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An Overview on Spinal Deformities

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Abstract:

Background: Spinal deformities represent a significant health concern in pediatric and adolescent populations, with conditions such as scoliosis and kyphosis being among the most prevalent musculoskeletal disorders. Adolescent idiopathic scoliosis (AIS) alone affects up to 2–5% of the general population and is associated with functional, cosmetic, and long-term cardiopulmonary complications. The multifactorial etiology, variable progression, and impact on quality of life necessitate a comprehensive understanding of diagnosis, monitoring, and management strategies.

Keywords: Spinal deformities, scoliosis, kyphosis, adolescent idiopathic scoliosis, Cobb angle, pediatric spine, intraoperative neuromonitoring

Introduction:

Back pain is a common problem in otherwise healthy pediatric and adolescent patients. It is estimated to affect up to one-third of this population. Back pain is more prevalent in patient populations affected by spinal deformity such as adolescent idiopathic scoliosis. Given that adolescent idiopathic scoliosis is found in up to 5% of the general population, this represents a significant potential financial burden. Since back pain, deformity, and bone health are linked, it is important to address the role of bone health in spine health (**1**).

Diseases of the musculoskeletal apparatus are some of the most common diseases in childhood. They are considered to be the oldest known human diseases. The first written references to their occurrence and treatment come from an old Indian religious mythological book from 3500-1800 BC. Deformities of the musculoskeletal apparatus, but especially spine and posture, are a serious problem of children. Particularly scoliosis represents the most frequent diagnosis for children visiting the rehabilitation department. According to American Department of Education, The National Scoliosis Research Society estimates that six million Americans have scoliosis, a lateral or side-to-side curvature of the spine (**2**).

In the United Kingdom the prevalence of adolescent idiopathic scoliosis is estimated to be 2% to 3% of children between 10 and 16 years of age, using a definition of over 10° spine curvature. Larger curves present at a lower frequency and it is estimated that 40-degree curves make up 0.1% of the total AIS population, whereas the frequency of curves between 20 and 30 degrees is approximately 0.3 to 0.5%. A recent Japanese cross-sectional study assessed the prevalence of curvature over 10° in an 11- to 12-year-old age group and a 13- to 14-year-old age group. Idiopathic scoliosis is the most common paediatric musculoskeletal disorder that causes a three-dimensional deformity of the spine. Early detection of this progressive aliment is essential (**3**).

The occurrence of spinal deformities in children has alarming proportions. It is partly caused by the current lifestyle of children, families, and entire communities, which is characterized by hypokinesia and long-term overloading of the locomotory system in a postural disadvantageous position as sitting. The lack of movement and long-term sitting contribute to the increased occurrence of spinal deformities and poor posture in children (**4**).

kyphosis and hyperkyphosis are described as the most common deformity of the spine in childhood and that thoracic kyphosis is dominant at the age of 6-7, The thoracic curvature was not the most critical segment that underwent deformity (**5**).

Types of spinal deformities

✓ Non Dystrophic Spinal Deformity

Non-dystrophic coronal curves (scoliosis) are also called “idiopathic like”; they typically present without morphological changes in the single vertebral elements (absent signs of osseous dysplasia) and behave similarly to idiopathic scoliosis. The prognosis is favorable, and the mainstays of treatment are observation for curves <20° and brace treatment for curves 20–40°, usually with a Cheneaux-type brace. Particular attention should be paid to these patients, and regular clinical and radiologic curve monitoring in 6–12 month intervals is mandatory since dystrophic features may occur over time and may be followed by transformation into dystrophic deformities—a process called “modulation” (**6**).

✓ Dystrophic Spinal Deformity

Dystrophic osseous changes are best seen on upright plain whole-spine radiographs, and meticulous evaluation for dystrophic features should be performed since management and prognosis of spinal deformity are highly dependent on the presence of dystrophic signs (**7**). Characteristic dystrophic features are listed in **Table 1** and extensively described in **Figure 1**.

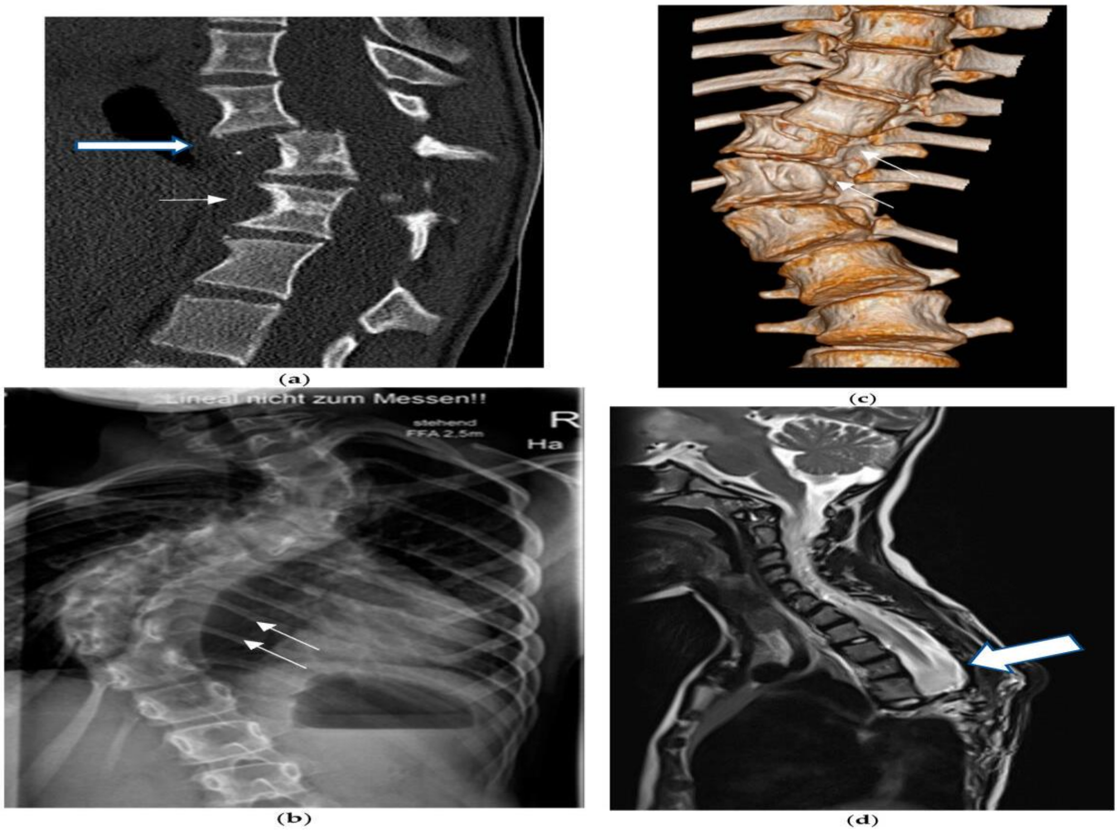

Figure 1: Dystrophic osseous features: (**a**) scalloping (thin arrow), rotation and dislocation with pathologic kyphosis (thick arrow), (**b**) rib penciling (white arrows), (**c**) wedging and rotatory dislocation (arrows) in a 3-D CT reconstruction, (**d**) widening of the spinal canal and dural ectasia (thick white arrow) (**8**).

Table 1: Radiographic features of dystrophic changes (**8**).

Feature	Location	Definition
Scalloping	Vertebral body	scalloping of the posterior, anterior or lateral wall *
Rotation	Vertebra	rotational deformity as compared to adjacent vertebra
Penciling	Rib	narrowing of the medial portion of the rib **

Wedging	Vertebral body	wedge shaped vertebral body ***
Spindling	Transverse process	transverse process thinned like a spindle
Widening	Spinal canal	enlarged interpedicular distance ****
Enlargement	Neuroforamen	enlarged neuroforamen *****
Soft tissue mass	Paravertebral	seen mostly on MRI

Dystrophic curves are typically short, extending over 3–5 spinal segments with poorly visible vertebral structures and a significant spinal rotation which occasionally leads to rotatory subluxation or complete dislocation, frequently accompanied by pathologic kyphosis (**Fig. 1a**). It has been hypothesized that dystrophic changes are either intrinsic (due to primary bone deformation) or appear secondary to increased pressure from dural ectasia or nerve root enlargement, leading to scalloping or neuroforaminal enlargement. The presence of dystrophic changes is of very important prognostic value. As a general rule, the more pronounced the dystrophic changes, the more unfavorable the prognosis. The presence of three or more dystrophic features has been related to worsening of the spinal deformity in over 85% of the cases (**10**).

Epidemiology

Idiopathic scoliosis represents around 80% of all paediatric patients with spinal deformity. Depending upon age at onset this can be classified into infantile (< 3 years), juvenile (4 to 9 years), and adolescent (10 to 18 years) which is the most common having a prevalence of approximately 2% to 3% in most populations (**10**).

The prevalence of scoliosis can vary between 1% and 12%.This increases with age with females being affected twice as often as males. Epidemiological studies from Arabic countries have indicated the aetiology of scoliosis to include 59% idiopathic, 17% congenital, 11% neuromuscular, and 13% as unclassified. Limited information exists regarding the incidence of severe scoliosis requiring surgery, and no previous study has reported on sagittal plane spinal deformities (**11**).

Etiology

Spinal deformity may be due to an intrinsic problem or secondary to an extrinsic factor such as a leg length discrepancy or infection. Resolution of the extrinsic cause will generally correct the spinal deformity although long standing secondary causes can result in fixed spinal deformity. The most common cause of scoliosis in the paediatric population is idiopathic (**12**).

The intrinsic causes of spinal deformity are classified by the cause (Scoliosis Research Society):

1. Idiopathic.
2. Congenital.
3. Neuromuscular.
4. Neurofibromatosis.
5. Mesenchymal disorders.
6. Trauma.
7. Infection.
8. Tumours.
9. Miscellaneous.

Scoliosis

Scoliosis is defined as a structural curvature of the spine in the horizontal, frontal and sagittal planes with a Cobb angle of at least 10°. The curvature involves torsion of the vertebral bodies in the transverse plane. As a result of this curvature, structural changes may occur in the axial skeleton as well as in the thorax. Scoliosis occurs in children and adolescents up to the age of 16 years, with a prevalence of approximately 2% (**13**).

Scoliosis can be classified into two main groups: idiopathic type and secondary scoliosis. The idiopathic form comprises approximately 80–90% of all the types of scoliosis and is a diagnosis of exclusion of other forms of scoliosis. Despite advanced research studies, the primary etiology remains unknown. In addition to having an important genetic component, many other molecular, biochemical, neurologic, and environmental factors have been described. Idiopathic scoliosis can occur at different stages of life (**9**): infantile scoliosis (0 to 3 years: ~1–5%), juvenile scoliosis (4 to 10 years: ~10–20%), and the most common form, adolescent scoliosis (>11 years: ~80–90%). Scoliosis that occurs at earlier ages may be associated with marked developmental and growth impairment. The second main group includes secondary scoliosis associated with neuropathic (with central or peripheral motor neuron involvement or both), myopathic, or syndromic etiologies (e.g., Marfan syndrome, Ehlers–Danlos syndrome, neurofibromatosis, or other skeletal dysplasias) (**14**).

Early-onset scoliosis (EOS) summarized a myriad of conditions, which is united by the documentation of scoliosis in young children. There is controversy regarding the upper age limit for diagnosis, but a consensus among some authors is that it should be around 10 years old. EOS includes spinal deformity resulting from neuromuscular conditions, from dysplasias and syndromes, from congenital malformations, and from idiopathic cases. The progression of EOS varies depending on its etiology, but the treatment remains challenging. If left untreated or managed through spinal fusion, which can result in a shorter trunk and spinal height, EOS can have serious health consequences, including increased morbidity and even mortality (**15**). **Table 2** shows possible differential diagnoses of scoliosis.

