Early-onset scoliosis

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Purpose of review
The aim of this review is to provide the reader with the most updated available information so that it can be helpful in the approach of patients with early-onset scoliosis (EOS).

Recent findings
While confirming the efficacy and safety of classic techniques for the treatment of EOS such as traditional growing rods or Mehta casting, recent research suggests that there is room for improvement with less invasive techniques.

Summary
The most important goal when treating patients with EOS should be to promote rib cage expansion and lung development. Different techniques have been described and may be used depending on the specific patient's characteristics.

Keywords
anesthesia in children, early-onset scoliosis, lung development

INTRODUCTION

Early-onset scoliosis (EOS) is defined as a curve greater than 10° (Cobb angle) in the coronal plane radiograph diagnosed before the age of 10 years. This definition encompasses a wide range of different conditions, each one with its own challenges and peculiarities.

This heterogenicity in conjunction with a low prevalence makes it difficult to study patients with EOS. There is limited consensus on treatment modalities, surgical techniques, and timing of surgery. Management decisions are mainly driven by the clinician's experience and training. The aim of this review is to provide the reader with the most updated available information in the management of patients with EOS.

Classification

The classification for early onset scoliosis (C-EOS) classification system was developed and validated by the Scoliosis Research Society (SRS) and is currently the most widely used for both clinical management and research purposes (Fig. 1) [1]. A new classification has been recently proposed based on an automated method to cluster EOS patients according to preoperative clinical parameters. Using this machine learning method, Viraraghavan *et al.* [2] identified three unique, data-driven subgroups for each C-EOS cause category (congenital, syndromic, idiopathic, and neuromuscular).

EOS constitutes a severe spinal condition because it can lead to abnormal rib cage development and may predispose the inability of the thorax to support normal lung growth and respiration, known as thoracic insufficiency syndrome (TIS). This is especially true in children presenting under the age of 6. The SRS defined EOS as scoliosis prior to age 10 years regardless of the cause. Regardless of the cause, any proposed treatment should be oriented to allow spinal and thoracic growth to enhance pulmonary capacity during the crucial initial years of life.

Respiratory function impairment

Untreated EOS may lead to respiratory failure with double the mortality rate compared to the general population. Increasing spinal deformity is directly correlated with decreased vital capacity, especially in curves greater than 70° and onset of curvature

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KEY POINTS

- The primary and most important goal of treatment should be to promote rib cage expansion and lung development.
- Repeated anesthesia in young children may cause permanent deleterious effect, especially in children younger than 3 years.
- Traditional growing rods are still the most predictable surgical technique for the management of EOS.
- Promising results may be expected for ongoing studies testing the efficacy and safety of bracing for the treatment of infantile scoliosis.

before 6 years. When left untreated or inappropriately treated, EOS can lead to TIS [3▪].

The source of the respiratory failure is a consequence of two different pathologic pathways, intrinsic alveolar hypoplasia and extrinsic disturbance of chest wall function.

Intrinsic alveolar hypoplasia

Alveolar hyperplasia is the primary contributor to lung growth until the age of 8 years, at which point hypertrophy becomes dominant, augmenting volume until maturity. The expansion of lung volume until age 5 years is propelled by a rapid increase in peripheral airway conductance concurrent with airway enlargement. Subsequently, hypertrophy coincides with the enlargement of thoracic circumference from age 10 years until maturity, culminating in a twofold rise in thoracic volume.

When a child has not grown to an average height by the age of 5 years, there is a high likelihood of developing TIS. That is why the 5 first years of life have been considered 'The Golden Period'. The thoracic spine length increases by 50% (from 12 to 18 cm) from birth to 5 years of age, up to 60% of adult spine length during the initial 5 years. In conjunction with direct spinal elongation, the thoracic circumference doubles in magnitude after age 10 years. Therefore, it is essential to facilitate alveolar hypertrophy and hyperplasia with a normal thoracic circumferential and length growth during these critical periods of thoracic expansion.

Extrinsic disturbance of chest wall function

External disruption of respiratory function arises from deformities in the ribs and/or chest wall, leading to reduced compliance or impaired function. Rib fusions lead to reduced compliance, where natural chest wall movements are constrained. In cases of rib absence that result in a localized flail or paradoxical chest wall segment, function is even more impaired. In patients suffering from neuromuscular conditions such as static encephalopathy, muscular dystrophy, muscle atrophy, spina bifida, or spinal cord injury, muscular impairment may exacerbate chest wall dysfunction [3▪].

