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Definitive Posterior Spinal Fusion After Magnetically Controlled Growing Rod Treatment in Early-Onset Scoliosis: A Single-Centre Longitudinal Analysis

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Summary

Abstract

Background

Early-onset scoliosis (EOS) is a complex condition requiring growth-preserving surgical strategies to allow continued spinal and thoracic development. Magnetically controlled growing rods (MCGRs) have become widely adopted for this purpose, as they enable non-invasive lengthening and reduce the number of surgical procedures during growth. While the outcomes of MCGR treatment during the lengthening phase have been extensively investigated, less attention has been devoted to the final stage of treatment, namely definitive posterior spinal fusion. In particular, limited evidence is available regarding radiographic outcomes and surgical strategies adopted at the time of final fusion, including implant density selection.

Methods

This retrospective, single-centre study included ambulatory patients with idiopathic, neuromuscular, or syndromic EOS who completed a full course of MCGR treatment and subsequently underwent definitive posterior spinal fusion. Clinical and radiographic data were collected at predefined time points covering the entire treatment pathway, from pre-MCGR implantation to the last available follow-up after final fusion. Radiographic outcomes in the coronal and sagittal planes, perioperative variables, and postoperative complications were analysed. To evaluate the influence of implant density at final fusion, patients were stratified into low-density and high-density groups based on a cohort-derived threshold. Non-parametric statistical methods were used.

Results

Definitive posterior spinal fusion provided additional correction of spinal deformity in both the coronal and sagittal planes, with maintenance of alignment at mid-term follow-up. Postoperative morbidity following final fusion was acceptable, despite the relatively high complication rate observed during the MCGR lengthening phase. Comparative analysis between low-density and high-density constructs did not demonstrate a significant advantage of higher implant density in terms of long-term radiographic outcomes. Lower-density constructs achieved comparable deformity correction without an increase in postoperative complications.

Conclusions

Definitive posterior spinal fusion represents a safe and effective final step in the treatment of early-onset scoliosis following MCGR therapy. The findings of this study suggest that in this cohort, lower implant density at final fusion was not associated with inferior mid-term radiographic outcomes. However, given the exploratory nature of the analysis and limited statistical power, these findings should be interpreted with caution and require confirmation in larger prospective studies. These results support a tailored, biomechanically informed approach to implant density selection and provide a basis for future prospective studies in this field.

INTRODUCTION

Scoliosis, derived from the Greek word skolios meaning “not straight,” refers to a spinal deformity marked by abnormal curvature in the coronal plane.

The understanding of scoliosis has expanded beyond the exclusive assessment of radiographic images. Scoliosis is now widely recognised as a three-dimensional deformity, involving coronal-plane deviation, alterations in the sagittal profile, and changes in rib-cage morphology. Classification is typically based on age at diagnosis: early-onset scoliosis (EOS), adolescent scoliosis, or adult scoliosis.

EOS includes various spinal deformities diagnosed before age 10 [1] and it may be present at birth or develop during growth [2]. Severe deformities in early childhood can disrupt spinal development, leading to significant morbidity and, in extreme cases, premature mortality [3].

The causes of EOS are broadly categorized as congenital, neuromuscular, syndromic, or idiopathic, and are often associated with additional comorbidities [4].

Conservative management of EOS may involve serial casting or bracing, depending on curve characteristics and age at onset, to limit deformity progression during growth. However, these methods are often insufficient for severe or progressive cases.

Historically, EOS was treated with early spinal fusion. However, premature fusion restricts spinal and thoracic growth, negatively impacting pulmonary and cardiopulmonary development. As a result, early definitive fusion is no longer considered optimal for young children with progressive scoliosis. New surgical techniques aim to control deformity while preserving spinal and thoracic growth. Growth-friendly strategies guide, rather than halt, spinal growth, allowing continued thoracic and lung development.

Traditional growing rod (TGR) systems were a significant advancement in EOS management. However, they require repeated surgical lengthening, exposing patients to multiple anaesthetic events and increasing the risk of wound complications, infections, and implant failures. Repeated surgeries also negatively affect patients' quality of life and psychosocial well-being [5].

Recent strategies focus on magnetically controlled growing rods (MCGRs) and minimally invasive instrumentation, which have greatly reduced the need for repeated surgical lengthening. MCGR systems allow non-invasive outpatient distractions, minimizing surgical exposure, anaesthesia-related risks, and complications from repeated operations. These advancements improve patient safety and quality of life [6].

1.1 Phases of Growth During Early Childhood

Spinal growth is remarkably rapid during the first five years of life, with an average increase of approximately two centimetres per year [7]. Thereafter, spinal growth slows to roughly one centimetre per year until around the age of ten. A second phase of accelerated growth occurs during puberty, a period during which adolescent scoliosis may develop. Overall, spinal height approximately doubles throughout childhood and adolescence.

Lung and alveolar development also progress rapidly during early childhood, with most alveoli forming within the first 2 years of life. It has been hypothesised that restriction of thoracic volume during this critical developmental window may impair normal pulmonary maturation [8]. Early-onset scoliosis can lead to restrictive lung disease due to reduced lung volume, increased thoracic cage stiffness, and abnormal diaphragmatic function.

In EOS, thoracic volume compromise is further exacerbated by a complex three-dimensional deformity involving scoliosis, kyphosis, and lordosis, as well as by associated structural abnormalities such as vertebral rotation, rib hump deformity, and, in some cases, congenital rib fusion.

1.2 Classification

In 1954, James classified pediatric scoliosis by age at onset into infantile (0–3 years), juvenile (4–10 years), and adolescent (11 years onward) [9]. Contemporary classification systems, however, are no longer based solely on age at onset but also take into account the underlying characteristics and behaviour of the deformity.

Early-onset scoliosis represents a heterogeneous population of children with a broad spectrum of diagnoses and associated comorbidities. To better capture this complexity, the Classification of Early-Onset Scoliosis (C-EOS) was developed by Williams and colleagues in 2014. This system incorporates age as a continuous variable, while aetiology, magnitude of the significant curve, and thoracic kyphosis are included as categorical variables. In addition, a progression modifier reflecting the annual rate of curve progression is used to characterise the dynamic behaviour of the deformity over time. The C-EOS classification, therefore, provides a comprehensive framework that integrates both static and progressive aspects of EOS, facilitating clinical decision-making and longitudinal assessment (Table 1).

Age	Etiology	Major curve angle	Kyphosis	Annual progression ratio modified
Continuous variable	Congenital	1: <20°	(-): <20°	P^0: <10° /year
	Neurological	2: 20-50°	N: 20-50°	P^1: 10–20° / year
	Syndromic	3: 51-90°	(+): >50°	P^2: >20° / year
	Idiopathic	4: >90°		

Table 1. C-Eos Classification

1.2.1 Congenital Early-Onset Scoliosis

Congenital scoliosis results from a developmental error that leads to structural anomalies of the vertebrae. These deformities arise from abnormalities in vertebral formation, segmentation, or both.

Formation defects represent the most common cause of congenital scoliosis. Incomplete formation may result in a wedge vertebra, characterised by the presence of both pedicles but asymmetric anterior–posterior development. Complete formation defects result in a hemivertebra, in which only one half of the vertebral body develops. Segmentation defects, on the other hand, may lead to the formation of an unsegmented bar that prevents normal growth on one side of the spine.

Vertebral deformities caused by congenital anomalies can lead to early-onset, rapid progression of scoliosis. Congenital scoliosis associated with hemivertebrae may be treated surgically with hemivertebrectomy, a procedure that involves resecting the malformed vertebral segment to correct the deformity and restore spinal balance.

Congenital scoliosis may also be associated with rib anomalies, including rib fusions or rib absence, which can further compromise thoracic development. In addition, both congenital and syndromic forms of EOS may be associated with obstructive pulmonary disease due to airway compression.

Congenital scoliosis is frequently associated with other developmental anomalies. The VACTERL association represents a constellation of congenital defects that includes vertebral anomalies, anal atresia, congenital heart disease, tracheoesophageal fistula or esophageal atresia, renal and urinary tract anomalies, and radial limb defects [10,11].

1.2.2 Neuromuscular Early-Onset Scoliosis

Neuromuscular disorders may be characterized by either hypertonia or hypotonia and include conditions such as cerebral palsy, myelomeningocele, spinal muscular atrophy, and Charcot–Marie–Tooth disease. Muscle tone asymmetry leads to an imbalance of forces acting on the spine, resulting in increased mechanical loading on one side of the vertebral column. In particular, compressive forces on the vertebral endplates are reduced, while distraction forces are increased.

These asymmetric biomechanical forces can contribute to the development of scoliosis, which typically progresses during growth. The deformity pattern associated with neuromuscular scoliosis is characteristic and often consists of a long, sweeping curve extending from the sacrum to the thoracic spine. Neuromuscular conditions may also be associated with pelvic obliquity, which can generate a compensatory scoliotic curve.

Severe scoliosis in non-ambulatory patients may significantly impair quality of life, increasing the risk of pressure sores, difficulties in maintaining a stable sitting position, and complications in daily care and management by caregivers and family members [12].

1.2.3 Syndromic Early-Onset Scoliosis

Several developmental disorders, including Marfan syndrome, Down syndrome, Ehlers–Danlos syndrome, and osteogenesis imperfecta, are associated with early-onset scoliosis [13]. Although these syndromes are uncommon, the prevalence of scoliosis is higher among affected individuals compared to the non-syndromic population.

Genetic syndromes are often accompanied by multiple systemic comorbidities, which may influence surgical decision-making as well as postoperative outcomes. Marfan syndrome represents one of the most common causes of syndromic EOS, with approximately 60% of affected patients developing scoliosis during growth. In contrast, between 7% and 50% of children with Down syndrome develop scoliosis during childhood.

Regarding Ehlers–Danlos syndrome and osteogenesis imperfecta, the reported incidence of scoliosis ranges from approximately 23% to 52% and around 50%, respectively [14,15]. The presence of connective tissue fragility, alterations in bone quality, and multisystem involvement in these syndromes poses additional challenges in the management of early-onset spinal deformities.

1.2.4 Idiopathic Early-Onset Scoliosis

Idiopathic scoliosis refers to a scoliotic deformity in which no specific underlying aetiology is identified. Idiopathic early-onset scoliosis is traditionally divided into infantile and juvenile forms. Infantile idiopathic scoliosis is defined as scoliosis with onset before the age of three years, whereas juvenile idiopathic scoliosis refers to deformities developing between three and ten years of age.

Moderate infantile idiopathic scoliosis associated with plagiocephaly has been shown to tend towards spontaneous resolution. According to Mehta and colleagues, infantile idiopathic scoliosis may also resolve with conservative management, particularly in cases identified early and closely monitored during growth [12,16].

1.3 Conservative Treatment

Initial conservative management with serial casting or bracing is commonly employed to correct mild deformities and, most importantly, to delay surgical intervention as long as possible. Surgical treatment in patients younger than four years of age is associated with a significantly increased risk of complications related both to the surgical procedure itself and to postoperative management. Consequently, delaying surgery through conservative treatment strategies reduces complication rates and helps prevent excessive progression of the spinal deformity.