The diagnosis of AIS usually bases on clinical symptoms and imaging. Typical symptoms include curvature of the spine, asymmetry of the shoulders and lower back, and tilting of the pelvis. A full-spine standing X-ray is a commonly used imaging modality to measure the angle of scoliosis and to determine the morphology of the spine. The degree of scoliosis varies from individual to individual, ranging from mild to severe. A scoliosis is clinically defined as a scoliosis with a scoliosis angle (the Cobb angle) of 10° or more (**16**).

Treatment of AIS includes observation, orthopedic treatment, physical therapy, and surgical correction. The choice of treatment usually depends on the patient's age, the degree and progression of scoliosis, and possible symptoms to ensure the most effective and individualized treatment plan. The main goals of treatment are multifaceted and aim to prevent the further progression of scoliosis and reduce the risk of long-term pulmonary and cardiac sequelae that may result, as well as to correct the deformity of the spine and restore symmetry and balance to the trunk (**17**).

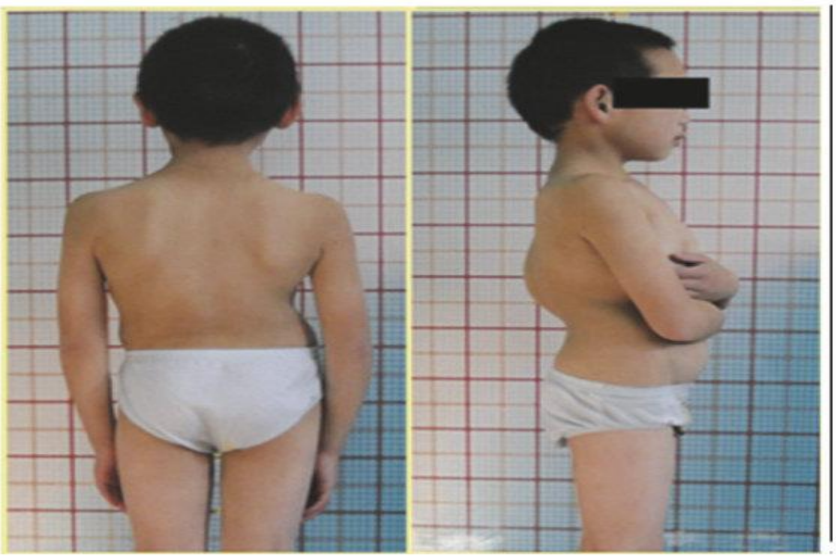

Figure 2: The patient was a 9 years old boy with lumbar congenital scoliosis. (a) Clinical feature preoperative. (b) Computer tomographic with 3-dimensional reconstruction showed multiple complex congenital deformity. (c)

Clinical feature at 2 years follow-up after PVCR. (d) X-ray of anterior-posterior and lateral at 2 years follow-up (**18**).

Table 2: Differential diagnoses of scoliosis (**19**).

Scoliosis	
Functional scoliosis	Compared to structural scoliosis, functional scoliosis is merely a dynamic lateral bending in the frontal plane without a rotational component, which does not show any changes in the shape or structure of the spine or vertebral bodies on radiological imaging. Functional scoliosis is always reversible and indicates a disturbance in postural or movement symmetry (e.g., leg length discrepancy).
Functional scoliosis in infants	Functional scoliosis of infants is a special form of functional scoliosis. It occurs a few months after birth and shows a multisegmental, C-shaped, left-convex lateral bending in the thoracolumbar region of the spine. Spontaneous remission is very common.

❖ Kyphosis

Kyphosis is a deformity that can appear in early childhood, where it can then increase with growth and development. The primary curve of the spine, the so-called the thoracic angle consists of 12 vertebrae (**20**). As children grow, the angle of the thoracic spine increases with age and is significantly more pronounced in girls than in boys (**21**). Hyperkyphosis or an increase in the thoracic curvature larger than the normal range is one of the most common disorders of the spine. Biomechanical data suggest that an increase in kyphosis could be associated with significantly higher spinal loads and torso muscle strength in an upright position, which could accelerate the degenerative process which in turn leads to further dysfunction and pain in the spine in children (**22**).

An increase in kyphosis is also associated with decreased physical function, impaired respiratory function, increased cervical pain, headaches and shoulder problems such as subacromial syndrome. It is an obvious fact that physical activity has a positive impact on the psycho-physical development of children, especially if it is implemented in an early period of childhood, with an adequately trained person (**23**). Critical periods taken in the development of deformities, related to the growth and development of active and passive forces in the body are: the period of the first year of life, the period of standing and standing; period 6.-7. years of age, period of starting school; period of puberty, a period of pronounced neuro-hormonal influence, with adolescent growth momentum. The treatment of kyphosis in school age is based on the same principles and similar procedures as the treatment of scoliosis (**24**). It should be emphasized that kyphotic poor posture is corrected faster with appropriate treatment than scoliosis (**25**).

But it should also be emphasized that kyphotic bad posture more often turns into kyphosis than scoliotic posture turns into scoliosis. The goals of kinesitherapy procedures in kyphotic posture are: relaxation of the shoulder, neck and back muscles, strengthening of the abdominal and long back muscles (extensors) that strengthen the spine. Procedures begin immediately after diagnosis. Kyphosis can develop due to trauma, developmental anomalies, degenerative disc disease, inflammatory and infectious diseases, as well as iatrogenic (**26**).


[redacted]

Figure 3: Demonstrating the rigidity of the kyphosis (**27**).

Traditional inspection techniques

2.1 Clinical examination

The idea that it is the child to be examined and not the scoliosis should be maintained. Record the patient's weight, height, and sitting height. Beginning to observe the child's posture as he or she walks helps to assess the overall posture. Then observe from the front, back, and side in a normal standing position. The pelvis should be level and lower limb discrepancies can be compensated for by lifting. A seated examination may be done in cases where the peripelvic situation is unclear (iliac spine torsion deformity, hip contracture, and sacroiliac joint pathology). A general neurologic examination is recommended; if any neurologic abnormality is suspected, a detailed examination is mandatory. Face the patient, and it is easy to observe asymmetries: head, shoulders, lumbar position, and alignment of the lower limbs. Observe skin pigmentation, facial deformities, and abnormalities of the teeth and palate. Assess chest mobility by observing chest expansion during deep breathing. Examine physiologic spinal curvature from the side (**28**).

Sagittal distances from the plumb line to the back can be recorded at the cervical, thoracic, lumbar, and sacral levels, and alternatively curvature can be assessed using a pedometer. Asymmetries usually become apparent and are systematically recorded when viewed from behind the trunk: shoulders, scapulae, and lumbar region. Trunk balance is assessed by means of a plumb line placed from the tip of the C7 spine or the extraoccipital nodes. It is also important to check for symmetry in forward flexion of the back (Adams' test). The trunk is gradually flexed forward and the observer can stop it at any angle and measure the trunk tilt with a scoliometer. That is, the angle of trunk inclination (ATI), also known as the angle of trunk rotation (ATR), is a parameter of high clinical value, comparable to the value of the radiographic Cobb angle. Although this method is simple and easy to perform, it is more subjective and has a relatively large error compared to imaging (**29**).

Table 3: Diagnostic features of scoliosis and Scheuermann's disease (**13**).

Diagnostic Features	Scoliosis	Scheuermann's Disease
Patient history	• Disorders (genetic, syndromes, neuromuscular diseases, secondary scoliosis) • Previous surgeries • Family history • Symptoms (painless?) • Spinal trauma	• Disorders (genetic, syndromes, neuromuscular diseases) • Previous surgeries • Family history • Symptoms (pain?) • Spinal trauma

	• Radiotherapy	• Radiotherapy
Clinical examination	• Asymmetrical waist triangles • Rib rotational deformities (rib prominence/hump): scoliometer test >5° • Lumbar prominence • Thoracic deformities (asymmetrical pectus excavatum/carinatum) • Leg length inequity • Pelvic obliquity • Shoulder height difference • Axial deviation of the spine from the perpendicular with lateral overhang of the trunk/trunk shift • Flat back due to reduction in thoracic kyphosis and lumbar lordosis	• Obesity • Thoracic hyperkyphosis • Lumbar hyperlordosis • Thoracic deformities • Gibbus • Contracture of ischiocrural muscles.
Radiological findings	• X-ray (posterior-anterior and lateral view), in the standing position (determination of the lateral inclination in the frontal plane:cobb angle)	• X-ray (posterior-anterior and latera view), in the standing position (determination of the deformity in the sagittal plane)

2.2 Digital radiography

Digital radiography (DR) remains the gold standard of imaging methods for scoliosis. Orthostatic and lateral standing radiographs are taken in normal (uncorrected) positions, and the magnitude of curvature is assessed by measuring the angle of scoliosis on the radiograph. As the simplest method, the Cobb method is widely accepted in the medical community. The earliest method was proposed by Ferguson in 1930, who assessed deformity by determining the angle between two straight lines connecting the centers of the terminal vertebrae to the centers of the parietal vertebrae, and by Cobb in 1948, who proposed another similar method for estimating the degree of scoliosis on radiographs (**30**).

The method consists of positioning the most inclined vertebrae above and below the apex of the curve and measuring the angle between intersecting lines drawn vertically between the apical margin of the top vertebra and the bottom margin of the bottom vertebra (**31**). The Cobb angular measurement has become a quantitative criterion for recognizing and observing the symptoms of patients with scoliosis (**19**). In practice, it reflects only the inclination of the two limiting vertebrae and does not give any information about the length of the curve, vertebral rotation, or lateral shift of the apex. Spinal rotation is assessed by measuring the axial rotation of the vertebrae on orthopantomograms which is usually at the apical level. The method of evaluating the position of the pedicle shadow relative to the vertebral body shadow was proposed by Nash and Moe. Historically, lateral curvature of the spine was often analyzed by inclinometers, replicators, and even back cast models. The spine and the entire trunk undergo growth changes similar to torsion in response to muscles and ligaments (**32**).

Cobb angles have utility in evaluating the initial curve, determining the magnitude of curve increase, and deciding when surgical intervention would be the most beneficial to the patient. The accuracy of Cobb angle measurement depends largely on the subjective experience of the radiologist. Previously, measurement was made using a device known as the Cobbometer, but the error was so great that it interfered with the diagnosis and treatment of patients with scoliosis. Therefore, in order to better evaluate full three-dimensional spinal deformities with modern diagnostic imaging techniques, other methods of measuring the Cobb angle have been developed. Both the Cobb and Ferguson methods are based on manual identification of the end vertebrae. However, the Cobb method is preferred due to better reproducibility, easier application, and the ability to measure larger angles to assess more severe spinal curvatures. Today, the Cobb method has been standardized and the key aspect of "repeatability" has been tested and confirmed in many studies. By far the irreplaceable advantage of DR is the ability to calculate the angle of torsion and observe the morphologic changes in the vertebrae using the Cobb method (**33**).