Vital capacity is diminished in patients with congenital scoliosis as compared to those with idiopathic scoliosis having equivalent curve magnitudes. This reduction is likely attributable to coexisting rib anomalies that exacerbate chest wall dysfunction. In non congenital deformities, scoliosis-induced rib deformities contribute to inefficient respiration. The intercostal spaces on the concave hemithorax become constricted, impede expansion, and cause a restrictive state. Simultaneously, the convex hemithorax displays widened intercostal spaces incapable of generating normal expiratory force. Interestingly, a recent study in pig model was able to replicate the common clinical features of EOS such as rib fusion, asymmetric thoracic cage, increased cobb angle,

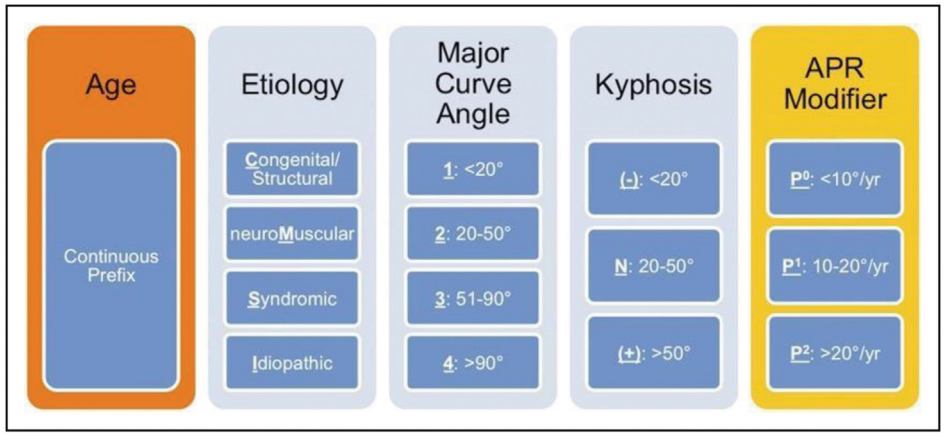

FIGURE 1. The classification of early-onset scoliosis (C-EOS). APR, annual progression ratio.

decreased TLV, and pulmonary hypoplasia and described transcriptomic changes in the EOS model that may cause pulmonary hypoplasia [4].

Thoracic volume hinges on the length of the T1-12 segment. Coupled with the coronal width and sagittal depth, it contributes to the rib cage volume. The potentially life-threatening scenario arises from the conjunction of progressive deformity without accompanying growth. Consequently, the primary objective of management should involve controlling spinal deformity without hampering thoracic growth to forestall the development of thoracic insufficiency. Additionally, advances in the understanding of cause and pathophysiology have allowed for the discovery of effective medical treatments to prevent curve progression in certain conditions. This is well illustrated by patients with Duchenne muscular dystrophy whoused to be treated surgically when curves were as small as 20°. Now with long-term use of glucocorticoids, there is a substantially decreased need for spinal surgery for scoliosis correction in patients with Duchenne muscular dystrophy.

TREATMENT

As stated above, the main goal of EOS treatment should be to optimize spine and thoracic cage growth, while halting curve progression. Additionally, to minimize the extent of any potential definitive spinal fusion, maximizing motion of chest and spine should be considered. Rib phase and rib-vertebral angle difference are the most important predictors for curve progression in young children (Figs. 2 and 3). Metha estimates that in infants with a rib not covering the apical vertebral edge (phase 1 rib), the scoliosis is likely to be progressive 80% of the time if the RVAD is at least 20°. If the rib head overlaps the vertebral edge (phase 2 rib), the curve will progress regardless of the RVAD [5]. Curve pattern (primary thoracic curve), Cobb angle at onset of puberty, and curve progression velocity are also considered predictive factors of curve progression. In curves associated with tethered spinal cord, early detethering has been suggested to reduce the scoliosis progression rate [6]. Infantile curves that reach 30° tend to continue to worsen without treatment. AlNouri *et al.* [7▪▪] described a new progression risk score based on the classic categories (age, curve type, curve magnitude, and cause). While this work focuses on conservative and surgical management of the spinal deformity, it is essential to understand the importance of multidisciplinary treatment of these children frequently affected by associated conditions and comorbidities.