In cases of infantile idiopathic scoliosis, conservative treatment has been shown not only to control progression but, in selected cases, to result in complete resolution of the deformity. Sanders and colleagues reported favourable outcomes in patients with infantile idiopathic scoliosis treated with serial casting when the major curve magnitude was less than 60° [17]. Similarly, Mehta described a series of patients treated with serial casting in whom early intervention, with a mean curve magnitude of 32°, led to resolution of scoliosis without the need for subsequent surgical treatment during follow-up [18].

In contrast, patients presenting with more severe curves (>52°) or those older than two years at the time of diagnosis generally continued to exhibit scoliosis progression. Nevertheless, conservative treatment in these cases was effective in delaying surgical intervention, in some instances until approximately 12 years of age.

1.4 Surgical Treatment with Growth-Friendly Instrumentation

According to current literature, surgical treatment is indicated for severe early-onset scoliosis, typically defined by curves exceeding 45-50°, or for progressive deformities that fail to respond adequately to conservative management. The rib–vertebral angle difference (RVAD) may be used to assess progression risk; values greater than 20° are associated with a high likelihood of progression.

Growth-friendly surgical techniques can be broadly categorised into distraction-based, guided-growth, and compression-based systems. Distraction-based systems aim to stimulate spinal growth by applying longitudinal distraction forces. Early distraction devices required repeated surgical lengthening procedures, exposing patients to multiple anaesthetic events and surgical risks. To overcome these limitations, newer growth-friendly implants capable of non-invasive lengthening have been developed, including MCGRs.

Guided-growth systems rely on a passive mechanism of spinal elongation without the application of distraction forces and do not require repeated surgical procedures. Compression-based systems, in contrast, apply compressive forces to the convex side of the deformity, aiming to correct the curve by modulating asymmetric growth [19–21].

1.4.1 Traditional Growing Rods (TGRs)

Harrington first described growing rod instrumentation for early-onset scoliosis in the 1960s. Akbarnia et al. later introduced the modern dual-rod construct, now considered the gold standard for distraction-based treatment of EOS [21]. Single-rod constructs are still used in selected cases, particularly for patients with complex spinal anatomy.

Most deformity correction occurs during the initial surgery. TGRs require surgical lengthening about every six-nine months, performed through a limited incision to access the distraction mechanism. After the growth phase, a definitive posterior spinal fusion is often performed to further correct and stabilize the deformity. An example of TGRs is reported in Figure 1.

Definitive fusion after TGR treatment carries inherent risks. About 20% of cases require additional surgery due to complications. The dual-rod technique is limited by higher rates of complications and infections.

Bess and colleagues reported that at least one complication occurred in 58% of patients treated with dual growing rods. The risk of complications rises with each procedure, with an estimated 24% additional risk per lengthening. Deep surgical site infection rates approach 50% after eight lengthenings. This risk is higher in non-ambulatory patients, those undergoing revision surgery, and patients with stainless steel implants. Delaying the initial surgery reduces complication risk by about 13% for each year of delay.

Mechanical complications of TGRs include rod fracture and implant failure, such as anchor pull-out. Continuous distraction forces may also cause unintended spontaneous autofusion, which can limit spinal growth and reduce deformity correction potential [2,5,22].

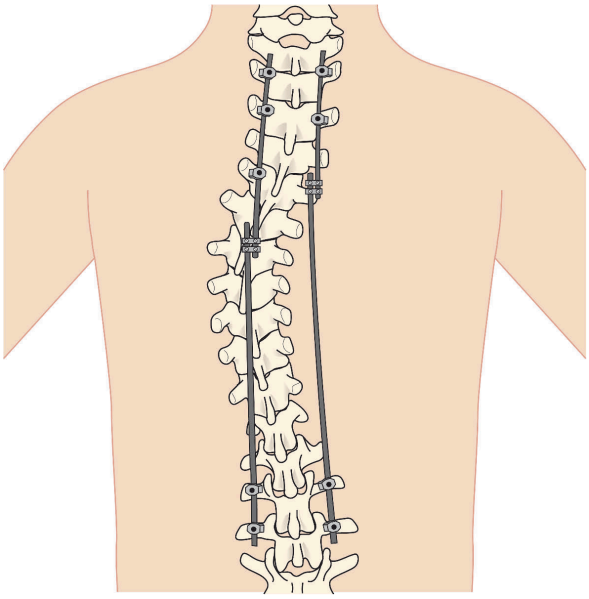


Figure 1. Traditional growing rods

1.4.3 Magnetically Controlled Growing Rods

To overcome the need for repeated surgical procedures associated with TGRs, MCGRs were developed (Figure 2). MCGRs are implanted using surgical techniques similar to those employed for TGRs. Both single-rod and dual-rod constructs can be used; however, dual-rod constructs are generally considered preferable due to improved mechanical stability.

Rod lengthening is achieved using an external magnetic device, typically at intervals of three to four months, thereby mimicking the physiological growth pattern of the spine. Lengthening procedures do not require anaesthesia and are performed in an outpatient setting, providing painless, minimally disruptive treatment.

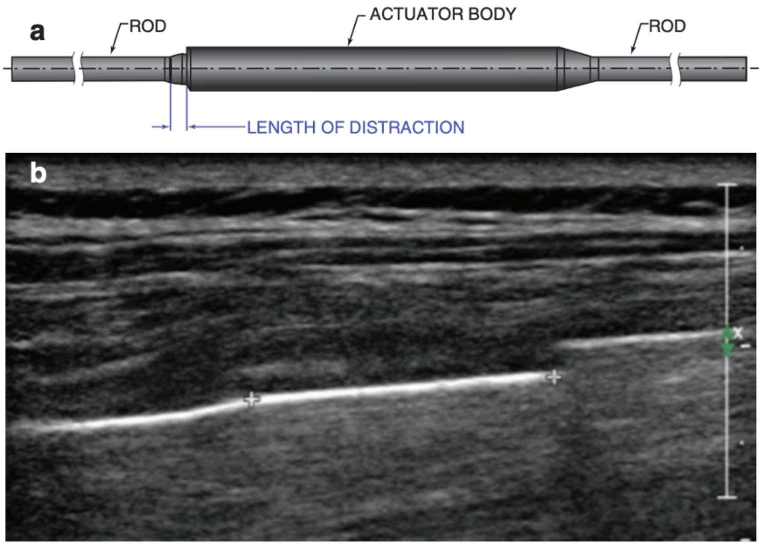


Figure 2. Representation of the MGR and the distractible segment (a). Ultrasonographic image showing measurement of the distractible segment after an outpatient lengthening procedure (b).

The first generation of MCGRs was constrained by mechanical limitations, which frequently led to complications such as loss of distraction. These issues have primarily been addressed with the introduction of second-generation magnetic rods. The reduction in the number of surgical procedures associated with MCGR treatment has been shown to decrease infection rates significantly.

Nevertheless, MCGR devices are relatively bulky and therefore may not be suitable for very small patients. In addition, metallosis has been identified in explanted MCGRs, although the long-term clinical implications of this finding remain unclear. Moreover, the autofusion process could limit the efficacy of the MCGRs system over the years.

Clinical outcomes following MCGR treatment have demonstrated satisfactory deformity correction. Akbarnia et al. reported comparable rates of deformity correction, thoracic growth, and complications between patients treated with MCGRs and those treated with TGRs. The primary advantage of MCGRs lies in the substantial reduction in the number of surgical interventions, which in turn is associated with a lower incidence of surgical site infections.

Although the initial cost of MCGRs is higher, this expense is offset over time by a significant reduction in cumulative hospital costs during the growth period. However, MCGRs may not be suitable for patients requiring repeated magnetic resonance imaging or those with implanted cardiac pacemakers. In such cases, TGRs remain the preferred treatment option [23–25]. An example of MGCRs is reported in Figure 3.

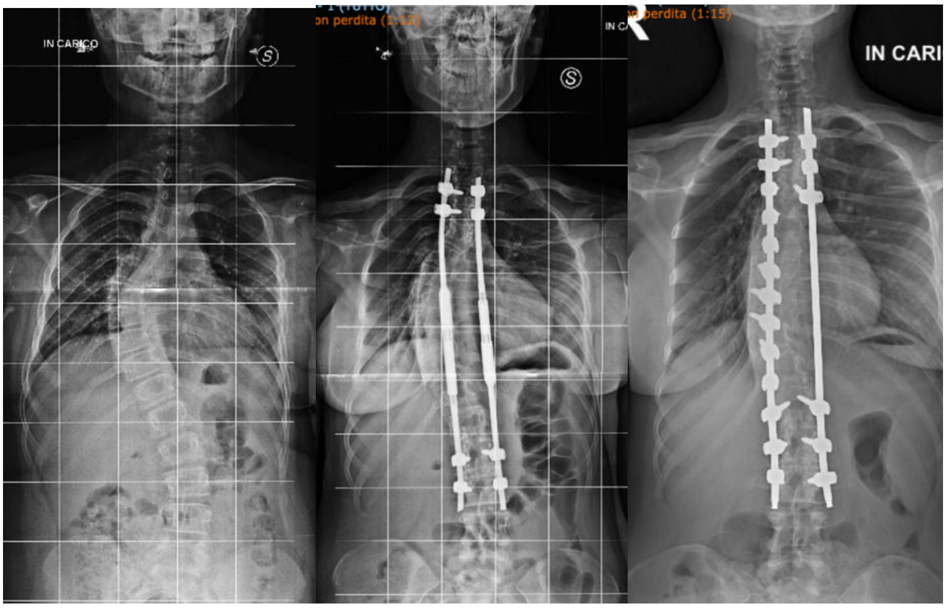


Figure 3. Magnetically Controlled Growing Rods and final implant

1.5 Quality of Life and Psychological Impact

Chronic diseases during childhood have a profound impact on the quality of life of both patients and their families. EOS is associated with a high prevalence of anxiety and depressive symptoms, affecting not only affected children but also their parents. Repeated surgical interventions further increase the psychological burden experienced by patients and caregivers.

Interestingly, correction of the spinal deformity itself does not appear to be the primary determinant of health-related quality of life (HRQoL). An extensive study involving 610 patients with EOS demonstrated that disease aetiology represents the main factor influencing HRQoL outcomes. In particular, patients with neuromuscular or syndromic EOS had significantly lower HRQoL scores.

Several health-related outcome measures have been developed to assess quality of life in patients with EOS. These findings indicate that early-onset scoliosis represents a condition with significant physical and psychological implications. Identifying minimally invasive treatment strategies that minimise the number of surgical procedures is therefore essential to improve the overall quality of life of both affected children and their families.

1.6 Rationale and Objectives of the Study

Over the past two decades, growth-friendly surgical techniques have deeply changed the management of EOS, allowing continued spinal and thoracic growth while mitigating the detrimental effects of early definitive fusion. Among these strategies, MCGRs have gained widespread adoption due to their ability to reduce the number of surgical procedures and anaesthesia exposures during the growth phase.

As a result, most published studies on MCGR treatment have focused on outcomes during the lengthening period, including curve control, spinal growth, and device-related complications. In contrast, comparatively a few attention has been devoted to the final stage of treatment. This represents a significant gap in the literature, as definitive fusion constitutes the final step in the growth-friendly treatment pathway and ultimately determines long-term spinal alignment, stability, and clinical outcomes.