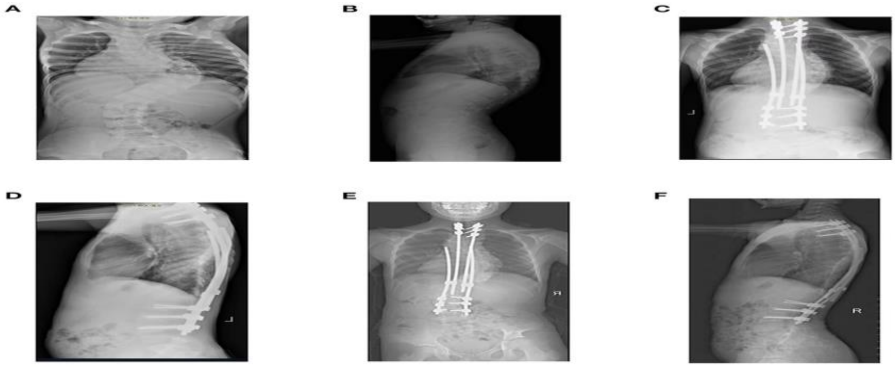

Figure 4: Boy aged 7 years and 8 months diagnosed with kyphotic early-onset scoliosis. (A,B) preoperative anteroposterior and lateral radiographs of the spine indicate coronal lateral bending of 91° and sagittal thoracic kyphosis of 63°. (C,D) X-ray re-examination shows satisfactory correction of kyphosis after growing-rod implantation. (E,F) X-ray re-examination at the 38th month of follow-up (the 4th strutting surgery) showed a satisfactory correction effect and an increase in spinal height (**34**).

2.3 Computed tomography

In idiopathic scoliosis, for reasons that are not yet clear, each vertebra in the curve is rotated from its normal position. This rotation can be characterized by the position of the longitudinal axis of rotation in which it occurs. Vertebral axis rotation has to a large extent been studied in vitro and in nonscoliosis. In these studies, the longitudinal axis of rotation was found to be determined by the orientation of the lesser joints and to be located predominantly within the confines of the vertebrae. However, the location of the longitudinal axis of rotation of the spine as well as the different extra-vertebral and intravertebral patterns of rotation in scoliotic spines, remains unknown, and the treatment and most of the etiologic concepts are based primarily on rotation (**35**).

Computed tomography (CT) scanning is considered the gold standard for the study of scoliosis spine rotation but there are limitations. First, CT scans are not performed upright but in the recumbent position. Previous studies have shown that both the Cobb angle and vertebral rotation are affected by body position (**36**). The longitudinal axis of rotation may also vary between body positions. In contrast, on CT examination, the clinician must set sufficient parameters to better examine the extent of disease or scoliosis. Therefore, quantitative assessment of spinal curvature using specifically developed methods can improve medical diagnosis, treatment, and management of spinal disorders, and will support physicians in their work. The primary indications for spinal CT examinations include primarily the evaluation of congenital anomalies, alignment abnormalities, and traumatic injuries as well as postoperative evaluation, sometimes with intrathecal contrast (**37**). Enhancement of CT methods with three-dimensional image processing is possible, which permits spatial imaging of the spine, detection of vertebral canal deformities, detection of congenital malformations of the spine, visualization of the position of spinal implants, and assessment of the quality of spinal immobilization. This examination plays an important role in the choice of surgical technique (**38**).

2.4 Magnetic resonance imaging

Magnetic resonance imaging (MRI) has revolutionized neuraxial imaging. Its ability to produce detailed images with excellent tissue contrast in any plane and without the use of ionizing radiation has made it an attractive method of evaluating scoliosis. However, the examination is very time consuming, and once the procedure has been performed, the presence of metalwork may make further MRI studies suboptimal, mainly because of magnetization artifacts from internal fixation. MRI is the technique of choice for patients with suspected spinal cord injury or compression in the presence of warning signs such as the cauda equina syndrome, tumors, or infections, or in the presence of complex low back pain (e.g. persisting for more than 6 weeks after conservative treatment). Also, young children require sedation and occasionally general anesthesia with MRI-compatible equipment (**37**).

Nonetheless, MRI continues to be advocated as the primary imaging modality for scoliosis evaluation after radiographs, especially in infants and adolescents, where the incidence of spinal cord abnormalities is high. The role of MRI in adolescent scoliosis is unclear. Those children with atypical curves (e.g. left thoracic spine) or abnormal neurologic findings would benefit from MRI. MRI is used in the diagnosis of patients with scoliosis, primarily to assess neurologic structures and the shape of the spinal canal. Once the decision has been made to surgically correct scoliosis, some providers now routinely perform a preoperative MRI to obtain images of the entire spine, specifically including the craniocervical junction. Experienced radiologists can often simulate the curve in their own three-dimensional mindset, a common misconception that scoliosis is simply a laterally deviated spine; however, the rotation of the associated vertebrae also plays a crucial role. Not only do the vertebrae rotate relatively to each other (axial intervertebral rotation), but there is also a degree of intrinsic rotation (axial intravertebral rotation or mechanical torsion), which can be accurately measured by CT, although this obviously exposes the child to further radiation. MRI may be beneficial to patients presumed to have idiopathic scoliosis, and its noninvasive and precise nature can help to accurately diagnose young patients with less unnecessary X-ray exposure (**39**).

Monitoring and correction of spinal deformity

Although nonoperative treatment may be helpful temporarily in some of these children, like those under the age of eight years, it usually has a very limited role in decreasing curve progression in CP. One exception may be those adolescent ambulatory patients with spastic diplegia who develop the idiopathic type of curve (type 1), where bracing may be useful to stop curve aggravation. Despite these few cases where conservative treatment may be indicated, surgery is the only definitive treatment to halt progression of spinal deformities in CP. However, spine surgery in these very disabled children is a risky procedure and there has been controversy on the benefits of these operations as well as no clear data showing the impact on the life expectancy from increasing severity of scoliosis (**40**).

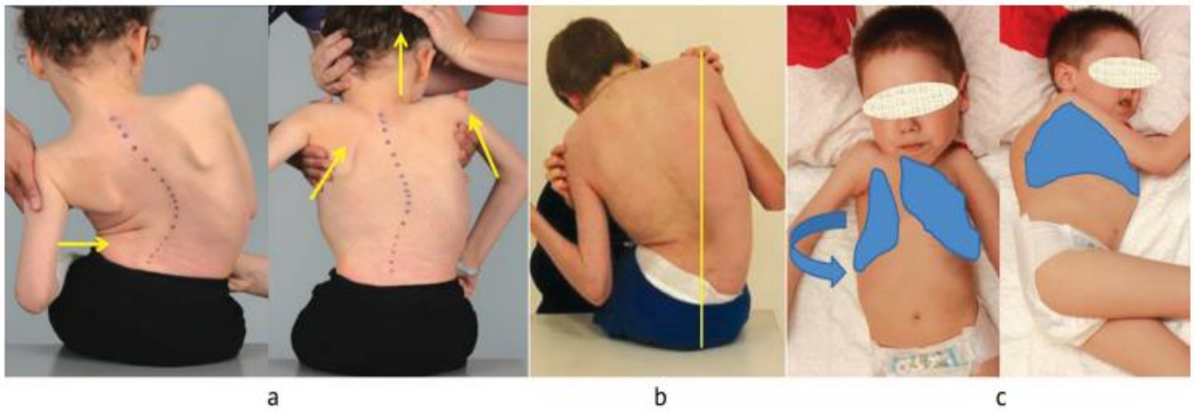

Figure 5: Clinical landmarks for identifying spinal mobility (a);disturbed frontal trunk balance (b); torsion chest deformity (c) (**41**).

Surgical Therapy

✓ Indication for Surgery

Although many spinal deformities respond well to conservative therapy and do not progress or progress very slowly, particularly severe progressive courses or therapy failures at a young age require early surgical treatment. In congenital disorders, the course may be marked and severe. In such cases, there is a risk of permanent inability to ambulate, impaired trunk posture and sitting ability, and restrictive ventilatory disorders due to an unstable thorax or severe thoracic deformities. To avoid respiratory insufficiency syndrome and allow further growth of the spine, surgical treatment by the most commonly used growth-guiding and distraction-based implants such as Growing Rods or VEPTR is indicated before definitive spondylodesis, which can be considered after the completion of spine growth. In cases of progressive deformity despite conservative therapy, a growth-guiding surgical procedure is indicated to ensure further growth, particularly of the thoracic spine, resulting in increased lung volume (**42**).

✓ Preoperative Radiological Assessment

The standard imaging is the X-ray of the entire spine (posterior–anterior and lateral view) in standing position. With the EOS™ Imaging procedure, as an alternative to conventional X-rays, a three-dimensional reconstruction can be made using low-radiation, biplanar images of the spine. With these images, the extent of spinal curvature in the frontal plane according to Cobb, the pattern of curvature in major and minor curvature, the sagittal profile or sagittal balance, the apical vertebra, the upper and lower neutral vertebra, the vertebral body rotation according to Nash/Moe to determine the rotational component, and the RVAD according to Mehta are displayed. The RVAD can be used to assess the progression of the extent of curvature in scoliosis. Values > 20° are associated with a high probability of progression and should therefore be treated surgically (**43**).

Bending images are indicated before surgical interventions for planning the extent of instrumentation. In these images, the curvature type is classified according to Lenke, or the extent and corrigibility of the primary curvature and the compensatory counter-curvature are determined. Before planned surgery or in the case of neurological deficits and in order to exclude other spinal pathologies such as vertebra malformation or syringomyelia, it is critical to obtain a magnetic resonance imaging (MRI) scan of the entire spine, since intraspinal anomalies occur in 20–50% of these patients. Formation and segmentation disorders can also trigger neurological symptoms (**44**).

✓ Growth Prognosis

Before initiating surgical therapy, knowledge of the patient’s growth potential is of immense importance, since without possible residual growth, some of the procedures cannot guarantee sufficient improvement of the extent of scoliosis. Spinal growth can be estimated on clinical and radiographic parameters. First, in girls, the onset of menarche is considered the point at which the pubertal growth spurt is complete and the growth tendency has already diminished. In most cases, the spine is fully grown about 2 years after the onset of menarche. In boys, the comparable counterpart is the change of voice. The most widespread radiographic method of determining the growth tendency and thus the ability of the spine to be corrected is based on the degree of ossification of the iliac apophysis according to Risser (**45**).

The iliac apophysis is divided into 6 stages according to different stages of ossification of the apophysis, which begins at the lateral iliac crest and progresses medially. A more reliable measurement is the Sanders classification (simplified Tanner–Whitehouse III system) using an X-ray of the non-dominant hand. The state of ossification of the epiphyses of the hand and wrist defines the expected skeletal growth in 8 groups: juvenile slow (1), preadolescent slow (2), adolescent rapid (early) (3), adolescent rapid (late) (4), adolescent steady (early) (5), adolescent steady (late) (6), early mature (7), mature (8) (**46**).

✓ Surgical Goals

Distraction-based (TGR, MCGR and VEPTR), compression-based (VBS, VBT) or growth-guiding (Shilla, Luqué trolley) procedures are used for surgical treatment. **Table 4** provides a comparative overview of various techniques used in the treatment of scoliosis, highlighting their specific systems, indications, advantages, and disadvantages.

Table 4: Summary of different surgical procedures for the treatment of scoliosis (**13**).