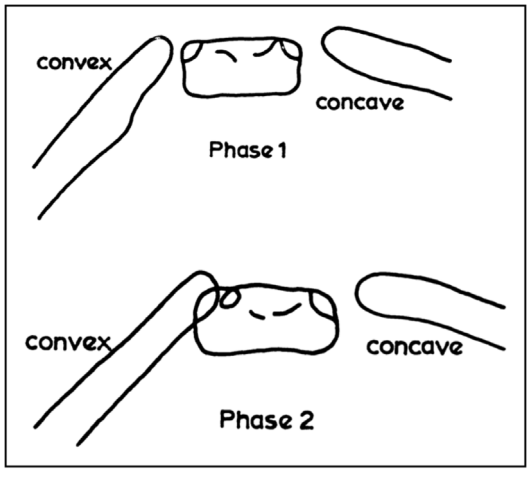

FIGURE 2. Rib phases according to Metha.

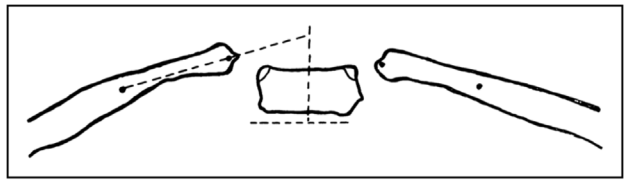

FIGURE 3. Rib-vertebra angle.

Observation

Because spontaneous correction might be expected in some infants with scoliosis (18–92%), observation is usually the first method of treatment for a young child with a spinal deformity. If curve progression is documented during follow up or the curve magnitude exceeds 30°–40° at presentation, therapeutic intervention should be considered.

Bracing

Casting has been considered a more effective method in infants and younger children than bracing because it provides a continuous corrective force. Bracing therapy is usually reserved for older children who no longer tolerate casting or when casting is contraindicated for medical reasons. However, there is growing interest in brace treatment as a primary option as it is more convenient than casting. It can be removed as desired and most often does not require general anesthesia. Sauvagnac and Rigo [8] reported 80% success of treatment with the 3D correction brace in patients under 5 years. As stated by the authors, these conclusions are consistent with findings from similar studies in other centers [8]. Some groups are currently working on randomized studies comparing casting versus bracing for EOS [9].

Casting

The Mehta casting is based on the Cotrel elongation, derotation, and flexion technique. It is technically demanding and requires the appropriate equipment. A recent technique has been described for Mehta casting on a Jackson table to avoid the need of any special equipment [10].

Infantile idiopathic scoliosis treated with serial casting before the age of two years may achieve complete correction and scoliosis resolution. Regan *et al.* [11] evaluated the efficacy of casting in children with an average age of 2.3 (0.8–5.4) years with idiopathic and nonidiopathic EOS. They reported successful treatment defined by a curve magnitude less than 20° in 62% of the children treated at 5-year follow up. This work also emphasizes the importance of follow up until skeletal maturity, as some patients who initially corrected, progressed in adolescence. In a multicenter, retrospective study, Fedorak *et al.* [12] found that children who underwent casting prior to 18 months of age were more likely to have a major curve of less than 15° at a minimum 2-year follow-up after casting. Glotzbecker *et al.* found similar results [13]. While recognizing the importance of early detection and treatment, other authors have highlighted the risk of over treatment, arising the doubt of how many of these patients could have experienced spontaneous resolution without any treatment [14]. There is also a rising concern about risks related with repetitive anesthesia events in young children. A recent study summarizes the risks of general anesthesia on children, emphasizing the problems related to repeated anesthesia events at early ages. They conclude that there is no impact after short and single exposure, uncertainty for duration more than 1 h and probable deleterious neurocognitive effects for repetitive exposures. Thus, treatment plans including repetitive anesthesia events should be carefully evaluated [15▪▪].

Nonidiopathic scoliosis is not a contraindication for casting, as it may reduce progression rate during early years of life. Ulusalugu *et al.* [16] concluded that serial casting can delay surgical correction in children younger than 7 years with a diagnosis of skeletal dysplasia and allows longitudinal growth of the spine with possible expansion of lung volume for a period up to 3 years. Johnson *et al.* [17] studied weight gain in a retrospective review of 32 patients younger than 6 years treated with serial casting. They found that the majority of patients increased their weight percentile during treatment. Patients with and without g-tubes were able to maintain or gain weight during casting treatment. They did not find a greater risk of cast or g-tube-related complications inf patients with gastrostomy tube [17].