In particular, data regarding radiographic correction, restoration of coronal and sagittal balance, and complication rates following definitive fusion in patients previously treated with MCGRs remain limited and heterogeneous. Moreover, surgical strategies adopted at the time of final fusion, such as implant configuration and pedicle screw density, vary widely among surgeons and institutions. While implant density has been extensively investigated in AIS, its role in definitive fusion following MCGR treatment has not been adequately explored, despite the unique biomechanical and biological challenges posed by prior lengthening procedures, autofusion phenomena, and altered spinal anatomy.

Most available studies investigating outcomes after graduation surgery following MCGR treatment are retrospective and report that definitive posterior spinal fusion can achieve additional deformity correction but remains associated with a substantial complication and reoperation burden. Reported postoperative complication rates commonly range from approximately 20% to over 40%, particularly in multicenter and heterogeneous cohorts.

Alternative strategies, including rod retention in situ or simple implant removal without arthrodesis, have been explored in selected cases to avoid further major surgery. However, longer-term follow-up has demonstrated progressive loss of correction and higher revision rates in these patients, supporting definitive fusion as the more durable strategy.

Importantly, there is currently a lack of high-level evidence guiding technical decisions at the time of graduation surgery, including implant configuration and pedicle screw density. No published study to date is adequately powered to demonstrate equivalence or non-inferiority between different construct strategies. As a result, existing evidence remains largely exploratory and insufficient to provide prescriptive recommendations for clinical practice

This thesis examines outcomes following definitive posterior spinal fusion (also named as “graduation surgery”) in patients with EOS previously treated with MCGRs. It evaluates the impact of final fusion on spinal alignment in the coronal and sagittal planes, as well as perioperative and postoperative complication rates. The study also compares high- and low-density implant constructs at definitive fusion, assessing radiographic correction, surgical burden, complication rates, and construct characteristics.

MATERIALS AND METHODS

2.1 Study Population

This retrospective study consecutively enrolled ambulatory pediatric patients diagnosed with idiopathic, neuromuscular, or syndromic EOS. All participants underwent treatment with the MCGR system (MAGEC®, Magnetic Expansion Control; NuVasive Specialised Orthopaedics, San Diego, CA, USA) according to a predetermined management protocol, followed by elective definitive posterior spinal fusion. The study was conducted at a single high-volume pediatric spine center from January 2017 to September 2024.

The initial MAGEC® device implantation within this cohort occurred in July 2011. Throughout the growth modulation phase, patients adhered to a standardized protocol involving non-invasive distraction every three months. Inclusion criteria specified exclusive use of the MAGEC® system during the entire lengthening period, without alternative distraction methods. Prior to definitive spinal fusion, all patients underwent comprehensive pulmonary and cardiovascular assessments and obtained formal medical clearance for surgery.

Exclusion criteria were applied apriori according to the different phases of treatment. During the lengthening period, patients were excluded if definitive rod explantation occurred before completion of the planned lengthening program or if a distraction system other than MCGR was used. With respect to the definitive fusion phase, exclusion criteria included:

- Non-walking patients
- Congenital EOS
- Failure to undergo final fusion after completion of the lengthening program
- Use of hybrid constructs at the time of definitive fusion (defined as instrumentation combining pedicle screws with hooks and/or sublaminar or universal clamps)

2.2 Study Design

This was a retrospective, single-centre observational study designed to evaluate radiographic and surgical outcomes following definitive posterior spinal fusion in patients with EOS who had previously undergone MCGR distraction systems.

The study used a longitudinal design, with clinical and radiographic assessments performed at multiple predefined time points spanning the entire treatment pathway. Evaluations were conducted before MCGR implantation (t1), after MCGR implantation (t2), at completion of the lengthening program and prior to definitive fusion (t3), at hospital discharge following posterior spinal arthrodesis (t4), and at the last available follow-up after definitive fusion (t5).

A minimum follow-up duration of two years after final fusion was required for inclusion in the final analysis.

Within this longitudinal framework, different analytical approaches were applied according to the specific study objectives:

- The impact of definitive posterior spinal fusion on residual spinal deformity, sagittal and coronal balance, and fusion-related complications was assessed by comparing outcomes before and after final arthrodesis.
- A comparative analysis was performed within the same cohort to evaluate the influence of posterior implant density at the time of definitive fusion. For this purpose, patients were stratified into a

High Density (HD) group and a Low Density (LD) group based on screw density.

The choice of implant density was determined by the surgeon based on clinical judgment and surgical experience, taking into account multiple patient- and surgery-related factors, including ambulatory status, bone quality, pedicle morphology and integrity, spinal rigidity, and duration of prior distraction treatment. These factors were considered to optimise construct stability while limiting surgical invasiveness and reducing the risk of complications.

Clinical evaluations and radiographic measurements were performed using standardised biplanar radiographs.

2.3 Surgical Procedure

All definitive posterior spinal fusion procedures were performed by the same experienced pediatric spine surgical team. Patients were placed prone on a radiolucent carbon operating table under general anaesthesia. Continuous intraoperative neurophysiological monitoring, including motor-evoked potentials (MEPs) and somatosensory-evoked potentials (SSEPs), was used throughout to ensure spinal cord integrity.

A midline posterior incision was made along the previous surgical scar, and the posterior spinal elements were exposed by subperiosteal dissection of the paraspinal musculature. The MCGR system and any previously used hybrid fixation devices, such as hooks or universal clamps, were fully removed. If the original MCGR construct included pedicle screws, these were either retained or replaced with larger screws based on preoperative assessment of fixation quality and bone stock.

Polyaxial pedicle screws were inserted into the remaining intact vertebrae using a free-hand technique, as allowed by anatomical constraints from prior surgeries and by physiological autofusion commonly seen after prolonged growing rod treatment. If intraoperative spinal stiffness was encountered, Smith Petersen osteotomies were performed at the apex of the deformity to increase segmental flexibility and facilitate correction.

Pedicle screw positioning was verified with fluoroscopy before connecting two 6 mm cobalt–chromium rods. Corrective maneuvers included rod derotation, in situ bending, and segmental correction techniques such as compression and distraction, as determined by the surgeon. Local autograft bone from the spinous processes was used to promote posterior spinal fusion.

Immediate postoperative anteroposterior and lateral radiographs were obtained to confirm construct positioning. Patients were monitored in the intensive care unit on the first postoperative day and, if clinically stable, transferred to the orthopaedic ward for continued recovery.

2.4 MAGEC System and Rod Lengthening Protocol

The MAGEC system (Figure 4) consists of one or two sterile titanium rods with an internal magnet in the actuator, enabling non-invasive postoperative lengthening. Rods are available in two diameters (4.5 mm and 5.5 mm), and diameter selection was based on patient age and body weight. The choice between single-rod and dual-rod constructs was left to the operating surgeon's discretion, based on curve characteristics, patient size, and intraoperative considerations.

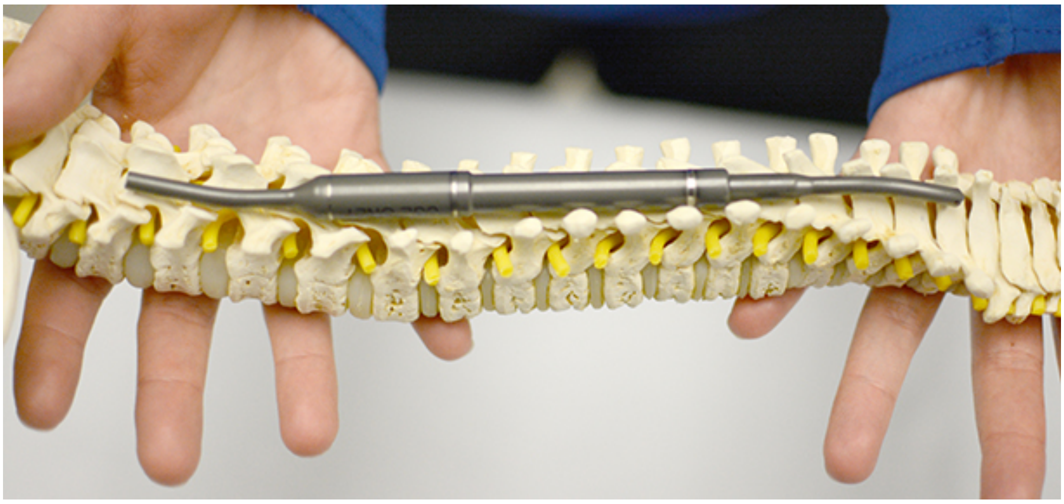


Figure 4. MAGEC magnetic growing rod on a model

Rod lengthening procedures were performed in the outpatient setting every four months using an External Remote Controller (ERC), with a target distraction of 5 mm per rod at each session. Several patient positions can be adopted during lengthening procedures (prone, seated, lateral decubitus, or held by a parent). In the present study, all patients were positioned prone during each lengthening session.

The actuator site was first localised and marked using a dedicated external magnet. The ERC (Figure 5) was then positioned over the actuator, and the planned distraction was applied to each rod. At the end of the procedure, an ultrasound examination was systematically performed to confirm the achieved lengthening and to assess the distractible segment. All lengthening procedures were well tolerated and performed without pain or discomfort for the patient.

Figure 5. MAGEC External Remote Controller (ERC)

2.5 Outcomes

The outcomes of this study were defined apriori according to the two main analytical objectives.

The primary objective was to assess the impact of definitive posterior spinal fusion following completion of MCGR treatment on spinal alignment and deformity correction. Primary radiographic outcomes included coronal plane parameters and sagittal plane parameters. These parameters were evaluated in the early postoperative period and at final follow-up and compared with pre-fusion values.

The secondary objective was to evaluate the influence of implant density during definitive fusion. For this purpose, outcomes were compared between patients treated with HD and LD posterior constructs.

Secondary outcomes for both analytical objectives included major postoperative complications, operative time, intraoperative blood loss, and length of hospital stay.

2.6 Study Variables and Outcome Measures

Patient medical records were retrospectively reviewed to collect demographic, clinical, surgical, radiographic, and instrumentation-related data. Information regarding the MCGR lengthening program and the definitive fusion procedure was also extracted from institutional records. All variables were defined and measured according to standardised and previously validated parameters. The list of clinical and radiographical variables is reported in Table 2.

2.6.1 Demographic and Clinical Variables

Collected demographic and baseline clinical variables included sex, age at final fusion, body mass index (BMI), scoliosis aetiology, curve characteristics, main curve convexity, lumbar modifier, and duration of follow-up. Follow-up was calculated both from MCGR implantation to final fusion and from final fusion to the last available follow-up.

2.6.2 Radiographic Variables

Radiographic evaluation included measurement of the main coronal curve using the Cobb method and calculation of the percentage of curve correction. Coronal, shoulder and pelvic balance were assessed. Sagittal alignment parameters included sagittal vertical axis (SVA), cervical lordosis (C2–C7), thoracic kyphosis (T5–T12), lumbar lordosis (L1–S1), and sacral slope. Spinal growth and length were assessed by measuring T1–T12 and T1–S1 distances. All radiographic parameters were recorded preoperatively, in the early postoperative period, and at final follow-up. The calculation methods for the angles and the radiographic data are reported in Table 2.

