,117} has confirmed that intraoperative spinal navigation results in a low rate of misplaced screws and related reoperations.

A potential criticism of intraoperative spinal navigation is the radiation exposure during intraoperative CT scanning, especially in the pediatric population.^{75,122} There are numerous studies that correlate early exposure to radiation in pediatric populations to long-term increased cancer risk.^{3,24,74} More long-term studies are necessary to assess long-term cancer risk in pediatric patients undergoing spinal instrumentation.

Long-Term Consequences of Fusion in a Growing Spine

A major difference between the pediatric spine and adult spine is the potential for continued growth from childhood

to adolescence.⁷¹ This growth must be factored into any decision of performing a long-segment fusion in a child. Adverse iatrogenic effects from spinal fusion include limitation of range of motion, stunting future growth, development of secondary deformity (e.g., crankshaft deformity), and adjacent-level disease.^{60,156–158}

Because there are no epiphyseal growth plates between the occiput and C2, it is not unexpected that several studies have shown minimal effect of vertical growth restriction across an occipitocervical fusion.^{5,8,12,52,74,98,113,146,152} A dedicated study analyzing spinal alignment and growth in children after subaxial cervical fusion demonstrated that there are continued dynamic changes across the fused segments.⁵⁴ The authors showed 79%, 83%, and 100% of expected growth across 4-level, 3-level, and 2-level fusions, respectively. Overall, 62% of patients with 24 months of follow-up showed growth across the fusion construct. Crankshaft deformity occurs when posterior fusion is

TABLE 2. Complications and avoidance strategies

Complications	Avoidance Strategies
Hardware-related skin breakdown	<ul style="list-style-type: none"> • Counter-sinking lower-profile spinal instrumentation to ensure no local prominence • Periop consultation & collaboration w/ plastic surgery to discuss need for soft-tissue flaps &/or expanders • Consultation to optimize nutritional status prior to surgery
Infection	<ul style="list-style-type: none"> • Preop nutrition consultation to control preop hyperglycemia & weight loss prior to surgery; remembering that an obese patient can still be malnourished • Following a standardized complex spine infection prevention protocol, including preop skin antisepsis w/ chlorhexidine surgical scrubs; use of adapted antimicrobial prophylaxis protocols w/ preincision cefazolin; intraop pulse irrigation w/ antibiotic solution & intraop topical vancomycin powder
Proximal junctional kyphosis/pseudarthrosis	<ul style="list-style-type: none"> • Decreasing rigidity at the top of long-segment constructs by placement of hooks rather than pedicle screws to provide a transition to the noninstrumented spine • Bending kyphosis into the rods at the rostral end of the spinal construct • Using rods that are less stiff, such as titanium alloy or cobalt-chrome, rather than stainless steel
Screw malpositioning	<ul style="list-style-type: none"> • Use of intraop computerized image-guided screw insertion techniques • Intraop CT to check postinsertion screw placement • Careful attention to trajectory & anatomical landmarks during screw placement, even when using adjuncts like image guidance
CSF leak	<ul style="list-style-type: none"> • Awareness of anatomical anomalies or bony defects on preop imaging • Meticulous attention to development of surgical planes between the dura & overlying bone or soft tissue during decompression procedures • Use of eggshell technique during use of the high-speed air-powered drill • Employing the surgical assistant to protect the dura while working close to it
Hardware failure	<ul style="list-style-type: none"> • Careful attention to spinal alignment during deformity correction—avoidance of over- or under-correction • Achieving a well-balanced spine will place less stress on the rods • Considering “outriggers” or a 4-rod construct that spans 3-column osteotomy sites or irreducible unbalanced spinal deformities
Nerve root/vertebral artery injury	<ul style="list-style-type: none"> • Careful study of preoperative imaging, such as CTA &/or MRI, particularly in cases of congenital anomalies of the spine at the craniocervical junction

achieved yet unrestricted growth continues in the anterior column of a young child.^{43,61,84} The posterior fusion mass then acts as a tether and center of rotation causing progressive angulation and lordosis. As mentioned previously, completion of a circumferential fusion (i.e., addition of an anterior fusion) may arrest crankshaft deformity.^{41,81} However, this possible solution for crankshaft deformity is controversial, debated, and being studied.^{26,129}

Long-segment thoracic fusion should be avoided in children younger than 8 years, as alveolar and lung development occurs until the age of 8 years.⁴⁰ Fusion of the spine while lung maturity is occurring can result in restrictive lung disease and subsequent pulmonary hypertension. Pulmonary hypertension can lead to right heart failure and iatrogenic death—a complication from inappropriate fusion across the thoracic spine and rib cage.