Despite the benefit provided by serial casting for the treatment of (EOS), there is concern about significant morbidity and caregiver burden. Sleem has recently reported not only clinical, but alsoradiologographic improvement after serial casting in patients with EOS. They also found improvement in the quality of life of the patients and their families as measured by the EOSQ-24. Henstenburg *et al.* [18], however, found in their study that patients treated with casting for EOS experience reversible declines in HRQoL. After patients transition from casting to bracing, EOSQ scores recovered to pretreatment baseline levels and were maintained at last follow-up [18], which suggests better tolerance of bracing over casting.

Traditional growing rods

Among all the described nonfusion surgical techniques, traditional growing rods (TGRs) are still the most widely accepted and used. Usually between three and six lengthenings are needed and can be spaced between 3 to more than 12 months [19]. The surgical technique has been widely described in the literature [20] with different variations depending on patient characteristics and surgeon's experience and preferences [21]. Zhao *et al.* [22] proposed an alternative method with a TGR in conjunction to apical derotation screws on the apex of the convexity. On a case match analysis, they found comparable spinal heights and better curve reduction at 2-year follow up. Wang *et al.* [23] described a more aggressive technique including apex vertebrectomy/hemivertebrectomy with similar results. It has been reported that the use of single TGR as the only therapeutic modality is associated with important complications and should be avoided whenever an alternative is feasible [24]. However, Hai *et al.* [25] reported similar outcomes using a single rod technique with distal foundation augmentation compared to classic dual rod technique.

TGR technique allows spinal lengthening and spinal deformity correction which provide the conditions that make improving pulmonary function possible in patients with EOS with severe deformities [26], but is not exempt of complications. Most commonly, complications are related to spontaneous fusion, surgical site problems, or mechanical failure (proximal junctional kyphosis, implant loosening/pullout, metal debris). Preoperative global kyphosis more than 50°, preoperative junctional proximal angle, postoperative proximal junctional angle more than 10°, large correction of sagittal alignment, unmatched proximal rod contouring, upper instrumented vertebra (UIV) close to the sagittal apex, and younger age have been associated

with higher risk for developing proximal junctional kyphosis (PJK) after TGR treatment [27–29]. Lower instrumented vertebra selection follows similar principles than fusion surgery in older children, depending on the etiology (idiopathic, neuromuscular, syndromic).

Magnetically controlled growing rods

Magnetically controlled growing rods (MCGRs) were initially designed to minimize problems associated with TGR. MCGR allow for noninvasive lengthening in the office setting, reducing the number of planned surgical interventions by avoiding repeated open lengthening procedures, thus decreasing the rate wound complications, surgical site infections and the number of anesthesia events. However, unexpected problems arose with the use MCGR. Tissue metallosis has been found in most patients treated with this technique [30,31], although the clinical significance of this finding is unclear. Unplanned return to operating room ratio and mechanical complication rates are higher in than in patients treated with TGR, most commonly due to the proximal rod pull-out. Shaw *et al.* [32] found that only 50% of MCGR continue to successfully lengthen 2 years postimplantation, dropping to less than 20% at 4 years. In addition, TGR provide better correction in the coronal and sagittal planes than the MGR system [30,33]. In a retrospective comparative study, Cheung *et al.* [34] concluded that from index surgery to maturity, TGR demonstrated better patient satisfaction with treatment and comparable overall HRQoL than MCGR during the treatment course. Both groups had similar accumulative total direct medical costs. For patients with cerebral palsy, Sun *et al.* [35] found no difference in the risk of unplanned return to operating room for children treated with TGR or with MCGR in a series of 120 patients. Saarinen *et al.* [36] concluded, in a recent retrospective review, that MCGR for severe EOS provided significantly better major curve correction with fewer unplanned revisions than TGR at a 2-year follow-up.

Vertical expandable prosthetic titanium rib

Vertical expandable prosthetic titanium rib (VEPTR) was designed to treat spinal and chest wall deformity with the aim of promoting normal thoracic development and improving pulmonary function in young children. A recent meta-analysis has shown that VEPTR was inferior in comparison to other correction techniques in terms of Cobb angle andT1-S1 height rates at all time points. Additionally, at final follow-up, VEPTR was associated with an important complication rate [37▪]. VEPTR is associated with higher complication rate compared to TGR including infection, implant failure, and pneumothorax [38]. However, this technique has some peculiarities that make it a valid alternative in selected cases. Namely, it is a versatile technique that allows different anchor combinations (rib to rib, rib to vertebra, rib to pelvis). As originally described by Campbell, VEPTR is still believed to be an acceptable option for patients with TIS.