Surgical variables included upper and lower instrumented vertebrae (UIV and LIV), number of fused levels, operative time, estimated blood loss, postoperative haemoglobin variation, and length of hospital stay. Instrumentation-related variables included the total number of pedicle screws used and implant density. All radiographic measurements were performed by a single evaluator to ensure internal consistency. Measurements were conducted according to standardized and widely accepted radiographic protocols. Interobserver reliability was not formally assessed due to the doctoral nature of the study.

Table 2. Study variables and calculation methods.

Preoperative Data	**Details**
Sex	Male/female (M/F)
Age at surgery	Age (years)
BMI	Measured in kg/m^2
Aetiology of scoliosis	Type (AIS, NMS, SS)
Curve characteristic	Thoracic/double/lumbar
Main curve side	Right/left convex
Lumbar modifier	A/B/C
Follow-up	Follow-up time (months) between MCGR and final fusion, and after final fusion

Postoperative Data	
UIV	UIV level (e.g., T2, T3, etc.)
LIV	LIV level (e.g., L3, L4, etc.)
Number of levels fused	Total levels fused (e.g., 10, 12, etc.)
Number of screws in the construct	Total number of screws (n)
Density of the implant	Screw density (high density (HD) or low density (LD))
Cost of the implant	Calculated by adding the cost of the screws, rods, and cross-links in Euros (EUR)
Posterior column osteotomies performed	Number of cases with at least one posterior column osteotomy
Duration of surgery	Total time of surgery (Minutes)
Blood loss	Total bleeding during surgery (mL)
Loss of Hb	Total points of Hb lost postoperatively (g/dL)
Complications	Type and number of perioperative complications (n, %) according to CDSC and type and number of late-onset complications (n, %)
LOS	Total duration of recovery (days)

AIS: Adolescent Idiopathic Scoliosis; NMS: Neuromuscular Scoliosis; SS: syndromic scoliosis; CDCS: Clavien–Dindo–Sink Classification; CR: correction rate; Hb: hemoglobin; LIV: Lower Instrumented Vertebra; LD: low-density; HD: high-density; SVA: Sagittal Vertical Axis; CL: Cervical Lordosis; TK: thoracic kyphosis; LL: Lumbar Lordosis; SS: Sacral Slope; UIV: Upper Instrumented Vertebra.

Radiographic data	
Main curve	Preoperatively, postoperatively, and at last follow-up (Cobb angle)
Percentage of curve correction	CR (%) for main curve
Frontal balance	The angle between the line connecting C7-S1 with respect to the vertical. Preoperatively, postoperatively, and at last follow-up.
Shoulder balance	The angle of the bi-coracoid line to the Horizontal. Preoperatively, postoperatively, and at last follow-up
Pelvis balance	The angle between the perpendicular to the line connecting the iliac wings and the line connecting T1-S1. Preoperatively, postoperatively, and at last follow-up
SVA	Measures the overall balance of the spine and corresponds to the horizontal distance between the plumb line of C7 and the posterosuperior corner of S1. Preoperatively, postoperatively, and at last follow-up
CL	Cobb angle between C2 and C7. Preoperatively, postoperatively, and at last follow-up
TK	Cobb angle between T5 and T12. Preoperatively, postoperatively, and at last follow-up
LL	Cobb angle between L1 and S1. Preoperatively, postoperatively, and at last follow-up
T1-T12 distance	Distance between the upper plate of T1 and the upper plate of T12. Preoperatively, postoperatively, and at last follow-up
T1-S1 distance	Distance between the upper plate of T1 and the upper plate of S1. Preoperatively, postoperatively, and at last follow-up
SS	The angle of the sacral plateau to the horizontal. Preoperatively, postoperatively, and at last follow-up

2.6.3 Implant Density Calculation

Implant density (ID) was determined by calculating the total number of fused spinal levels and the corresponding number of pedicle screws used in each case. The average number of screws per fused level was then derived using the following formula:

Implant density = total number of screws divided by the number of fused levels

This parameter was calculated for all patients included in the study. The cohort's cumulative mean implant density was 1.11 screws per fused level. Based on this value, patients were stratified into two groups: LD group, defined as an average implant density below 1.11, and a HD group, defined as an average implant density equal to or greater than 1.11.

No standardized, universally accepted threshold currently exists in the literature to define low- versus high-density screw constructs in posterior spinal fusion, particularly in early-onset scoliosis. Consequently, the cutoff value in this study was derived from the distributional characteristics of the analyzed cohort to facilitate internal comparison between groups using a consistent, reproducible framework. This threshold should be regarded as a cohort-specific value that reflects the anatomical, biomechanical, and clinical characteristics of the study population, rather than as a universally applicable or generalizable standard. This approach is consistent with previous exploratory implant-density analyses in AIS literature, where cohort-derived thresholds have been used to generate hypothesis-driven comparisons rather than prescriptive guidelines.

Additionally, an economic analysis was performed to compare LD and high-density HD implant constructs within the MCGR-treated cohort.

2.6.4 Postoperative Clinical Outcomes

Postoperative clinical outcomes included operative time, postoperative haemoglobin variation, and length of hospital stay. Operative time was recorded as the interval from skin incision to acquisition of the immediate postoperative radiograph. Postoperative haemoglobin loss was calculated as the difference between the last preoperative haemoglobin value and the first postoperative measurement. Length of hospital stay (LOS) was defined as the total duration of hospitalisation, calculated from the day of admission to the day of discharge.

2.6.5 Complications

Perioperative complications were classified according to the Clavien–Dindo Classification (CDC) adapted for pediatric patients.

Major perioperative complications were defined as events graded ≥ IIIb. Complications were analysed in relation to both the MCGR treatment course and the definitive posterior spinal fusion procedure.

Surgical site infections (SSIs) were classified according to the time of onset. Early SSIs were defined as infections occurring within the first 90 days postoperatively, whereas delayed SSIs were defined as infections occurring beyond 90 days postoperatively.

2.7 Statistical Analysis and Ethics

Statistical analyses utilized R Studio statistical software. Due to the limited sample size and heterogeneity of the study population, normality assumptions could not be reliably verified. Therefore, non-parametric statistical methods were employed for all analyses.

Continuous variables were summarized as means with standard deviations. Data distributions were assessed using the Shapiro–Wilk test. However, the small sample size rendered distributional assumptions unreliable for selecting statistical tests.

Longitudinal comparisons of radiographic parameters at multiple time points were conducted using non-parametric methods suitable for repeated measures. To address multiple comparisons, p-values were adjusted with the Bonferroni correction. The overall significance level was set at $\alpha = 0.1$, resulting in a corrected threshold of $p \leq 0.0091$.

Comparisons between independent groups, including analyses of HD and LD constructs, were conducted using the Brunner–Munzel test. This test offers a robust alternative to the Mann–Whitney U test when variances are unequal and distributions are non-normal.

Non-parametric bootstrapping procedures were applied to further assess the robustness of the findings, providing additional confirmation of observed effects independent of distributional assumptions. All statistical tests were two-sided.

The study was conducted in accordance with international ethical standards for clinical research, as outlined in the Declaration of Helsinki and the Istanbul Declaration. In compliance with local institutional review board regulations, formal ethical approval was not required for this retrospective study because all data were anonymized prior to analysis.

RESULTS

3.1 Patient Selection

Figure 6 outlines the patient selection process. Between July 2011 and September 2024, 69 patients with EOS received MCGR treatment. Thirty-seven were excluded: 31 remained in the lengthening phase, three had prior TGR treatment, two required early MCGR explantation due to complications, and one received a bipolar fixation construct.

Of the 32 patients who completed the lengthening program, one was excluded because graduation surgery was not performed after a serious intraoperative complication, leading to MCGR removal without definitive fusion. Among the 31 who underwent final fusion, four more were excluded: two were non-ambulatory, one had congenital EOS (T4 hemivertebra), and one received a hybrid construct. The final study cohort included 27 patients.

For comparative analysis, the 27 patients were divided by screw density: 14 in the LD group (implant density < 1.11) and 13 in the HD group (implant density ≥ 1.11).

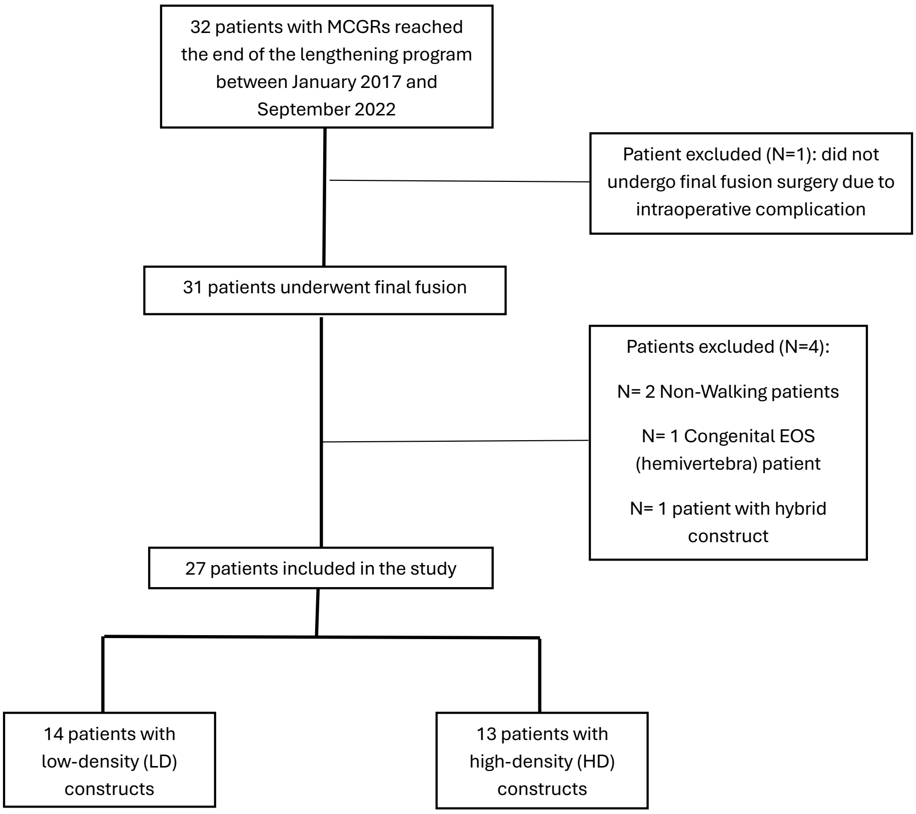


Figure 6. Patient selection flow-chart

3.2 Baseline Patient Characteristics

The final study cohort comprised 27 patients, including 20 females (74.1%) and seven males (25.9%). Idiopathic EOS was the most common aetiology, accounting for 13 patients (48.1%), followed by syndromic scoliosis in 10 patients (37.0%) and neuromuscular scoliosis in four patients (14.9%).

The predominant curve pattern was thoracic, observed in 17 patients (62.9%), followed by double curves in eight patients (29.6%) and lumbar curves in two patients (7.4%). Thoracic curves were predominantly right convex. According to the lumbar modifier classification, modifier A was the most frequently observed pattern (14 patients, 51.8%), followed by modifiers B and C. Baseline demographic characteristics and curve features of the overall cohort are summarised in Table 3.