Features	Distraction-Based Techniques	Compression-Based Techniques	Growth-Guiding Techniques
Systems	• Traditional growing rods • Magnetic-controlled growing rods	• Vertebral body stapling (VBS)	• Shilla technique

	• Vertical Expandable Prosthetic Titanium Rib (VEPTR) • ApiFix® • Harrington rods	• Vertebral body tethering (VBT)	• Luqué trolley technique
Indication	• Early onset scoliosis • Thoracic Cobb angle >50° • Lumbar Cobb angle >40–45° • Sanders ≤3	• Adult idiopathic scoliosis <60° • Bending <25° • Kyphosis <40° • Sanders ≤5	• Early onset scoliosis • Thoracic Cobb angle >50° • Lumbar Cobb angle >40–45° • Sanders ≤3
Advantages	• Fusionless procedure • Preservation of residual growth capacity of the spine • No consecutive revision surgery for correction (except for traditional growing rods, Harrington rod, VEPTR) • Preservation of the mobility of the spine (VBT)		
Dis-advantages	• Consecutive revision surgery for correction for traditional growing rods, Harrington rod, VEPTR) • Proximal junctional kyphosis • Spontaneous fusion • Magnetic-controlled growing rods: contraindicated in patients who require repetitive MRI	• Limited indication: not suitable for secondary or early onset scoliosis • Less severe scoliosis • No valid long-term results	• No valid long-term results

The goal of surgical correction using distraction-based growing rods is to achieve effective and balanced correction of all levels while preserving as many mobile spine segments as possible and avoiding neurological complications. Both ventral and dorsal surgical procedures can yield good results in terms of correction, functionality, and patient satisfaction when treating AIS. Ventral surgical procedures, in a single session, can typically address single-curve deformities (Lenke Type 1 or Type 5) (**47**).

The highest vertebra that can be reached via ventral surgery is approximately the fifth thoracic vertebra (T5) (**48**). Dorsal correction has an advantage over ventral corrective spondylodesis in AIS because nearly all types of curvatures can be addressed dorsally. Double-curve and high-thoracic curvatures can generally only be corrected dorsally. Another limitation of ventral surgery is related to pulmonary function. Patients with significantly impaired lung function should not undergo ventral thoracic surgery due to the increased intraoperative and postoperative risk of further deterioration in lung function (**49**).

With distraction-based systems, the growth of unfused vertebral bodies is guided, and affected segments are continually derotated and guided to the correct position in the frontal and sagittal planes. By growth guidance of the spine, a sufficient and best possible trunk height can be achieved to avoid dwarfism or body dysmetria with possible stigmatization. In recent years, there has been a significant increase in MCGR compared to TGR, VEPTR, or growth-guiding procedures such as Shilla and Luqué trolley procedures. Distraction-based MCGRs now represent over 80% of all implanted growth rods (**50**).

Pedicle screws are the standard in posterior scoliosis correction and are superior to hook systems. Sublaminar bands and wires have a similar potential for coronal correction as pedicle screws. It is important to keep the desired fusion of the instrumented vertebral segments as short as possible to prevent spontaneous fusion of the adjacent segments due to periosteal irritation. In cases of stiffer AIS curvatures or pronounced sagittal deviation, Ponte osteotomies can be performed. However, there is no specific threshold of stiffness, Cobb angle, or sagittal profile that indicates when a Ponte osteotomy is recommended, so these decisions are made on a case-by-case basis (**48**).

- ***Distraction-Based Techniques***
  - ✓ **Traditional Growing Rods**

Growing rods are distraction-based systems that allow correction of the scoliotic spine in children and adolescents during growth. Since the first surgical techniques were described by Harrington in the 1960s (**Fig. 6**), with the goal of achieving spinal alignment by distraction without vertebral body fusion, there has been a significant evolution in the field of non-fusion techniques for scoliosis treatment. Because of this advancement, growing rods represent a standard procedure in the treatment of EOS. The idea behind TGRs is to straighten and realign the spine during growth by periodic lengthening of the instruments at least two times per year until completion of growth followed by definitive fusion (**51**).

Figure 6: Patient post-Harrington instrumentation from T4 to L1 performed in 1980 (reprinted with permission (**52**).

- ✓ **Vertical Expandable Prosthetic Titanium Rib**

The VEPTR system is a special type of scoliosis correction, and it is not considered as a classic growing rod. Originally, the system was used in children with congenital and highly progressive spinal deformities including unilateral brace formation and rib deformities with impending thoracic insufficiency syndrome (**53**). The average age of 3.3 years at the time of surgery is lower for the VEPTR procedure in contrast to the TGR procedures. Currently, the main indication is thoracic scoliosis in congenital scoliosis with rib fusion, unilateral unsegmented braces, and contralateral hemivertebrae. This deformity is associated with severe thoracic asymmetry and markedly limited vital capacity of the lungs. The advantage of expansion thoracoplasty is that secondary correction of the spine can be achieved via correction of the rib deformity by rib osteotomies and VEPTR implantation without using a second approach in this area and thus increasing the risk for spontaneous fusions (**54**).

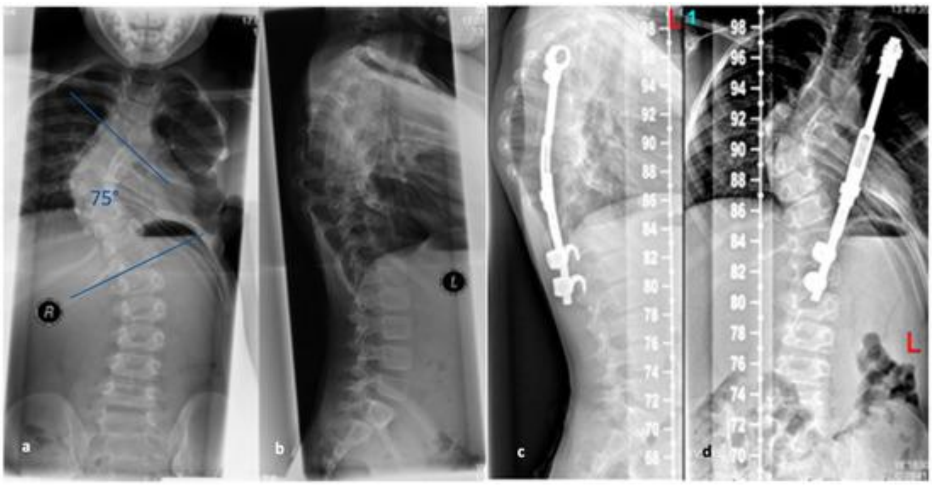

Figure 7: (**a**,**b**). Preoperative representation of the scoliosis and (**c**,**d**). Postoperative image following expansion thoracoplasty and implantation of the vertical expandable prosthetic titanium rib (VEPTR), attached proximal to the rib and distal to the laminae (reprinted with permission (**52**)

Intraoperative Complications

➢ Bleeding

Surgical correction of spinal deformities may be associated with significant blood loss and consequent risks including blood transfusion requirements, organ hypoperfusion, spinal cord hypoperfusion, and increased length of stay (**55**). Allogeneic or autologous blood transfusion rates for paediatric patients undergoing surgical correction of spinal deformity have been reported at between 18.2–25.1% (**56**).

It is, therefore, critical to optimise haemoglobin level and coagulation profile preoperatively, with consultation with haematological specialists, and consideration of iron supplementation or recombinant erythropoietin (**57**). During the positioning of patients prone for surgery, the abdomen must be kept free from direct pressure to avoid increased venous pressure in vertebral vessels and risk of increased intraoperative bleeding within the surgical field. Local anaesthetic with epinephrine may be infiltrated prior to skin incision. Controlled hypotensive anaesthesia during surgical dissection decreases blood loss by 55%, transfusion requirements by 53% and mean operative duration by 81 min. The use of topical haemostatic agents, intraoperative cell salvage, tranexamic acid (as bolus, infusion, and/or to soak surgical sponges), fibrinogen concentrate infusion, electrocautery throughout surgical dissection, bipolar tissue sealants, and ultrasonic bone scalpel for osteotomies may reduce intraoperative bleeding (**58**). When used in conjunction with other blood conservation techniques, autologous blood transfusion wound drains used postoperatively lead to a reduced need for allogeneic blood transfusion in patients undergoing scoliosis surgery (**59**).

➢ Neurological Injury

Neurological injury may range from transient peripheral nerve palsy to paralysis with complete spinal cord injuries. Neurological deficit may be due to vascular, metabolic, mechanical, or instrument-related complications (**60**). Recent reports from the Scoliosis Research Society (SRS) Morbidity and Mortality Database identified the overall neurological deficit rate as 0.71–0.94%. Patients undergoing surgery for congenital kyphosis, thoracic hyperkyphosis and needing corrective osteotomies are at increased risk of neurological complications (**61**).

Intraoperative neuromonitoring (IOM) provides routine contemporaneous recording of spinal cord function by utilising somatosensory (SSEPs) and transcranial motor evoked potentials (tcMEPs). Multimodal IOM is reported to provide 100% sensitivity in detection of spinal cord injury. True events have identifiable precipitating factors, most of which can be reversed effectively. Diagnostic criteria for IOM events that are true, transient, false, positive and negative, as well as decision algorithms, have been reported in response to MEP events during spinal surgery (**62**).

An intraoperative checklist has also been reported to optimise responses to IOM events when they occur. Steps in these algorithms include stopping the operation and gaining control of the operating room and senior theatre personnel, optimising the mean arterial pressure (MAP)/haematocrit/blood pH and pCO2, seeking normothermia, discussing the potential need for the Stagnara wake-up test with anaesthetic staff, assessing anaesthetic agents/extent of neuromuscular blockade/paralysis, checking IOM electrodes and connections, determining timing and pattern of IOM signal changes, consultation with a colleague, and checking cervical and limb positions (**63**).

Surgical considerations include reviewing surgical steps prior to IOM signal changes and a consideration of reversing surgical manoeuvres (such as traction, distraction or corrective forces, removing rods or removing screws and probing screw tracks) to the time of last normal signals, assessing for spinal cord compression, and reviewing osteotomy and laminotomy sites (**64**).

If IOM signals recover, the surgical procedure may be completed if IOM signals remain stable. Consideration is needed to modify the surgical plan and to accept a more moderate correction with the prerequisite that IOM signals are stable. The surgical procedure may need to be staged, and consideration given to administration of IV steroids. If IOM signals do not recover, there is risk of permanent neurological deficit and consideration must be given to abandoning the procedure and removing all instrumentation (**62**).

The neurological status of the patient must be assessed on waking. Intraoperative or peri-operative imaging (CT/MRI) should be considered to evaluate for neurological injury or compression, as well as the position of all instrumentation. Neurological recovery has been reported in 87.7% of patients with neurological deficit following surgery for spinal deformity; 70.8% of these patients had complete recovery at long-term follow-up, with recovery occurring during the first one to two years postoperatively (**60**).

In patients with a preoperative neurological deficit, further insult to the spine can occur during surgery to correct deformity. The surgical strategy should, therefore, include moderate corrective manoeuvres to prevent progression of deformity and decompression to permit neurological recovery. Dural tear may occur during osteotomies, decompression or directly due to the placement of pedicle screw instrumentation; repair should include watertight closure with sutures or clips with or without supplemental fibrin glue and/or overlying patch sealant (**65**).

Traction may be utilised to perform gradual correction of spinal deformity, which may increase the tolerance of the spinal cord to subsequent corrective manoeuvres and definitive surgery. The most common cause of neurological complications during surgery for paediatric spinal deformity is mechanical injury. This includes cord compression by spinal instrumentation, haematoma, ligament, or bone. Complete neurological recovery has been reported following surgical decompression or removal of aberrant pedicle screws. Overcorrection, causing neurological compromise, can be reversed by loosening the spinal instrumentation. The recovery of neurological impairment following an ischaemic insult to the spinal cord has been reported as less predictable, emphasising the importance of maintaining optimal MAP during surgery requiring osteotomies and extensive spinal instrumentation (**66**).