Shilla technique

Shilla technique is a guided growth system consisting of dual rods with pedicle screws to the curve's apex with proximal and distal gliding screws placed with minimal subperiosteal dissection to avoid spontaneous fusion. It uses passive growth guidance to correct the deformity and does not necessitate planned surgeries. Kim *et al.* [37▪] found that Shilla obtained better initial coronal correction with similar correction rates than TGR and MCGR at final follow up. The overall rate of infection was lower for Shilla than VEPTR and TGR. T1-S1 lengthgain was lower than TGR. Interestingly, Balioğlu *et al.* [39] evaluated the effect of complications on spinal growth and deformity correction. They found that the lordosis angle and T1–S1 length were significantly lower in the early and final postoperative controls of those who developed complications compared to those who did not [39].

Luque trolley

This technique is based on the same guided growth principles of the Shilla technique.

It uses sublaminar wires to fix rods segmentally to the spine. However, this technique is not routinely used due to documented spontaneous spinal fusion and implant failures in conjunction with limited ability to allow spinal growth and to correct the spinal deformity. More recently, a new guided growth system has been proposed, but no clear data supporting these new techniques have been published.

Vertebral body tethering

Vertebral body tethering (VBT) is a growth modulation technique currently accepted for selected cases in early adolescent scoliosis. It consists of placing anterior vertebral body screw anchors with a tightened flexible tether between them to preserve motion at the instrumented levels. There are additional advantages. VBT may be performed thoracoscopically as a minimally invasive technique and allows early return to daily life activities such as

sports. It also prevents adjacent disc disease [40,41]. The main disadvantage is that curve behavior after index surgery is less predictable and a has a significant reoperation rate, especially in patients who had surgery when their triradiate cartilage was still open [42]. Mackey *et al.* [41] found that in older idiopathic EOS patients, MCGR, PSF, and VBT effectively controlled curves and increased spinal height.

VBT and PSF showed a lower hazard ratio for an unplanned revision and improved QoL [43]. Silk *et al.* [44] found that preoperative fulcrum bending can predict the initial correction gained with VBT surgery.

Hemivertebrectomy

Hemivertebrectomy with short segmental fusion is a well tolerated and effective method to treat structural kyphoscoliotic deformity caused by a congenital thoracic or thoracolumbar hemivertebra for one or more consecutive levels [22,45]. Haapala *et al.* [46] recently reported better correction with similar improvement in pain, self-image and function than VEPTR. Wang *et al.* [22] suggested similar correction with lower complication rates delaying hemivertebrectomy until the age of 3 years. Lin *et al.* [47] described a trend towards anterior cage implantation and shorter fusions during the last 10 years. Other techniques such as stapling or hemiepiphysiodesis progressively have been losing prominence in favor of posterior hemivertebrectomy. Instrumentation without fusion is a safer procedure with lower correction potential that may be useful in less severe cases.

Halo traction

Large, stiff curves may not benefit from serial casting, as the cast does not reduce the curve and may be a cause of decubitus ulcers. In these scenarios, gradual correction of severe deformities can be achieved in some individuals by means of preoperative halo gravity traction for 6–12 weeks. Halo gravity traction constitutes a safe and efficient method to partially reduce the deformity and, indirectly, improve respiratory mechanics [48,49]. Simon *et al.* [48] analyzed the 3D shape of the thorax in patients treated with preoperative halo traction. Their 3D trunk analysis showed significant postoperative gains in thoracic and spinal lengths as well as in thoracic volume [48].

CONCLUSION

Early-onset scoliosis is a complex condition with immense variation in deformity pattern and severity, impact, and, thus, treatment options. Advances in diagnosis and treatment during the last two decades have made possible a substantial improvement in quality of lie and life expectancy for patients with EOS. Up to now, no surgical technique has proved superior to TGRs and casting is still the most effective nonsurgical treatment. Both conservative and surgical approaches have been evolving towards treatment options that reduce hospital stay, radiation exposure, and anesthesia events, as well as patient and family burden. However, the safety and efficacy of these promising new methods have yet to be determined. Regardless of the treatment choice, the main goal of treatment in a child with EOS should be to preserve and protect pulmonary development and function.

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Conflicts of interest

None.

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- ■■ of outstanding interest

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