Table 3. Baseline characteristics.

Variable	**Patients (N=27) (%)**	**HD (N=13) (%)**	**LD (N=14) (%)**
Sex			
M	7 (25.9)	3 (23.1)	4 (28.5)
F	20 (74.1)	10 (76.9)	10 (71.5)
Etiology			
Idiopathic	13 (48.1)	9 (69.2)	4 (28.5)
Syndromic	10 (37)	2 (15.4)	8 (57.1)
Prader-Willi Syndrome	3 (11.1)		3 (21.4)
Sotos Syndrome	2 (7.4)		2 (14.2)
Cornelia De Lange Syndrome	1 (3.7)	1 (7.7)	
Robinow Syndrome	1 (3.7)		1 (7.1)
Coffin Syndrome	1 (3.7)		1 (7.1)
DiGeorge Syndrome	1 (3.7)		1 (7.1)
Larsen Syndrome	1 (3.7)	1 (7.7)	
Neuromuscular	4 (14.9)	2 (15.4)	2 (14.2)
Perinatal Asphyxia	2 (7.4)	2 (15.4)	
Congenital Myopathy	1 (3.7)		1 (7.1)
IIH	1 (3.7)		1 (7.1)
Curve Characteristic			
Thoracic	17 (62.9)	10 (76.9)	7 (50)
Double	8 (29.6)	2 (15.4)	6 (42.8)
Lumbar	2 (7.4)	1 (7.7)	1 (7.1)
Main Curve Side			
Right Convex	17 (62.9)	9 (69.2)	8 (57.1)
Left Convex	10 (37.1%)	4 (30.6)	6 (42.8)
Lumbar Modifier			
A	14 (51.8)	7 (53.8)	7 (50)
B	8 (29.6)	4 (30.6)	4 (28.5)
C	5 (18.6)	2 (15.4)	3 (21.4)

IIH: Idiopathic Intracranial Hypertension

3.3 MCGR Surgery and Lengthening Characteristics

At the time of MCGR implantation, the mean age of the patients was 9.1 ± 2.1 years, and the mean BMI was 18.7 ± 3.8 kg/m². All patients underwent treatment exclusively with the MCGR system and followed a standardised lengthening protocol, with non-invasive distractions performed at three-four month intervals until completion of the growth modulation program.

The mean cost of the MCGR implants was €21,150 ± 552.3. Additional details regarding MCGR population and the lengthening period are reported in Table 4.

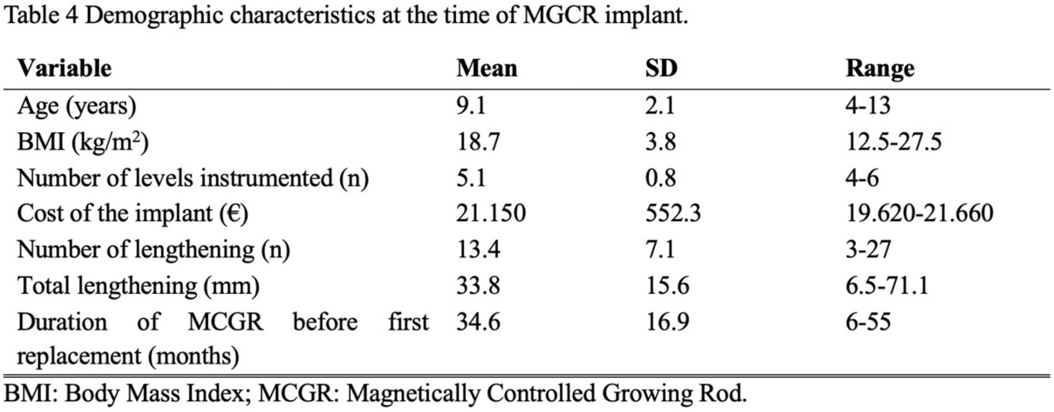


Table 4 Demographic characteristics at the time of MGCR implant.

Variable	Mean	SD	Range
Age (years)	9.1	2.1	4-13
BMI (kg/m^2)	18.7	3.8	12.5-27.5
Number of levels instrumented (n)	5.1	0.8	4-6
Cost of the implant (€)	21.150	552.3	19.620-21.660
Number of lengthening (n)	13.4	7.1	3-27
Total lengthening (mm)	33.8	15.6	6.5-71.1
Duration of MCGR before first replacement (months)	34.6	16.9	6-55

BMI: Body Mass Index; MCGR: Magnetically Controlled Growing Rod.

3.4 Baseline Comparison Between HD and LD Groups

Of the 27 patients, 13 were assigned to the HD group and 14 to the LD group according to implant density. Idiopathic EOS was most common in the HD group (9 patients, 69.2%), while syndromic EOS was most frequent in the LD group (8 patients, 57.1%). The proportion of neuromuscular scoliosis cases was similar in both groups.

Thoracic curves were the most common in both groups, present in 10 patients (76.9%) in the HD group and seven (50.0%) in the LD group. The LD group had a higher proportion of double curves than the HD group

(42.8% versus 15.4%). The distribution of main curve laterality and lumbar modifiers was similar between groups.

At the time of the graduation surgery, the mean age was 14.3 ± 1.4 years, and the mean BMI was 21.9 ± 5.8 kg/m^2. The mean duration from MCGR implantation to definitive fusion was 60.1 ± 25.0 months in the HD group and 66.5 ± 29.6 months in the LD group. Mean follow-up after definitive fusion was 43.6 ± 23.7 months for the HD group and 33.6 ± 12.4 months for the LD group. No statistically significant differences were found in baseline demographics or follow-up duration between groups ($p > 0.05$). Baseline characteristics are summarised in Table 5.

Table 5. Demographic characteristics at the time of graduation surgery.

Parameters	Patients	HD (N = 13)	LD (N = 14)	p
Age (years, mean, SD, range)	14.3 ± 1.4 (11–17)	14.2 ± 1.2 (13–17)	14.5 ± 1.6 (11–17)	0.483
BMI (kg/m^2, mean, SD, range)	21.9 ± 5.8 (12.4–36.5)	21.3 ± 3.5 (15.3–26.5)	22.5 ± 7.5 (12.4–36.5)	0.572
Follow-up time between MCGR and final fusion (months, mean, SD, range)	63.4 ± 27.1 (24-128)	60.1 ± 25 (31–128)	66.5 ± 29.6 (24–125)	0.748
Follow-up time after final fusion (months, mean, SD, range)	38.4 ± 19.0 (24-96)	43.6 ± 23.7 (24–96)	33.6 ± 12.4 (24–60)	0.575

BMI: Body Mass Index.

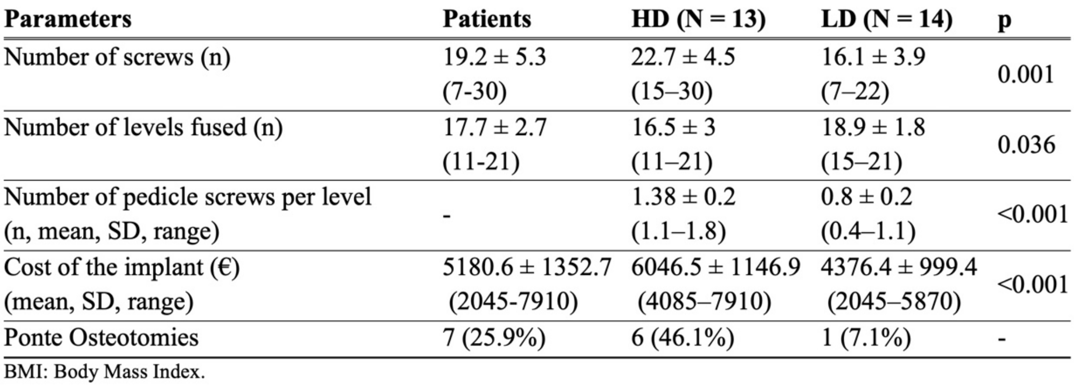
3.5 Fixation and Implant Characteristics at Final Fusion

Tables 6 and 7 show fixation and implant characteristics at definitive fusion. The HD group had significantly more pedicle screws per procedure, more fused spinal levels, and a higher average number of screws per fused level than the LD group ($p < 0.05$).

Posterior column osteotomies were more common in patients with LD constructs. Six patients (46.1%) in the HD group underwent at least one PCO, compared to one patient (7.1%) in the LD group.

Selection of the UIV and LIV was generally similar between groups, but extended distal fusion was more common in the LD group. An LIV at L4 was present in eight patients (57.1%) in the LD group and four patients (30.8%) in the HD group. This difference reflects the underlying characteristics and extent of the spinal deformity. Table 8 summarizes changes in instrumentation levels.

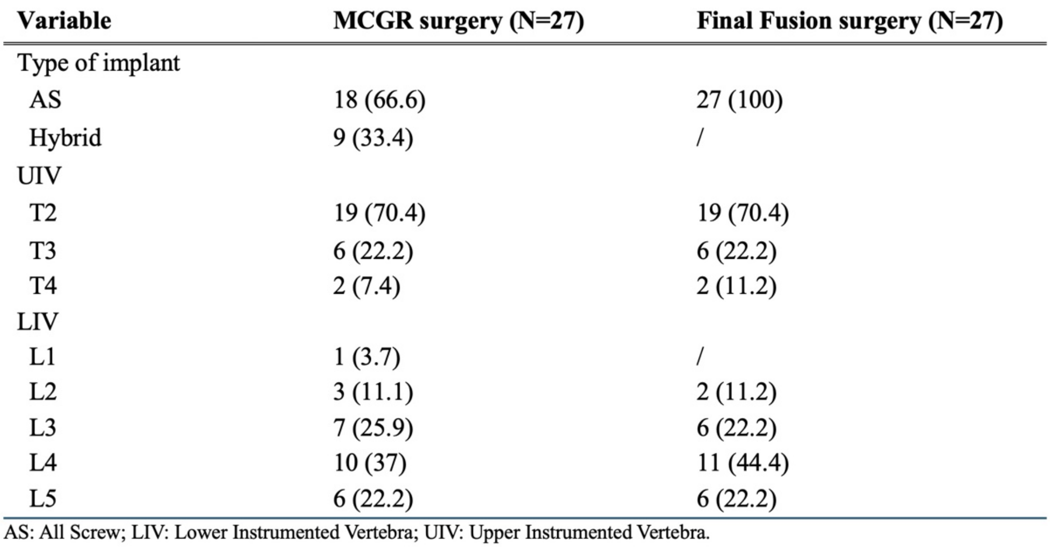
Table 6 Fixation and Implant Characteristics at Final Fusion.



Parameters	Patients	HD (N = 13)	LD (N = 14)	p
Number of screws (n)	19.2 ± 5.3 (7-30)	22.7 ± 4.5 (15–30)	16.1 ± 3.9 (7–22)	0.001
Number of levels fused (n)	17.7 ± 2.7 (11-21)	16.5 ± 3 (11–21)	18.9 ± 1.8 (15–21)	0.036
Number of pedicle screws per level (n, mean, SD, range)	-	1.38 ± 0.2 (1.1–1.8)	0.8 ± 0.2 (0.4–1.1)	<0.001
Cost of the implant (€) (mean, SD, range)	5180.6 ± 1352.7 (2045-7910)	6046.5 ± 1146.9 (4085–7910)	4376.4 ± 999.4 (2045–5870)	<0.001
Ponte Osteotomies	7 (25.9%)	6 (46.1%)	1 (7.1%)	-

BMI: Body Mass Index.