Following surgery with neurological deterioration, the optimisation of physiological parameters and active prevention of secondary complications may be appropriate for patients without spinal stenosis or cord compression. Repeat neurological assessment and documentation during the postoperative recovery is fundamental. Delayedonset postoperative neurological deficit has also been reported; CT and MR imaging is required to determine location of any spinal cord compression or malposition of spinal instrumentation to inform whether or not surgical intervention may be beneficial (**67**).

- **Positioning**

Postoperative blindness or visual loss (POVL) are debilitating complications of surgery to correct paediatric spinal deformity. The incidence of POVL following surgery for paediatric spinal deformities has been reported as up to 0.03-0.16%. Risk factors for POVL include inadequate patient positioning, increased blood loss, and long duration of surgery (**68**). POVL can be avoided by the surgical team, anaesthetic team, and operating personnel ensuring that the patient's eyes are free from any pressure. Paediatric patients undergoing spinal surgery are more likely than adults to develop non-ischaemic optic neuropathy and non-central retinal artery occlusion. Spinal surgery of duration greater than 6.5 h, or blood loss greater than 44.7% of estimated blood volume, may place patients at high risk of POVL (**69**).

Other positioning-related complications include perioperative peripheral nerve injury (PPNI), which more frequently affects the brachial plexus, the ulnar, median or radial nerves, or the lateral femoral cutaneous nerve. PPNI can be caused by direct pressure, stretch, and/or ischaemia of nerve fibres; these processes are often interdependent. The brachial plexus is stressed most in positions of contralateral cervical spine flexion, lateral rotation of the shoulder, shoulder abduction and wrist extension. Ulnar neuropathy may occur with the elbow kept flexed for prolonged length of time. Elbow extension and wrist hyperextension may overstretch the median nerve; median neuropathy often leads to sustained dysfunction. Radial nerve injury may occur from direct pressure on the arm, especially in the lateral position. Careful preparation during patient positioning and protection of bony anatomical prominences with pads can protect against peripheral nerve palsies and brachial plexus injuries (**70**).

Deformity and its effect on bone density

Pathology in collagen synthesis or calcium metabolism can create a biomechanical environment ripe for vertebral fractures, disordered growth, or both in the spine. Either event has been theorized to be an inciting event for the development of scoliotic deformity in all the above-mentioned disease states (**71**). The combination of altered bone health and deformity can then unfortunately create a feed-forward condition that drives deformity progression through both mechanical and biochemical factors. The Heuter-Volkmann principle postulates that mechanical loading beyond normal values retards growth while reduced loading accelerates axial growth (**72**).

Therein lies a potential rationale for the success of bracing scoliosis curves with ample growth remaining – by selectively loading and unloading the concave and convex portions, respectively, the practitioner can change the mechanical environment of the bone and intervertebral disc, mitigating progression of the curve (**73**).

With delayed muscular maturation, typically lower bone density and Body Mass Index in scoliotic patients from multiple etiologies, there is a loss in tensegrity or the optimal balance of forces. This in turn lowers bone mineral density (BMD) and increases ligamentous tension in the anterior longitudinal ligament as the ligament becomes "locked in," which in turn alters the forces across the growing vertebral body, allowing for differential growth that gives rise to the observed deformities (**74**).

While this theory remains difficult to evaluate, certain empiric observations do support the interplay between bone health, deformity, and how they interact to drive progression. For instance, bone density on the concavity of the deformity has been noted to have higher BMD than on the convexity. In considering Marfan syndrome, laxity, biologic female sex, and low muscle volume have been linked to increased risk of progression (**75**).

Each risk factor may correlate to lower bone density and altered loading of the bone. Moreover, Sponseller showed that patients with Marfan are more likely to progress and fail brace therapy for the same indications as idiopathic patients, suggesting that with altered tissue quality, changing the mechanical environment alone is insufficient to effect change. This observation is likewise corroborated by the observable increase in dural ectasia over time in patients with Marfan syndrome. In both Osteogenesis imperfecta (OI) and Duchenne muscular dystrophy (DMD), fragility fractures seem to lead to earlier onset of scoliosis whereas preservation of ambulation seem to be associated with diminished risk of progression of scoliosis (**1**).

Intraoperative Neurophysiological Monitoring

Intraoperative neurophysiological monitoring (IONM) is a real-time monitoring and assessment of the nervous system's function and integrity during surgeries, used in a wide range of surgical procedures such as brain surgery, spinal surgery, vascular surgery, peripheral nerve surgery, orthopedic surgery, and otolaryngology procedures involving the nerves(**76**).

IONM necessitates a collective approach with a team comprising neurophysiologists, neurosurgeons, anesthesiologists, neurologists, and technologists, to set up and interpret monitoring equipment, analyze real-time data, and convey critical information to the surgical team. It provides anatomical and functional information about the integrity of neural structures to the neurosurgeons, such as motor pathways, sensory pathways, and neural networks, improving the patient's safety and post-operative outcomes (**77**).

- **IONM Techniques in Neurosurgery**
  - **Electrocorticography (ECoG) and Stereo-Electroencephalography (SEEG)**

Electrocorticography (ECoG) is a specific electroencephalographic technique which entails positioning electrode grids directly on the brain's surface for neurophysiological analysis. These grids consist of multiple (4 to 32) electrodes strategically positioned to capture and analyze electrical activity from the cortical surface in real time with higher spatial and temporal resolution compared to non-invasive electroencephalography (EEG)(**78**).

ECoG allows the neurosurgery team to real-time identify and preserve essential areas responsible for various functions, including motor control, sensory perception, language, and epileptic activity. Furthermore, ECoG detects stimulation artifacts while stimulating the cortex, verifying that the stimulation is provided properly and the occurrence of stimulation-induced after discharges and seizures (**79**).

Neurological effects seen with stimulation-associated afterdischarges or seizures may not be related to the cortical region stimulated; rather, they may be linked to the propagation of hypersynchronous neuronal activity to more distant sites. Evidence of afterdischarges can alert the surgical team to the development of epileptic seizures, enabling them to employ preventive techniques such as irrigation of the cortex with cold water (**80**).

The SEEG procedure involves multiple phases and is relatively complex, relying on the placement of intracranial electrodes via a stereotactic frame and a double grid system. The use of specialized implantation devices and the integration of multimodal neuroimaging techniques have further improved the methodology and clinical application of SEEG, reducing its complexity and enhancing safety (**81**).

The intracranial SEEG can precisely identify the epileptogenic zone and pinpoint the location of the "eloquent cortex". Hence, SEEG is an essential neuro-monitoring in cases when imaging is normal, noninvasive assessments show discrepancies, and a detailed mapping of cortical function is required due to the proximity of the presumed epileptogenic zone to the eloquent cortex, or in syndromes predisposed to multiple lesions (**81**).

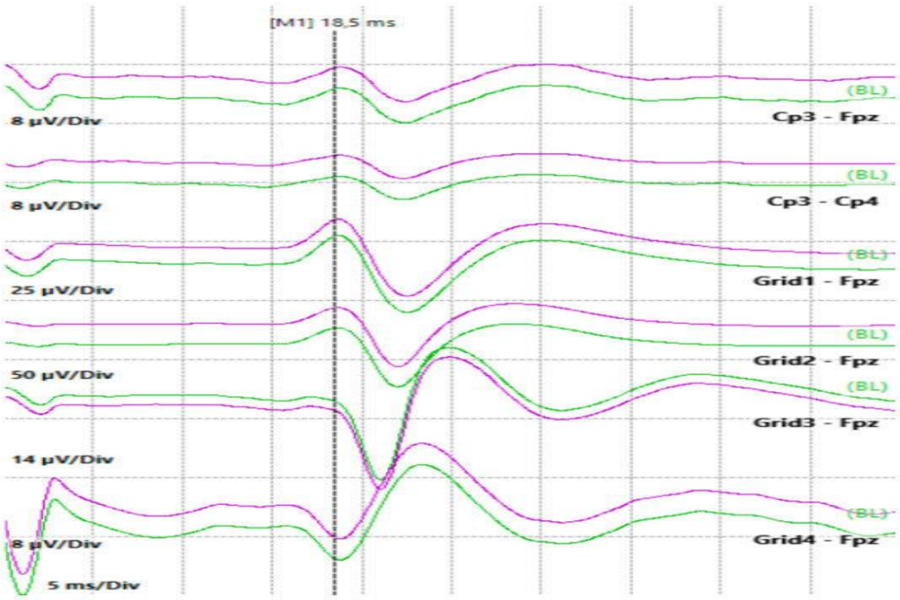

Figure 8: Phase reversal achieved by stimulating the right median nerve and recording at the cortical level with a subdural strip containing 4 contacts. The technique was used to identify the Rolandic sulcus, which in this case is identified by the phase reversal between contacts 3 and 4 of the strip (**82**).

- **Electromyography (EMG)**

Electromyography (EMG) specifically evaluates the activity and functional integrity of somatic efferent nerves using subdermal or intramuscular electrodes. The procedure includes the depolarization of a motor nerve, triggering the generation of electrical potential within the innervated muscles (**83**).

One of the primary applications of EMG is the identification and preservation of peripheral nerves through its direct stimulation during peripheral nerve surgery. Reduced muscle activity or abnormal EMG patterns serve as warning signs of potential nerve injury. EMG is also used in monitoring neuromuscular responses during neurosurgical procedures, such as resection of brain or spinal cord tumors. Finally, EMG provides real-time feedback to the surgeon about the integrity of the nerve–muscle connection, specifically during nerve repair or grafting procedures (**84**).

- **Somatosensory Evoked Potentials (SSEPs)**

Somatosensory evoked potentials (SSEPs) monitor the dorsal column–medial lemniscus pathway, which plays a role in tactile discrimination, vibration, and proprioception. The process involves stimulating sensory receptors in the skin, activating peripheral sensory nerves that extend through the nerve root to the ipsilateral dorsal root ganglia in the spinal levels (**85**).

These initial neurons project to form the fasciculi gracilis and cuneatus, transmitting impulses from the lower and upper extremities, respectively. The first synapse occurs in the lower medulla, followed by the crossing over of the impulses at the brainstem level and the formation of the medial lemniscus. Subsequently, the impulse ascends to the contralateral thalamus, ultimately conveying information to the primary sensory cortex in the parietal lobe (**85**).

The ability to detect any changes in SSEPs, such as alterations in amplitude, latency, or waveform, is crucial during surgery. These changes can indicate potential damage or compromise to the sensory pathways, signaling the need for immediate corrective measures (**86**).

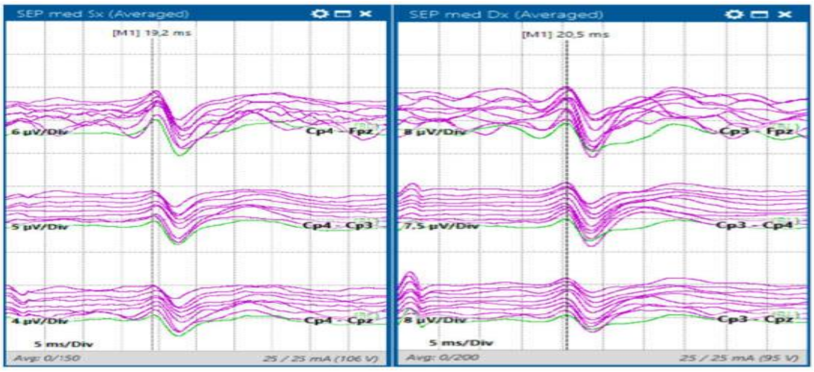

Figure 9: SSEPs of the upper limbs with stimulation from the median nerve using adhesive electrodes and recording from the scalp with corkscrew electrodes positioned according to the International 10–20 system (**82**).