Adjacent-level disease is defined as premature degeneration of supra- or subjacent levels to fusion. The fused segment is spared biomechanical force, but this excess force is distributed to the next mobile segments above and below. The rate of development of adjacent-level disease during the first 10 years after anterior cervical discectomy and fusion is estimated to be 2.9% per year in adult studies. In the adult lumbar spine, the rate of adjacent-level disease is estimated to be 3.6% per year.⁴⁹ To our knowledge, the rate of adjacent-segment degeneration in children has not been assessed. Logically, children should carry a much greater risk of adjacent-segment degeneration given a much longer life expectancy. Further studies are needed to elucidate this risk.

Fusionless Spine Surgery

The future of spine surgery in children may lie in the continued refinement of fusionless techniques to allow growth and preserve motion. Growing rod constructs, such as traditional growing rods, the Shilla technique, vertical expandable prosthetic titanium rib (VEPTR, DePuy Synthes), and magnetic expansion control (MAGEC, NuVasive) rods, have been used to address early-onset scoliosis.^{27,70,99} However, these techniques are plagued with complications and unexpected outcomes, including wound breakdown, infection, premature auto-fusion, and device failure.^{17,80,89,153}

Vertebral body growth modulation is a new and exciting area in the field of fusionless deformity surgery. Progression of skeletal deformity during growth is thought to be governed by the Hueter-Volkman law.¹⁰⁰ This law states that growth depends on the amount of compression on the growth plate. Increased compression retards growth, while decreased compression accelerates growth. If this principle is applied to the growing child with scoliosis, then the concave portion of the scoliotic spine will have increased loading on the vertebral body growth plate—retarding growth—and the convex portion of the curve will have decreased loading—increasing growth—leading to an overall vicious cycle of curve progression. Various skeletal fixation devices have been successfully used in animal models to correct induced scoliosis curves.^{23,101,105,107,108}

Based on the above principles, vertebral body stapling and vertebral body tethering were developed. The results

with each technique appear to be promising. Vertebral body stapling involves placing unilateral disc-sparing staples on the convex side of a scoliotic curve to increase compression on the growth plate and reduce overall growth.^{18,19,128}

There is mounting evidence that intricate underlying genetic abnormalities contribute to the 3D structural deformities found in scoliosis. Prior studies have identified candidate genes associated with adolescent idiopathic scoliosis, such as *GPR126*,⁷⁷ *BNC2*,¹¹¹ *PAX1*,¹³⁵ *LBX1asl*,¹⁶³ *POC5*,¹¹⁴ and *AKAP2*.⁸⁸ More recently, *MapK7* was shown to be associated with severe spinal deformity and a defective osteogenesis phenotype in idiopathic scoliosis.¹⁶² Understanding the molecular underpinnings that generate spinal deformities may allow for early targeted therapy based on a child's underlying genetic profile. The development and refinement of new fusionless surgical techniques may allow for early treatment of pediatric patients with high risk of deformity progression without the long-term consequences of current fusion constructs.

Conclusions

Pediatric neurosurgeons with an interest in complex spine disorders in children should develop a comprehensive armamentarium of safe techniques for placing rigid and nonrigid spinal instrumentation even in the smallest of children, with low complication rates. The present review provides some benchmarks and outcomes for comparison, and furnishes a historical perspective of the past and future of pediatric spine surgery.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Conception and design: Jea, Mendenhall, Mobasser. Acquisition of data: Jea, Mendenhall, Mobasser. Analysis and interpretation of data: Jea, Mendenhall, Mobasser. Drafting the article: Jea, Mendenhall, Mobasser. Critically revising the article: Jea, Mendenhall. Reviewed submitted version of manuscript: Jea, Mendenhall, Mobasser. Approved the final version of the manuscript on behalf of all authors: Jea. Administrative/technical/material support: all authors. Study supervision: Jea, Mendenhall, Mobasser. Illustration: Relyea.

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