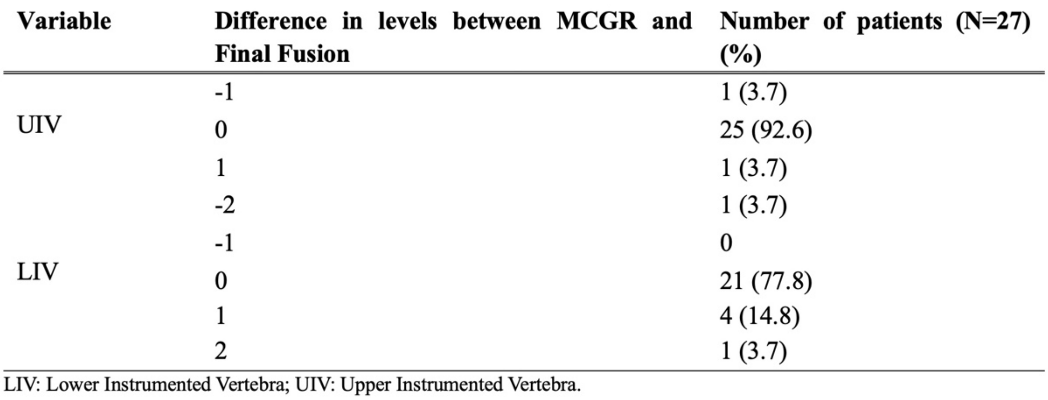
Table 7. MCGR and Final Fusion Surgery Fixation Characteristics.



Variable	**MCGR surgery (N=27)**	**Final Fusion surgery (N=27)**
Type of implant		
AS	18 (66.6)	27 (100)
Hybrid	9 (33.4)	/
UIV		
T2	19 (70.4)	19 (70.4)
T3	6 (22.2)	6 (22.2)
T4	2 (7.4)	2 (11.2)
LIV		
L1	1 (3.7)	/
L2	3 (11.1)	2 (11.2)
L3	7 (25.9)	6 (22.2)
L4	10 (37)	11 (44.4)
L5	6 (22.2)	6 (22.2)

AS: All Screw; LIV: Lower Instrumented Vertebra; UIV: Upper Instrumented Vertebra.

Table 8. Changes in Instrumentation Levels from MCGR to Final Fusion



Variable	**Difference in levels between MCGR and Final Fusion**	**Number of patients (N=27) (%)**
UIV	-1	1 (3.7)
	0	25 (92.6)
	1	1 (3.7)
LIV	-2	1 (3.7)
	-1	0
	0	21 (77.8)
	1	4 (14.8)
	2	1 (3.7)

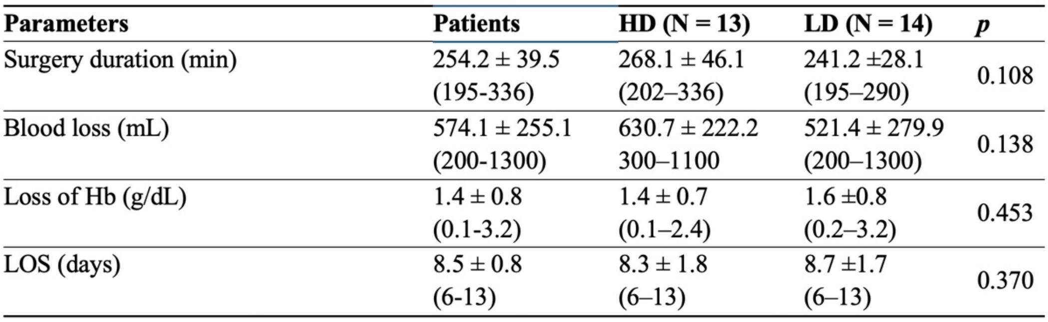
LIV: Lower Instrumented Vertebra; UIV: Upper Instrumented Vertebra.

3.6 Final Fusion Surgical Outcomes

Final fusion surgical outcomes are summarised in Table 9. The mean operative time was 254.2 ± 39.5 minutes. Mean intraoperative blood loss was 574.1 ± 255.1 mL, with a postoperative haemoglobin decrease of 1.4 ± 0.8 g/dL.

The mean length of hospital stay following definitive posterior spinal fusion was 8.5 ± 1.8 days.

Table 9. Final Fusion Surgical Outcomes



Parameters	**Patients**	**HD (N = 13)**	**LD (N = 14)**	***p***
Surgery duration (min)	254.2 ± 39.5 (195-336)	268.1 ± 46.1 (202–336)	241.2 ±28.1 (195–290)	0.108
Blood loss (mL)	574.1 ± 255.1 (200-1300)	630.7 ± 222.2 300–1100	521.4 ± 279.9 (200–1300)	0.138
Loss of Hb (g/dL)	1.4 ± 0.8 (0.1-3.2)	1.4 ± 0.7 (0.1–2.4)	1.6 ±0.8 (0.2–3.2)	0.453
LOS (days)	8.5 ± 0.8 (6-13)	8.3 ± 1.8 (6–13)	8.7 ±1.7 (6–13)	0.370

3.7 Coronal and Sagittal Plane Characteristics (Overall Cohort)

Tables 10 and 11 present coronal and sagittal alignment parameters at each study time point. At the end of the lengthening period (t3) and immediately after definitive fusion (t4), radiographic measurements show that arthrodesis significantly improved the major coronal curve and TK. The mean major curve decreased from 45.5° to 33.5° ($p = 0.003$, Brunner–Munzel test statistic = −3.869), while TK increased from 13.5° to 19.8° ($p = 0.002$, Brunner–Munzel test statistic = −2.259). These improvements remained at the final follow-up (t5).

After definitive fusion, T1–T12 and T1–S1 spinal lengths increased by 8.8 mm and 24.7 mm, respectively. However, these changes were not statistically significant after correction for multiple comparisons (p > 0.0091). The mean postoperative coronal curve correction rate (CR) was 27.4 ± 18.5% (range, 3.9–76.2), decreasing to 20.4 ± 16.0% (range, 0.1–56.5) at the final follow-up. This corresponds to a mean loss of correction of 6.9 ± 7.4% (range, 0.4–26.1).

Table 10. Coronal Plane Characteristics (A) and P-values (B)

Variable	**Before MCGR (mean, SD, range) (t1)**	**After MCGR (mean, SD, range) (t2)**	**End of lengthening (mean, SD, range) (t3)**	**After final fusion (mean, SD, range) (t4)**	**Last Follow Up (mean, SD, range) (t5)**
Main Curve (°)	64.1 ± 24 (40.5-136.6)	31.9 ± 14.7 (5.6-64.5)	45.5 ± 12.2 (23.6-73.1)	33.5 ± 12.7 (8.4-62.4)	36.4 ± 12.6 (14.2-64.7)
Frontal Balance (°)	2.9 ± 2.3 (0.6-9.7)	3.5 ± 2.6 (0.1-11.2)	3.3 ± 3.5 (0.8-14.2)	4.5 ± 4.9 (0.3-19.9)	3.1 ± 3.9 (0.2-17.1)
Shoulder Balance (°)	4.6 ± 2.5 (0.1-10.6)	3.1 ± 2.5 (0.3-9.6)	4.3 ± 4 (0.1-17.6)	4.1 ± 3.6 (0-14.7)	4.6 ± 4.7 (0-19.8)
Pelvis Balance (°)	4.1 ± 2.8 (0-11.1)	2.9 ± 2 (0.3-9.2)	3.5 ± 2.9 (0.1-12.8)	3.7 ± 3.4 (0.5-15.9)	3 ± 2.7 (0.3-11.2)

MCGR: Magnetically Controlled Growing Rod; 1: before MCGR; t2: after MCGR; t3: end of lengthening; t4: after final fusion; t5: last follow up

Variable	**p-value (t3-t4)**	**p-value (t4-5)**	**p-value bootstrap (t3-t4)**	**p-value bootstrap (t4-5)**
Main Curve (°)	<0.009*	0.377	<0.009*	0.396
Frontal Balance (°)	0.410	0.099	0.3244	0.234
Shoulder Balance (°)	0.932	0.812	0.999	0.695
Pelvis Balance (°)	0.820	0.392	0.850	0.458

Table 11. Sagittal Plane Characteristics (A) and P-values (B)

Variable	Before MCGR (mean, SD, range) (t1)	After MCGR (mean, SD, range) (t2)	End of lengthening (mean, SD, range) (t3)	After final fusion (mean, SD, range) (t4)	Last Follow Up (mean, SD, range) (t5)
SVA (mm)	0.9 ± 49.1 (-86.5- 111.3)	22.9 ± 32.9 (-65.89-96.45)	-3.3 ± 48.9 (-111.4-79.6)	5.1 ± 47.6 (-81.2-169.8)	14.7 ± 47.2 (-79.3-99.5)
LL (°)	52.2 ± 20.1 (-25.5-88.6)	39.5 ± 9.4 (20.2-54.2)	49.3 ± 15.8 (22.8-82.3)	46.3 ± 15.1 (23.9-82.1)	44.7 ± 19.1 (2.1-82.1)
TK (°)	27.7 ± 20.1 (-32.3-64.1)	12.2 ± 9.8 (-2.45-36.2)	19.8 ± 16.7 (23.7-62.2)	13.5 ± 11.7 (-14.1-48.68)	14.7 ± 14.1 (-13.1-62.7)
CL (°)	7.9 ± 23.7 (-26.6-58.3)	10.1 ± 19.7 (-21.4-51.2)	4.5 ± 22.1 (-25.1-83.2)	-0.1 ± 24-86 (-31.64-67.9)	5.3 ± 23.2 (-33.5-62.7)
SS (°)	36.8 ± 9.6 (18.6-65.4)	34.3 ± 8.1 (18.2-50.2)	35.3 ± 10.2 (17.7-54.4)	36.5 ± 12.1 (17.6-65.4)	37.1 ± 10.9 (18.7-61.2)
T1-T12 (mm)	194.9 ± 28.2 (138.7-252.3)	217.6 ± 26.8 (154.9-265.5)	221.2 ± 28.6 (139.1-294.9)	230 ± 48.2 (146.9-406.9)	243.8 ± 52.5 (143.3-426)
T1-S1 (mm)	310.7 ± 50.6 (193.1-400.8)	353.3 ± 68.7 (248.5-418.2)	386.5 ± 38.3 (276.9-460.6)	411.2 ± 59.1 (294.9-591.9)	424.9 ± 66.8 (284.8-623.4)

CL: Cervical Lordosis; LL: Lumbar Lordosis; SS: Sacral Slope; SVA: Sagittal Vertical Axis; TK: Thoracic Kyphosis; MCGR: Magnetically Controlled Growing Rod; 1: before MCGR; t2: after MCGR; t3: end of lengthening; t4: after final fusion; t5: last follow up

Variable	p-value (t3-t4)	p-value (t4-5)	p-value bootstrap (t3-t4)	p-value bootstrap (t4-5)
SVA (mm)	0.833	0.269	0.525	0.460
LL (°)	0.462	0.979	0.472	0.750
TK (°)	<0.009*	0.993	<0.009*	0.743
CL (°)	0.2830	0.247	0.471	0.400
SS (°)	0.7928	0.741	0.700	0.858
T1-T12 (mm)	0.376	0.279	0.0736	0.437
T1-S1 (mm)	0.210	0.082	0.431	0.321

3.8 Coronal and Sagittal Plane Characteristics: Comparison Between HD and LD Groups

Tables 12 and 13 present coronal and sagittal alignment parameters by implant density at three time points: end of lengthening (t1), post-definitive fusion (t2), and final follow-up (t3).