- **Motor Evoked Potentials (MEPs) and Direct Cortical Stimulation (DCS)**

Motor evoked potentials (MEPs) represent a specialized monitoring technique that concentrates on evaluating motor pathways within the nervous system. It is achieved through transcranial or direct electric stimulation of the motor cortex (DCS), inducing the excitation of corticospinal projections at different levels. The intensity of stimulation and the precise electrode placement are pivotal factors in pinpointing the specific brain areas where MEPs originate (**87**).

The electrical potential generated during MEPs can be recorded at different locations, either directly at target muscles or from the epidural space at the spinal cord (d-waves). The latter is the best choice to monitor corticospinal tract integrity during spinal surgery. The stability of the d-wave is a predictive indicator for favorable motor outcomes, even when the intraoperative transcranial MEPs are abolished or diminished (**88**).

Direct cortical stimulation (DCS) is another technique that involves the application of electrical currents directly to the brain cortex. DCS involves placing some electrodes (generally a 6-contact strip) directly on the exposed cortical surface, in the subdural space, or inserted into the brain tissue. Electrical stimulation is delivered using a stimulator, and the responses are observed and recorded. Compared to MEPs, DCS necessitates less stimulation intensity and delivers highly localized and superficial motor cortex stimulation. DCS is often used to map the functional areas of the brain before surgical procedures. It can also be employed to identify the epileptic focus in patients with drug-resistant epilepsy or in some cases of awake brain surgery to allow the assessment of cognitive and language functions (**89**).

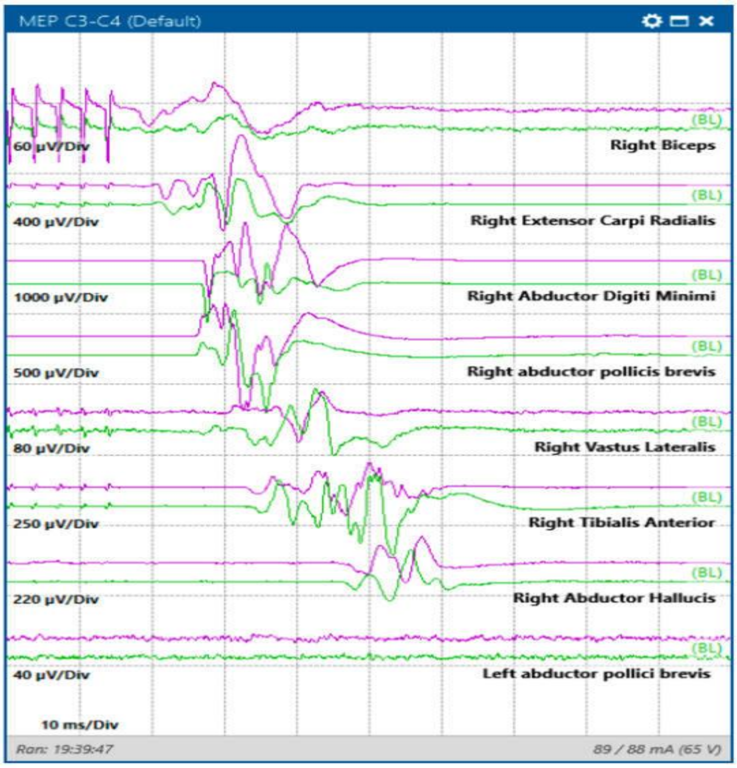

Figure 10: Transcranial motor evoked potentials (MEP) obtained by stimulating with corkscrew electrodes in the C3–FZ position at a threshold of 90 mA in a case of left parietal lesion (**82**).

- **Brainstem Auditory Evoked Potentials (BAEPs)**

Brainstem auditory evoked potentials (BAEPs)monitor the functionality of the auditory nerve and the auditory pathways within the brainstem. The auditory signal originates at the cochlear hair cell, where sound waves are converted into electrical signals. It then progresses through a series of anatomical structures, including the vestibulocochlear nerve, the superior olivary complex, the lateral lemniscus, the inferior colliculus, and the medial geniculate body. This sequential relay system guarantees the transmission of auditory information toward the primary auditory cortex, where it undergoes processing and interpretation (**82**).

BAEPs, consisting of seven distinct positive waves, are small auditory evoked potentials in response to an auditory stimulus, captured using A1 and A2 electrodes as the active points, while Cz or Fz is employed as the reference electrode positioned on the scalp. It finds common usage in the surgical treatment of different pathologies involving the posterior cranial fossa and the cerebellopontine angle, such as acoustic neuroma, neurovascular compression syndrome, and brainstem tumor (**82**).

- **Visual Evoked Potentials (VEPs)**

Visual evoked potentials (VEPs) assess the functional integrity of the optic pathways responsible for transmitting visual stimuli from the retina to the brain's visual cortex in response to light. The process begins with the conversion of visual stimuli into nerve signals within the retina. Then, the nerve signals traverse through the optic nerve and reach the optic chiasma, where a partial crossing of fibers occurs. Subsequently, the signals continue their path through the optic tract, leading them to the lateral geniculate body, an important relay station. From there, the signals are further transmitted through the optic radiation, a bundle of nerve fibers, ultimately reaching their destination in the visual cortex located in the occipital lobe of the brain (**90**).

VEPs are captured through active electrodes (O1, O2, and Oz), referencing the vertex to the Cz reference electrode on the scalp over the occipital cortex in response to light stimuli. When dealing with occipital brain lesions, subdural strip electrodes may be employed for recording. Recent attention to VEP monitoring has been sparked by the growing utilization of simultaneous electroretinogram (ERG) recording, progress in light-emitting diodes (LEDs) manufacturing, and the adoption of white light stimulation (**91**).

To ensure adequate flash stimuli are delivered to the retina, ERG is recorded simultaneously with VEPs, as the dislocation of goggles could lead to inadequate stimulation of the retina. Nevertheless, VEPs may not be detectable in individuals with visual acuity below 0.1 and/or a visual field defect larger than hemianopsia. Initial findings showed that a correlation existed between postoperative declines in visual acuity and the absence of VEPs for a duration exceeding four minutes (**92**).

➢ IONM in Spinal Surgery

Spine surgery inherently carries a risk of causing harm to critical neural structures, with neurological complications ranging from 1.3% to 31%. These complications may arise from direct mechanical forces on the spinal cord and indirect ischemic changes during corrective maneuvers. To mitigate these risks, neurosurgeons employ monitoring techniques such as MEPs and SSEPs to safeguard spinal cord integrity (**93**).

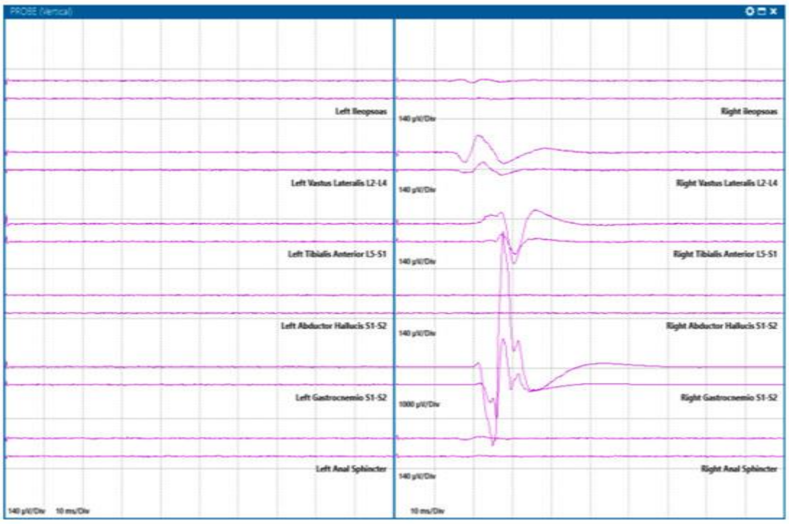

Figure 11: Motor evoked potentials in spinal surgery. The figure reports the MEP obtained, from top to bottom, in the left and right iliopsoas, vastus lateralis, tibialis anterior, abductor hallucis, gastrocnemius, and anal sphincter in a case of cauda surgery. The stimulation was obtained with a bipolar probe at 0.4 mA (**82**).

In anterior cervical spinal cord surgery, SSEPs are the most commonly used IONM technique (99.9%), followed by EMG (81.3%) and MEPs (64.8%). However, the value of monitoring during anterior cervical discectomy and fusion surgery is questionable due to the high incidence of false positives. Conversely, the simultaneous use of intraoperative MEPs and SSEPs is preferred during posterior approaches for cervical spondylotic myelopathy surgeries (**94**).

The role of IONM in intradural extramedullary tumors remains debated. While MEPs may not be deemed essential, recent findings suggest SSEPs significantly contribute to neurological preservation. Further research is needed to assess the feasibility and significance of the D-wave technique in this surgery. Conversely, for intramedullary spinal cord tumors, combining dorsal column mapping and spinal cord stimulation for SSEPs can be useful in identifying the anatomical midline, often distorted by the tumor's anatomy. In patients with traumatic spinal cord injury, the use of transcranial MEPs has also been investigated. Given the low prevalence of neurological complications (2.3%) and the low positive predictive value (18.4%), single usage of transcranial MEP monitoring during traumatic spinal injury surgery has not been recommended. It remains to be understood if the application of a multimodal IONM may improve the positive predictive value in this scenario (**95**).

References:

1. **Paranjape, C. S., & Welborn, M. C. (2024).** Spine health: Back pain and deformity progression. Journal of the Pediatric Orthopaedic Society of North America, 7, 100062.
2. **Rusnák, R., Kolarová, M., Aštaryová, I., & Kutiš, P.** (2019). Screening and early identification of spinal deformities and posture in 311 children: results from 16 districts in Slovakia. *Rehabilitation Research and Practice*, *2019*(1), 4758386.
3. **Sudo, H., Kokabu, T., Abe, Y., Iwata, A., Yamada, K., Ito, Y. M., Iwasaki, N., & Kanai, S.** (2018). Automated noninvasive detection of idiopathic scoliosis in children and adolescents: A principle validation study. *Scientific Reports*, *8*(1), 17714.
4. **Mitova, S.** (2015). Frequency and prevalence of postural disorders and spinal deformities in children of primary school age. *Research in Kinesiology*, *43*(1), 21–24.
5. Grabara, M., Bieniec, A., & Nawrocka, A. (2017). Spinal curvatures of children and adolescents-A cross-sectional study. Biomedical human kinetics, 9(1), 69-74.
6. **Haleem, S., & Nnadi, C.** (2018). Scoliosis: a review. *Paediatrics and Child Health*, *28*(5), 209–217.
7. **Yifei, G., Xiaolong, S., Yang, L., Peng, C., & Wen, Y.** (2019). Clinical outcomes of anterior correction and reconstruction for n eurofibromatosis-associated severe cervical kyphotic deformity. *International Orthopaedics*, *43*, 639–646.
8. **Mladenov, K. V, & Stücker, R.** (2024). Recent Developments in Surgical Treatment of Spinal Deformity in Pediatric Patients: Experience from a Single-Center Series of 42 Neurofibromatosis Type 1 Patients. *Cancers*, *16*(23), 4079.
9. **El-Hawary, R., & Akbarnia, B. A.** (2015). Early onset scoliosis-time for consensus. *Spine Deformity*, *3*(2), 105–106.
10. **Tsirikos, A. I., Roberts, S. B., & Bhatti, E.** (2020). Incidence of spinal deformity surgery in a national health service from 2005 to 2018: an analysis of 2,205 children and adolescents. *Bone & Joint Open*, *1*(3), 19–28.
11. **von Heideken, J., Iversen, M. D., & Gerdhem, P.** (2018). Rapidly increasing incidence in scoliosis surgery over 14 years in a nationwide sample. *European Spine Journal*, *27*, 286–292.
12. **Aresti, N. A., & Barry, M.** (2016). Paediatric spine. *Paediatric Orthopaedics in Clinical Practice*, 53–68.
13. **Braun, S., Brenneis, M., Schönnagel, L., Caffard, T., & Diaremes, P.** (2023). Surgical treatment of spinal deformities in pediatric orthopedic patients. *Life*, *13*(6), 1341.
14. **Ruiz, G., Torres-Lugo, N. J., Marrero-Ortiz, P., Guzmán, H., Olivella, G., & Ramírez, N.** (2022). Early-onset scoliosis: a narrative review. *EFORT Open Reviews*, *7*(8), 599–610.
15. **Helenius, I. J.** (2020). Standard and magnetically controlled growing rods for the treatment of early onset scoliosis. *Annals of Translational Medicine*, *8*(2), 26.
16. **Liu, J., Zhang, H., Dong, P., Su, D., Bai, Z., Ma, Y., Miao, Q., Yang, S., Wang, S., & Yang, X.** (2025). Intelligent measurement of adolescent idiopathic scoliosis x-ray coronal imaging parameters based on VB-Net neural network: a retrospective analysis of 2092 cases. *Journal of Orthopaedic Surgery and Research*, *20*(1), 9.
17. **Bettany-Saltikov, J., Weiss, H., Chockalingam, N., Taranu, R., Srinivas, S., Hogg, J., Whittaker, V., Kalyan, R. V, & Arnell, T.** (2015). Surgical versus non-surgical interventions in people with adolescent idiopathic scoliosis. *Cochrane Database of Systematic Reviews*, *4*.
18. **Song, Z., Zhang, Z., Yang, X., Zhao, Z., Li, T., Bi, N., Xie, J., & Wang, Y.** (2022). Posterior vertebral column resection for severe spinal deformity correction: comparison of pediatric, adolescent, and adult groups. *Computational Intelligence and Neuroscience*, *2022*(1), 5730856.
19. **Zhou, G.-Q., Jiang, W.-W., Lai, K.-L., & Zheng, Y.-P.** (2017). Automatic measurement of spine

curvature on 3-D ultrasound volume projection image with phase features. *IEEE Transactions on Medical Imaging*, *36*(6), 1250–1262.

20. **Żurawski, A. Ł., Kiebzak, W. P., Kowalski, I. M., Śliwiński, G., & Śliwiński, Z.** (2020). Evaluation of the association between postural control and sagittal curvature of the spine. *PloS One*, *15*(10), e0241228.
21. **Yokoyama, Y., Nishiwaki, Y., Michikawa, T., Imamura, H., Nakamura, T., Takebayashi, T., & Takahashi, H.** (2017). The association of kyphosis assessed in supine and standing positions with future activities of daily living dependence: the Kurabuchi Study. *Archives of Osteoporosis*, *12*, 1–9.
22. **Bruno, A. G., Anderson, D. E., D'Agostino, J., & Bouxsein, M. L.** (2012). The effect of thoracic kyphosis and sagittal plane alignment on vertebral compressive loading. *Journal of Bone and Mineral Research*, *27*(10), 2144–2151.
23. **Witton, C., Talcott, J. B., & Henning, G. B.** (2017). Psychophysical measurements in children: challenges, pitfalls, and considerations. *PeerJ*, *5*, e3231.
24. **Zappalá, M., Lightbourne, S., & Heneghan, N. R.** (2021). The relationship between thoracic kyphosis and age, and normative values across age groups: a systematic review of healthy adults. *Journal of Orthopaedic Surgery and Research*, *16*, 1–18.
25. **Jung, S., Hwang, U., Ahn, S., Kim, J., & Kwon, O.** (2020). Effects of manual therapy and mechanical massage on spinal alignment, extension range of motion, back extensor electromyographic activity, and thoracic extension strength in individuals with thoracic hyperkyphosis: a randomized controlled trial. *Evidence-Based Complementary and Alternative Medicine*, *2020*(1), 6526935.
26. **Zećirović, A., Bjelica, B., Pajović, L., & Aksović, N.** (2021). Postural status and kyphosis in school-age children. *International Journal of Academic Health and Medical Research*, *5*(11), 90–97.
27. **Chatterjee, A. D., Hassan, K., & Grevitt, M. P.** (2012). Congenital kypho-scoliosis: a case of thoracic insufficiency syndrome and the limitations of treatment. *European Spine Journal*, *21*, 1043–1049.
28. **Kuznia, A. L., Hernandez, A. K., & Lee, L. U.** (2020). Adolescent idiopathic scoliosis: common questions and answers. *American Family Physician*, *101*(1), 19–23.
29. **Kotwicki, T.** (2008). Evaluation of scoliosis today: examination, X-rays and beyond. *Disability and Rehabilitation*, *30*(10), 742–751.
30. **Karpiel, I., Ziębiński, A., Kluszczyński, M., & Feige, D.** (2021). A survey of methods and technologies used for diagnosis of scoliosis. *Sensors*, *21*(24), 8410.
31. **Jin, C., Wang, S., Yang, G., Li, E., & Liang, Z.** (2022). A review of the methods on cobb angle measurements for spinal curvature. *Sensors*, *22*(9), 3258.
32. **Asher, M. A., & Burton, D. C.** (2006). Adolescent idiopathic scoliosis: natural history and long term treatment effects. *Scoliosis*, *1*, 1–10.
33. **Watanabe, K., Aoki, Y., & Matsumoto, M.** (2019). An application of artificial intelligence to diagnostic imaging of spine disease: estimating spinal alignment from Moiré images. *Neurospine*, *16*(4), 697.
34. **Cao, J., Zhang, X., Cao, J., Gao, R., & Guo, D.** (2022). Efficacy of the growing rod technique on kyphotic early-onset scoliosis. *Frontiers in Pediatrics*, *10*, 982295.
35. **Molnár, S., Manó, S., Kiss, L., & Csernátony, Z.** (2006). Ex vivo and in vitro determination of the axial rotational axis of the human thoracic spine. *Spine*, *31*(26), E984–E991.
36. **Brink, R. C., Colo, D., Schlösser, T. P. C., Vincken, K. L., van Stralen, M., Hui, S. C. N., Shi, L., Chu, W. C. W., Cheng, J. C. Y., & Castelein, R. M.** (2017). Upright, prone, and supine spinal morphology and alignment in adolescent idiopathic scoliosis. *Scoliosis and Spinal Disorders*, *12*, 1–8.
37. **Addai, D., Zarkos, J., & Bowey, A. J.** (2020). Current concepts in the diagnosis and management of adolescent idiopathic scoliosis. *Child's Nervous System*, *36*, 1111–1119.
38. **Brink, R. C., Homans, J. F., Schlösser, T. P. C., van Stralen, M., Vincken, K. L., Shi, L., Chu, W. C. W., Viergever, M. A., Castelein, R. M., & Cheng, J. C. Y.** (2019). CT-based study of vertebral and intravertebral rotation in right thoracic adolescent idiopathic scoliosis. *European Spine Journal*, *28*, 3044–3052.
39. **Mineiro, J., & Yazici, M.** (2020). Technical aspects of surgical correction of spinal deformities in

cerebral palsy. *Journal of Children's Orthopaedics*, *14*(1), 30–40.

40. **Ryabykh, S. O., Pavlova, O. M., Savin, D. M., Burtsev, A. V, & Gubin, A. V**. (2018). Surgical management of myelomeningocele-related spinal deformities. *World Neurosurgery*, *112*, e431–e441.
41. **Tikoo, A., Kothari, M. K., Shah, K., & Nene, A.** (2017). Current concepts-congenital scoliosis. *The Open Orthopaedics Journal*, *11*, 337.
42. **Tarhan, T., Froemel, D., & Meurer, A.** (2015). EOS imaging acquisition system: 2D/3D diagnostics of the skeleton. *Der Orthopäde*, *44*, 977–988.
43. **Stücker, R.** (2010). Die idiopathische Skoliose. *Orthopädie Und Unfallchirurgie Up2date*, *5*(01), 39–56.
44. **Risser, J. C.** (2010). The classic: the iliac apophysis: an invaluable sign in the management of scoliosis. *Clinical Orthopaedics and Related Research®*, *468*(3), 646–653.
45. **Sanders, J. O., Khoury, J. G., Kishan, S., Browne, R. H., Mooney III, J. F., Arnold, K. D., McConnell, S. J., Bauman, J. A., & Finegold, D. N.** (2008). Predicting scoliosis progression from skeletal maturity: a simplified classification during adolescence. *JBJS*, *90*(3), 540–553.
46. **Ruf, M., Drumm, J., & Jeszenszky, D.** (2020). Anterior instrumented fusion for adolescent idiopathic scoliosis. *Annals of Translational Medicine*, *8*(2), 31.
47. **Schulte, T. L., Geiger, F., Mladenov, K., & Wiedenhöfer, B.** (2024). Zusammenfassung der S2k-Leitlinie „Adoleszente Idiopathische Skoliose ". *Die Wirbelsäule*, *8*(02), 75–77.
48. **Chen, L., Sun, Z., He, J., Xu, Y., Li, Z., Zou, Q., & Li, B.** (2020). Effectiveness and safety of surgical interventions for treating adolescent idiopathic scoliosis: a Bayesian meta-analysis. *BMC Musculoskeletal Disorders*, *21*, 1–15.
49. **Klyce, W., Mitchell, S. L., Pawelek, J., Skaggs, D. L., Sanders, J. O., Shah, S. A., McCarthy, R. E., Luhmann, S. J., Sturm, P. F., & Flynn, J. M.** (2020). Characterizing use of growth-friendly implants for early-onset scoliosis: a 10-year update. *Journal of Pediatric Orthopaedics*, *40*(8), e740–e746.
50. **Kocyigit, I. A., Olgun, Z. D., Demirkiran, H. G., Ayvaz, M., & Yazici, M.** (2017). Graduation protocol after growing-rod treatment: removal of implants without new instrumentation is not a realistic approach. *JBJS*, *99*(18), 1554–1564.
51. **Braun, S., Mueller-Broich, J., Diaremes, P., Fleege, C. S., & Meurer, A.** (2021). Nonfusion procedures in pediatric scoliosis. *Der Orthopade*, *50*(6), 497–508.
52. **Campbell Jr, R. M., Smith, M. D., & Hell-Vocke, A. K.** (2004). Expansion thoracoplasty: the surgical technique of opening-wedge thoracostomy: surgical technique. *JBJS*, *86*(suppl_1), 51–64.
53. **Hell, A. K., Campbell, R. M., & Hefti, F.** (2005). The vertical expandable prosthetic titanium rib implant for the treatment of thoracic insufficiency syndrome associated with congenital and neuromuscular scoliosis in young children. *Journal of Pediatric Orthopaedics B*, *14*(4), 287–293.
54. **Fletcher, N. D., Bellaire, L. L., Dilbone, E. S., Ward, L. A., & Bruce, R. W.** (2020). Variability in length of stay following neuromuscular spinal fusion. *Spine Deformity*, *8*, 725–732.
55. **Mange, T. R., Sucato, D. J., Poppino, K. F., Jo, C., & Ramo, B. R.** (2020). The incidence and risk factors for perioperative allogeneic blood transfusion in primary idiopathic scoliosis surgery. *Spine Deformity*, *8*, 695–702.
56. **Switzer, T., Naraine, N., Chamlati, R., Lau, W., McVey, M. J., Zaarour, C., & Faraoni, D.** (2020). Association between preoperative hemoglobin levels after iron supplementation and perioperative blood transfusion requirements in children undergoing scoliosis surgery. *Pediatric Anesthesia*, *30*(10), 1077–1082.
57. **Liang, J., Shen, J., Chua, S., Fan, Y., Zhai, J., Feng, B., Cai, S., Li, Z., & Xue, X.** (2015). Does intraoperative cell salvage system effectively decrease the need for allogeneic transfusions in scoliotic patients undergoing posterior spinal fusion? A prospective randomized study. *European Spine Journal*, *24*, 270–275.
58. **Loughenbury, P. R., Berry, L., Brooke, B. T., Rao, A. S., Dunsmuir, R. A., & Millner, P. A.** (2016). Benefits of the use of blood conservation in scoliosis surgery. *World Journal of Orthopedics*, *7*(12), 808.
59. **Li, J., Hu, Z., Qian, Z., Tang, Z., Qiu, Y., Zhu, Z., & Liu, Z.** (2022). The prognosis and recovery of major postoperative neurological deficits after corrective surgery for scoliosis: an analysis of 65 cases at

a single institution. *The Bone & Joint Journal*, *104*(1), 103–111.