At t1, radiographic parameters were similar between the HD and LD groups, except for lumbar lordosis, which was significantly greater in the HD group (56.2 ± 14.2°) than in the LD group (42.8 ± 14.9°, $p = 0.023$).

At t2, the LD group had significantly higher thoracic kyphosis (16.3 ± 7.6° vs. 10.9 ± 14.4°, $p = 0.021$) and greater T1–S1 spinal height (433 ± 67 mm vs. 391 ± 43 mm, $p = 0.039$) than the HD group.

At t3, T1–S1 spinal height remained significantly greater in the HD group (454 ± 70 mm vs. 397 ± 51 mm, $p = 0.021$). No other significant differences in coronal or sagittal alignment were found between the groups.

Table 12. Frontal plane characteristics in HD and LD groups.

Variable	End of Lengthening (t1, Mean, SD, Range)			After Final Fusion (t2, Mean, SD, Range)			Last Follow-up (t3, Mean, SD, Range)		
	HD	LD	*p*	HD	LD	*p*	HD	LD	*p*
Main Curve (°)	44.6 ± 10.2 (25.5–65.9)	46.3 ± 14.2 (23–73)	0.787	30.7 ± 11.7 (9.6–49.1)	36 ± 13.4 (8.4–62.4)	0.368	32.6 ± 10.7 (15.2–50.2)	39.9 ± 13.6 (14.2–64.7)	0.126
Frontal Balance (°)	2.4 ± 2.1 (0.7–9.1)	4.2 ± 4.3 (0.9–14.1)	0.435	4.3 ± 5.4 (0.3–19.9)	4.7 ± 4.5 (0.5–14.8)	0.465	2.9 ± 2.9 (0.2–10.3)	3.2 ± 4.7 (0.3–17.6)	0.412
Shoulder Balance (°)	2.8 ± 1.9 (0.4–7.6)	5.4 ± 5 (0.1–17.6)	0.254	3.8 ± 2.4 (0.4–8.5)	4.6 ± 4.5 (0.1–14.7)	0.984	5.1 ± 4.4 (1.3–17.7)	4.3 ± 5.1 (0.1–19.8)	0.368
Pelvis Balance (°)	2.7 ± 2.1 (0.3–8.5)	4.2 ± 3.5 (0.1–12.8)	0.207	3.5 ± 4.1 (0.5–16)	3.8 ± 2.9 (0.9–9.6)	0.412	2.8 ± 2.8 (0.1–11.1)	3.2 ± 2.8 (0.1–8.6)	0.849

Table 13. Sagittal plane characteristics in HD and LD groups.

Variable	End of Lengthening (t1, Mean, SD, Range)			After Final Fusion (t2, Mean, SD, Range)			Last Follow-up (t3, Mean, SD, Range)		
	HD	LD	*p*	HD	LD	*p*	HD	LD	*p*
SVA (mm)	−13.4 ± 54.9 (−111.3–79.6)	5.9 ± 42.6 (−86.4–78.9)	0.453	7.6 ± 62.1 (−81.2–169.8)	2.6 ± 31 (−50.2–67.7)	0.984	3.8 ± 52.3 (−79.3–88.6)	24.8 ± 41.3 (−26.8–99.5)	0.509
LL (°)	56.2 ± 14.2 (38.5–82.3)	42.8 ± 14.9 (22.9–74.9)	0.023	45.8 ± 16.6 (23.9–76.7)	46.7 ± 14.1 (26.6–82)	0.825	42.4 ± 20.8 (2.2–71.2)	46.9 ± 18 (15.4–82.1)	0.718
TK (°)	23.4 ± 13.8 (8.3–62.2)	16.5 ± 18.9 (−23.7–55.2)	0.197	16.3 ± 7.6 (8.6–38.7)	10.9 ± 14.4 (−14.1–48.9)	0.021	15.8 ± 9.5 (2.7–32.4)	13.7 ± 18.4 (−13.1–62.7)	0.293
CL (°)	9.4 ± 28.2 (−25–83.2)	−0.1 ± 14.2 (−21.8–27)	0.541	7.4 ± 25.6 (−28.8–67.9)	−7.2 ± 22.7 (−31.6–45.3)	0.767	9.5 ± 25.1 (−24.9–62.7)	−0.3 ± 21 (−33.5–51.1)	0.509
SS (°)	38.1 ± 9.5 (23.1–52.6)	32.8 ± 10.5 (17.7–54.4)	0.254	35.1 ± 12.1 (17.6–57.1)	38.1 ± 12.3 (19.6–65.4)	0.509	35.9 ± 11.3 (19.9–58.2)	38.2 ± 10.9 (18.–61.2)	0.596
T1-T12 (mm)	22.5 (±2.2) (26.2–19.9)	21.8 (±3.3) (13.9–29.5)	0.624	24.2 (±5.6) (15.5–40.7)	21.9 (±3.7) (14.7–29.6)	0.167	26.2 (±5.9) (17.8–42.6)	22.7 (±3.9) (14.3–28.7)	0.126
T1-S1 (mm)	39.8 (±3.6) (35.6–46)	37.5 (±3.8) (27.7–44.7)	0.214	43.3 (±6.7) (31.1–59.1)	39.1 (±4.3) (29.5–46.9)	0.039 *	45.4 (±7) (33.4–62.3)	39.7 (±5.1) (28.5–47.5)	0.021 *

CL: Cervical Lordosis; LL: Lumbar Lordosis; SS: Sacral Slope; SVA: Sagittal Vertical Axis; TK: Thoracic Kyphosis.

Table 15. Postoperative complications between HD and LD groups.

Variable	**HD (N = 13) (%)**	**LD (N = 14) (%)**
Patients with complications (n, %)	3 (23.1)	3 (21.4)
Perioperative complications (n, %)	2 (15.4)	0
Deep SSI	1 (7.7)	/
CSF leak	1 (7.7)	/
	/	/
Late-onset complications (n, %)	1 (7.7)	3 (21.4)
Delayed SSI	/	1 (7.1)
Rod rupture	1 (7.7)	/
DJK	/	2 (14.2)
Perioperative complications classified according to CDC (n, %)		
Grade I	/	/
Grade II	/	/
Grade IIIa	/	/
Grade IIIb	1.7 (7.7)	/
Grade IVa	/	/
Grade IVb	1.7 (7.7)	/
Grade V	/	/

CDSC: Clavien–Dindo–Sink Classification; CSF: cerebrospinal fluid, DJK: distal junctional kyphosis;

SSI: surgical site infection.

DISCUSSION

4.1. Principal Findings

This study evaluated the clinical and radiographic outcomes of definitive posterior spinal fusion in patients with EOS who had previously completed a lengthening program with MCGRs. The principal finding is that definitive arthrodesis provided a statistically significant and durable improvement in spinal alignment, with acceptable surgical morbidity, supporting its role as a reliable concluding step following MCGR treatment.

From a radiographic standpoint, both the major coronal curve and thoracic kyphosis demonstrated significant correction immediately after final fusion, which was maintained at mid-term follow-up ($p = 0.003$ and $p = 0.002$, respectively). Specifically, the major curve showed a significant reduction following arthrodesis and remained stable at the last follow-up. Similarly, thoracic kyphosis improved after definitive surgery and did not deteriorate postoperatively, suggesting adequate sagittal plane control.

In addition to angular correction, definitive fusion was associated with further gains in spinal length, as reflected by increases in both T1–T12 and T1–S1 distances. Although these increments did not reach statistical significance, they indicate that final fusion does not compromise spinal height and may contribute to additional longitudinal growth or consolidation of previously achieved lengthening. These findings are clinically relevant in the EOS population, in whom preservation of spinal and thoracic growth remains a significant concern even after treatment.

A key strength of the present study lies in its methodological consistency. All patients were treated at a single high-volume pediatric spine centre by the same surgical team, minimising variability in surgical technique and postoperative management. Furthermore, including only ambulatory patients treated exclusively with MCGRs and excluding hybrid constructs at final fusion reduced heterogeneity and enabled a more focused evaluation of outcomes. The uniform use of pedicle screw instrumentation at definitive surgery further strengthened the comparability of radiographic results.

Taken together, these findings suggest that definitive posterior spinal fusion after MCGR treatment is not merely a stabilising procedure, but an effective intervention capable of providing additional deformity correction, maintaining sagittal balance, and achieving durable outcomes with an acceptable complication rate [26].

4.2. Final Fusion after MCGR: Comparison with the Literature

Since the introduction of MCGRs, the management of EOS has undergone a substantial paradigm shift, primarily due to the elimination of repeated surgical lengthening procedures [27]. While the efficacy of MCGRs during the growth phase has been extensively investigated, evidence regarding outcomes following definitive spinal fusion after completion of MCGR treatment remains comparatively limited, and available data are often heterogeneous [26,28,29].

Previous studies have suggested that the majority of coronal plane correction is achieved at the time of initial MCGR implantation [26], with only modest additional correction obtained during graduation surgery. Cheung et al. reported outcomes in a cohort of 10 graduated EOS patients and found a mean additional coronal correction of only 7.1° following final fusion, with a subsequent loss of approximately 4° at two-year follow-up [30]. These findings led some authors to question the necessity of definitive fusion in selected cases, particularly before safety warnings regarding metallosis associated with MCGR devices were issued.

In this context, earlier literature explored alternative strategies, including permanent retention of MCGRs or simple rod removal at the end of growth, to avoid the risks associated with a further major surgical procedure [31–34]. However, such approaches raised concerns regarding long-term spinal stability, particularly in the absence of solid arthrodesis. Repeated lengthening procedures may reduce the likelihood of spontaneous fusion [35]. Moreover, rod removal without definitive fusion has been associated with progressive loss of correction and decrease of radiographic parameters over time [36,37].

More recent evidence has increasingly supported the role of definitive fusion as a necessary step in MCGR treatment. Multicenter series have reported postoperative complication rates following final fusion ranging from 22% to 27%, with unplanned reoperation rates up to 20%. However, these studies often included heterogeneous patient populations, multiple surgical teams, and varying instrumentation strategies, which may partly explain the relatively high complication rates observed.