60. **Bivona, L. J., France, J., Daly-Seiler, C. S., Burton, D. C., Dolan, L. A., Seale, J. J., de Kleuver, M., Ferrero, E., Gurd, D. P., & Konya, D.** (2022). Spinal deformity surgery is accompanied by serious complications: report from the Morbidity and Mortality Database of the Scoliosis Research Society from 2013 to 2020. *Spine Deformity*, *10*(6), 1307–1313.
61. **Tsirikos, A. I., Duckworth, A. D., Henderson, L. E., & Michaelson, C.** (2020). Multimodal intraoperative spinal cord monitoring during spinal deformity surgery: efficacy, diagnostic characteristics, and algorithm development. *Medical Principles and Practice*, *29*(1), 6–17.
62. **Zuccaro, M., Zuccaro, J., Samdani, A. F., Pahys, J. M., & Hwang, S. W.** (2017). Intraoperative neuromonitoring alerts in a pediatric deformity center. *Neurosurgical Focus*, *43*(4), E8.
63. **Vitale, M. G., Skaggs, D. L., Pace, G. I., Wright, M. L., Matsumoto, H., Anderson, R. C. E., Brockmeyer, D. L., Dormans, J. P., Emans, J. B., & Erickson, M. A.** (2014). Best practices in intraoperative neuromonitoring in spine deformity surgery: development of an intraoperative checklist to optimize response. *Spine Deformity*, *2*(5), 333–339.
64. **West, J. L., Arnel, M., Palma, A. E., Frino, J., Powers, A. K., & Couture, D. E.** (2018). Incidental durotomy in the pediatric spine population. *Journal of Neurosurgery: Pediatrics*, *22*(5), 591–594.
65. **Mehrpour, S., Sorbi, R., Rezaei, R., & Mazda, K.** (2017). Posterior-only surgery with preoperative skeletal traction for management of severe scoliosis. *Archives of Orthopaedic and Trauma Surgery*, *137*, 457–463.
66. **Boachie-Adjei, O., Duah, H. O., Yankey, K. P., Lenke, L. G., Sponseller, P. D., Sucato, D. J., Samdani, A. F., Newton, P. O., Shah, S. A., & Erickson, M. A.** (2021). New neurologic deficit and recovery rates in the treatment of complex pediatric spine deformities exceeding 100 degrees or treated by vertebral column resection (VCR). *Spine Deformity*, *9*, 427–433.
67. **De la Garza-Ramos, R., Samdani, A. F., Sponseller, P. D., Ain, M. C., Miller, N. R., Shaffrey, C. I., & Sciubba, D. M.** (2016). Visual loss after corrective surgery for pediatric scoliosis: incidence and risk factors from a nationwide database. *The Spine Journal*, *16*(4), 516–522.
68. **Roberts, S. B., & Tsirikos, A. I.** (2022). Paediatric spinal deformity surgery: complications and their management. *Healthcare*, *10*(12), 2519.
69. **Kamel, I., & Barnette, R.** (2014). Positioning patients for spine surgery: avoiding uncommon position-related complications. *World Journal of Orthopedics*, *5*(4), 425.
70. **Liu, G., Chen, J., Zhou, Y., Zuo, Y., Liu, S., Chen, W., Wu, Z., & Wu, N.** (2017). The genetic implication of scoliosis in osteogenesis imperfecta: a review. *Journal of Spine Surgery*, *3*(4), 666.
71. **Jain, V., Lykissas, M., Trobisch, P., Wall, E. J., Newton, P. O., Sturm, P. F., Cahill, P. J., & Bylski-Austrow, D. I.** (2014). Surgical aspects of spinal growth modulation in scoliosis correction. *Instructional Course Lectures*, *63*, 335–345.
72. **Wong, S. H.** (2021). *Design and development of anisotropic textile brace for adolescent idiopathic scoliosis (AIS)*.
73. **Smit, T. H.** (2020). Adolescent idiopathic scoliosis: The mechanobiology of differential growth. *JOR Spine*, *3*(4), e1115.
74. **Taniguchi, Y., Matsubayashi, Y., Kato, S., Doi, T., Takeda, N., Yagi, H., Inuzuka, R., Oshima, Y., & Tanaka, S.** (2021). Predictive physical manifestations for progression of scoliosis in Marfan syndrome. *Spine*, *46*(15), 1020–1025.
75. **Garofalo, E., Bruni, A., Scalzi, G., Curto, L. S., Rovida, S., Brescia, V., Gervasi, R., Navalesi, P., Innaro, N., & Longhini, F.** (2021). Low-dose of rocuronium during thyroid surgery: Effects on intraoperative nerve-monitoring and intubation. *Journal of Surgical Research*, *265*, 131–138.
76. **Tomasello, F., Angileri, F. F., Conti, A., Scibilia, A., Cardali, S., La Torre, D., & Germanò, A.** (2019). Petrosal meningiomas: factors affecting outcome and the role of intraoperative multimodal assistance to microsurgery. *Neurosurgery*, *84*(6), 1313–1324.
77. **Simon, M. V, Nuwer, M. R., & Szelényi, A.** (2022). Electroencephalography, electrocorticography, and cortical stimulation techniques. *Handbook of Clinical Neurology*, *186*, 11–38.
78. **Cuisenier, P., Testud, B., Minotti, L., Tiali, S. E. B., Martineau, L., Job, A.-S., Trébuchon, A.,**

Deman, P., Bhattacharjee, M., & Hoffmann, D. (2020). Relationship between direct cortical stimulation and induced high-frequency activity for language mapping during SEEG recording. *Journal of Neurosurgery*, *134*(4), 1251–1261.

79. **Nossek, E., Matot, I., Shahar, T., Barzilai, O., Rapoport, Y., Gonen, T., Sela, G., Grossman, R., Korn, A., & Hayat, D.** (2013). Intraoperative seizures during awake craniotomy: incidence and consequences: analysis of 477 patients. *Neurosurgery*, *73*(1), 135–140.
80. **Iida, K., & Otsubo, H.** (2017). Stereoelectroencephalography: indication and efficacy. *Neurologia Medico-Chirurgica*, *57*(8), 375–385.
81. **Guzzi, G., Ricciuti, R. A., Della Torre, A., Lo Turco, E., Lavano, A., Longhini, F., & La Torre, D.** (2024). Intraoperative neurophysiological monitoring in neurosurgery. *Journal of Clinical Medicine*, *13*(10), 2966.
82. **Ghatol, D., & Widrich, J.** (2023). Intraoperative neurophysiological monitoring. In *StatPearls [Internet]*. StatPearls Publishing.
83. **Taskiran, E., & Seidel, K.** (2022). Current use of intraoperative neurophysiology in neurosurgery: Supratentorial part 1. *Turkish Neurosurgery*, *32*(2).
84. **Niu, J., Ding, L., Li, J. J., Kim, H., Liu, J., Li, H., Moberly, A., Badea, T. C., Duncan, I. D., & Son, Y.-J.** (2013). Modality-based organization of ascending somatosensory axons in the direct dorsal column pathway. *Journal of Neuroscience*, *33*(45), 17691–17709.
85. **MacDonald, D. B., Dong, C., Quatrale, R., Sala, F., Skinner, S., Soto, F., & Szelényi, A.** (2019). Recommendations of the International Society of Intraoperative Neurophysiology for intraoperative somatosensory evoked potentials. *Clinical Neurophysiology*, *130*(1), 161–179.
86. **Wong, A. K., Shils, J. L., Sani, S. B., & Byrne, R. W.** (2022). Intraoperative neuromonitoring. *Neurologic Clinics*, *40*(2), 375–389.
87. **Shigematsu, H., Ando, M., Kobayashi, K., Yoshida, G., Funaba, M., Morito, S., Takahashi, M., Ushirozako, H., Kawabata, S., & Yamada, K.** (2023). Efficacy of d-wave monitoring combined with the transcranial motor-evoked potentials in high-risk spinal surgery: A retrospective multicenter study of the monitoring committee of the japanese society for spine surgery and related research. *Global Spine Journal*, *13*(8), 2387–2395.
88. **Kabir, S. S., Jahangiri, F. R., Rinesmith, C., Vilches, C. S., Chakarvarty, S., Rinesmith, C. B., & Chakravarty, S.** (2023). Intraoperative testing during the mapping of the language cortex. *Cureus*, *15*(3).
89. **De Moraes, C. G.** (2013). Anatomy of the visual pathways. *Journal of Glaucoma*, *22*, S2–S7.
90. **Rajashekar, D., Lavrador, J. P., Ghimire, P., Keeble, H., Harris, L., Pereira, N., Patel, S., Beyh, A., Gullan, R., & Ashkan, K.** (2022). Simultaneous motor and visual intraoperative neuromonitoring in asleep parietal lobe surgery: dual strip technique. *Journal of Personalized Medicine*, *12*(9), 1478.
91. **Olmsted, Z. T., Silverstein, J. W., Einstein, E. H., Sowulewski, J., Nelson, P., Boockvar, J. A., & D'Amico, R. S.** (2023). Evolution of flash visual evoked potentials to monitor visual pathway integrity during tumor resection: illustrative cases and literature review. *Neurosurgical Review*, *46*(1), 46.
92. **Lavano, A., Della Torre, A., Guzzi, G., & La Torre, D.** (2024). Plica mediana dorsalis as a potential risk for spine surgery. *Journal of Neurosurgical Sciences*.
93. **Zileli, M., Borkar, S. A., Sinha, S., Reinas, R., Alves, Ó. L., Kim, S.-H., Pawar, S., Murali, B., & Parthiban, J.** (2019). Cervical spondylotic myelopathy: natural course and the value of diagnostic techniques–WFNS spine committee recommendations. *Neurospine*, *16*(3), 386.
94. **Ushirozako, H., Yoshida, G., Imagama, S., Machino, M., Ando, M., Kawabata, S., Yamada, K., Kanchiku, T., Fujiwara, Y., & Taniguchi, S.** (2023). Role of transcranial motor evoked potential monitoring during traumatic spinal injury surgery: A prospective multicenter study of the monitoring committee of the Japanese society for spine surgery and related research. *Spine*, *48*(19), 1388–1396.