In contrast, monocentric studies performed at high-volume pediatric spine centres have demonstrated more favourable outcomes. Gurel et al. reported a postoperative complication rate of 22.9% in a cohort of 48 graduated patients, with an unplanned reoperation rate of 12.5% [38]. The present study further contributes to this body of evidence, demonstrating a lower overall postoperative complication rate of 18.5%, with major complications occurring in a small proportion of cases. These findings suggest that surgical expertise, institutional experience, and procedural standardisation may play a critical role in optimising outcomes after final fusion.

From a radiographic perspective, the results of the present study are consistent with those previously reported. In line with these reports, definitive fusion can provide additional, durable coronal correction when performed in a standardised setting.

Furthermore, the maintenance of sagittal alignment and the absence of significant postoperative deterioration in thoracic kyphosis observed in this study contrast with concerns raised in earlier literature. These findings support the notion that modern posterior-only techniques using pedicle screw constructs can achieve stable coronal and sagittal correction at the end of MCGR treatment.

4.3. Complications and Safety Profile

Complications remain a central concern in EOS management, and MCGR-treated patients require a phase-specific interpretation of adverse events during the lengthening period and after definitive fusion.

In the present study, a relatively high complication rate was observed during the MCGR lengthening phase [39], with complications occurring in 44.4% of patients. However, unplanned surgical interventions were required in nearly one-third of cases.

Despite these challenges, complications occurring during the lengthening phase did not appear to negatively influence the subsequent definitive fusion negatively. Following final fusion, the overall complication rate in the present cohort was 18.5%, with only one major perioperative complication classified as Grade ≥ IIIB according to the CDC. Notably, the majority of postoperative complications occurred during follow-up rather than in the immediate perioperative period. All the complications were successfully managed, requiring few cases of revision surgery.

Another relevant finding is the limited incidence of severe neurological or life-threatening complications following final fusion. Cerebrospinal fluid leakage occurred in a small number of cases and was managed effectively without long-term sequelae. Surgical site infections, both early and delayed, remained within acceptable limits and did not exceed rates reported for complex pediatric spinal reconstructions.

The issue of metallosis deserves particular attention in the context of MCGR treatment. While concerns about metal debris and elevated serum metal ion levels have led to recommendations for device removal or replacement, the clinical consequences of metallosis remain incompletely understood [40]. In the present cohort, cases of inflammatory reactions related to metallosis were rare and did not translate into an increased rate of complications following final fusion. Nonetheless, this aspect reinforces the importance of concluding MCGR treatment with a definitive strategy rather than prolonged device retention.

4.4. Clinical Implications of Final Fusion After MCGR Treatment

The findings of the present study seems to support that final fusion represents a mandatory and effective surgical step, consolidating alignment and optimising deformity correction after the growth modulation phase [41]. These findings indicate that posterior-only definitive fusion with modern pedicle screw constructs can achieve satisfactory sagittal balance without postoperative deterioration, reinforcing the importance of careful sagittal planning at the time of definitive surgery [42,43].

Equally relevant is the observation that final fusion did not compromise spinal length. Although longitudinal growth potential is exhausted mainly at this stage, maintenance of spinal height and, in some cases, modest improvement suggest that definitive fusion can be performed without sacrificing the gains achieved during the lengthening phase. This finding has implications for both spinal balance and overall trunk proportions, which are particularly important in this young patient population.

Safety considerations remain central to clinical decision-making in EOS. The relatively low incidence of significant complications observed after final fusion in this study supports the feasibility of this approach when performed in experienced centres. Importantly, the complication burden associated with growth-friendly treatment does not appear to translate into an excessive risk during the definitive fusion phase. This observation may alleviate concerns regarding cumulative surgical risk in patients who have already undergone multiple interventions.

Another key implication of these findings relates to the organisation of care. The consistency of outcomes observed in this monocentric series highlights the potential benefits of treatment centralisation and continuity of surgical strategy. Managing both the growth modulation phase and the definitive fusion within the same specialised centre may reduce variability in technique, facilitate tailored surgical planning, and improve complication management.

Taken together, these considerations support a paradigm in which definitive posterior spinal fusion is viewed as a strategic component of the MCGR treatment pathway, rather than an optional or secondary procedure. The focus of surgical decision-making should therefore shift from questioning whether final fusion is necessary to determining how to optimise it for each patient. This includes careful selection of fusion levels, alignment goals, and instrumentation strategies, setting the stage for a more nuanced discussion of implant density and construct design at the time of definitive treatment.

4.5. Implant Density at Final Fusion After MCGR Treatment: High-Density Versus Low-Density Constructs

The main finding is that, although HD constructs were associated with higher implant costs and provided modest early advantages in sagittal alignment and spinal length, they were not associated with statistically detectable superior long-term radiographic outcomes or lower complication rates in this cohort compared with LD constructs.

This data is particularly relevant given the growing body of literature in AIS suggesting that increased screw density does not necessarily translate into improved clinical or radiographic outcomes [44–46]. Extensive comparative studies and pooled analyses in AIS populations have consistently shown comparable coronal correction, sagittal alignment, and health-related quality of life between HD and LD constructs, while highlighting reduced operative time, blood loss, and hospital costs with lower-density strategies [47]. Estimated cost savings associated with LD constructs have been substantial, without compromising correction or stability. However, extrapolation of these findings to EOS patients remains challenging due to fundamental biomechanical and biological differences between the two populations [48].

Unlike AIS, the EOS spine at the time of final fusion is frequently characterised by altered tissue planes, reduced flexibility, and varying degrees of spontaneous auto-fusion resulting from prolonged instrumentation and repeated distractions [49]. In this context, the biomechanical demands placed on the definitive construct may be lower than initially assumed, potentially reducing the need for uniformly high implant density.

In this cohort, HD constructs resulted in greater early restoration of thoracic kyphosis and increased T1–S1 length immediately after final fusion. Thoracic kyphosis was significantly higher in the HD group during the early postoperative period, but this benefit diminished over time. At final follow-up, sagittal alignment did not differ significantly between groups. These findings suggest that while HD constructs may achieve faster initial sagittal correction, they do not provide lasting long-term advantages over LD constructs.

Coronal correction and overall alignment maintenance were comparable between groups. The absence of significant differences in major curve correction indicates that higher implant density does not enhance deformity correction at definitive fusion in this population. This result aligns with previous EOS studies, which show that final coronal outcomes depend more on curve characteristics, flexibility, and prior growth modulation than on the number of fixation points.

Overall complication rates were similar between HD and LD constructs. However, early perioperative complications, including deep surgical site infection and cerebrospinal fluid leak, were more frequent in the HD group. The LD group experienced only late-onset complications, such as distal junctional kyphosis and delayed infection. Although the study was not powered to detect statistically significant differences in complication patterns, this trend suggests that higher screw density may increase the risk of early perioperative morbidity.

The greater number of screws used in HD constructs inevitably increases surgical complexity, operative exposure, and the potential for iatrogenic injury. Previous reports have linked higher screw density to increased risks of neurologic, dural, and infectious complications, particularly in complex pediatric deformity surgery. In EOS patients, who often present with fragile anatomy, scar tissue, and altered biomechanics following prolonged treatment, minimising unnecessary instrumentation may therefore represent a prudent surgical strategy.

Cost considerations are especially relevant in this patient population. EOS patients treated with MCGRs already incur substantial healthcare costs during the lengthening phase. In this study, HD constructs were associated with significantly higher implant costs, without demonstrating clear long-term clinical advantages. These findings support prior cost-effectiveness analyses suggesting that more expensive constructs do not necessarily yield proportional clinical benefits. In resource-constrained healthcare systems, avoiding excessive implant density can meaningfully contribute to cost containment without compromising outcomes.

Taken together, the results of this study support a selective and tailored approach to implant density at the time of definitive fusion after MCGR treatment. While dual-rod constructs remain biomechanically advantageous, routine use of LD fixation across all fused levels does not appear justified in this setting. Instead, screw density should be individualised based on curve characteristics, bone quality, presence of auto-fusion, and intraoperative stability, rather than applied uniformly.

It is important to emphasize that the absence of statistically significant differences between HD and LD constructs in this study should not be interpreted as proof of equivalence or non-inferiority. Given the limited sample size and the exploratory nature of the analysis, the study is underpowered to exclude clinically meaningful differences in radiographic or complication outcomes. Therefore, the present findings should be interpreted as hypothesis-generating rather than definitive evidence that implant density does not influence final fusion outcomes after MCGR treatment.

Limitations

This study has several important limitations. First, the relatively small sample size (n = 27) limits statistical power and precludes formal equivalence or non-inferiority testing between high- and low-density constructs. Although no statistically significant differences were detected, the study is underpowered to exclude clinically meaningful differences in radiographic outcomes or complication rates. Second, the implant density threshold (1.11 screws per fused level) was derived from the distribution of the present cohort and applied post hoc for exploratory stratification. This cohort-specific cutoff does not represent a validated or universally accepted clinical threshold, thereby limiting external validity. Third, substantial selection bias is present due to strict inclusion and exclusion criteria. Non-ambulatory patients, congenital EOS, hybrid constructs, and patients who did not undergo definitive fusion were excluded. While this approach enhanced internal homogeneity, it resulted in a highly selected, lower-risk cohort and likely underestimates complication rates compared with the broader EOS population. Consequently, generalizability of the findings is limited. Fourth, imbalance in scoliosis etiology between HD and LD groups introduces potential confounding that cannot be adequately controlled given the limited sample size. Fifth, radiographic measurements were performed by a single evaluator. Although standardized measurement protocols were used, interobserver reliability was not formally assessed. Finally, patient-reported outcome measures were not included, which limits evaluation of the functional and quality-of-life impact of definitive fusion after MCGR treatment.

Conclusions

This study evaluated radiographic and surgical outcomes of definitive posterior spinal fusion in patients with EOS after completion of MCGR treatment. Final fusion was a safe and effective endpoint, providing additional and durable correction in both the coronal and sagittal planes with maintenance of alignment at mid-term follow-up. This is the first study to specifically investigate the role of implant density at final fusion in MCGR-treated patients. However, given the exploratory nature and limited statistical power of this study, these findings should not be interpreted as evidence of equivalence and require confirmation in larger prospective cohorts. Further prospective studies are warranted to refine implant density selection in this complex patient population.

Abbreviations

AIS: Adolescent Idiopathic Scoliosis

AP: Anteroposterior

AS: All-screw

BMI: Body Mass Index

CDC: Clavien Dindo Classification

CDCS: Centers for Disease Control and Prevention Scale

CNS: Central Nervous System

CR: Correction Rate

DSI: Delayed Surgical Site Infection

EOS: Early-onset Scoliosis

FUP: Follow-up

Hb: Hemoglobin

HC: Hybrid Constructs

HD: High-density

ICU: Intensive Care Unit

LD: Low-density

LIV: Lower Instrumented Vertebra

LL: Lumbar Lordosis

LOS: Length of Hospital Stay

MCGR: Magnetically Controlled Growing Rods

MEPs: Motor-evoked Potentials

PCOs: Posterior Column Osteotomies

PROMs: Patient-Reported Outcome Measures

SEPs: Sensory-evoked Potentials

SSI: Superficial Site Infection

STROBE: Strengthening the Reporting of Observational Studies in Epidemiology

TGR: Traditional Growing Rods

TK: Thoracic Kyphosis

TPN: Total Parenteral Nutrition

UIV: Upper Instrumented Vertebra

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