# The 3-dimensional effects of distracting magnetically controlled growing rods

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**The effect of Magnetically Controlled Growing Rods on 3-dimensional changes in deformity correction**


## Abstract

**Study Design:** Prospective radiographic study.

**Objectives:** To determine the 3-dimensional (3D) changes in deformity correction with magnetically controlled growing rod (MCGR) distractions.

**Summary of background data:** MCGRs can achieve similar coronal plane correction as traditional growing rods. The changes in the sagittal and axial planes are unknown and should be studied as these factors reflect potential for proximal junctional kyphosis and rotational deformity. Frequent MCGR distractions may potentially improve axial plane deformities to the same extent as coronal and sagittal plane deformities.

**Methods:** Early onset scoliosis (EOS) patients who underwent dual MCGRs with minimum 2-year follow-up were included in this study. 3D reconstructions of 6-monthly biplanar images were used to study changes in coronal, sagittal and axial planes. Changes in growth parameters (body height and arm span) were scaled to changes in coronal Cobb angles, sagittal profile (T1-12, T4-12, L1-L5, L1-S1), and rotational profile at the proximal thoracic, main thoracic and lumbar curves, and pelvic parameters (sagittal pelvic tilt, lateral pelvic tilt and pelvis rotation).

**Results:** A total of 10 EOS patients were studied. The mean age at index surgery was 8.2±3.0 years and mean postoperative follow-up of 34.3±9.5 months. Six patients had rod exchange at mean 29.5±11.8 months after initial implantation. Despite consistent gains in body height and arm

span, the main changes in coronal and rotational profiles only occurred at the initial rod implantation surgery with only small changes occurring with subsequent follow-ups. Patients with proximal junctional kyphosis had higher preoperative proximal junctional angles and flattening of the sagittal plane occurred at initial surgery with early rebound. No changes in pelvic parameters were observed.

**Conclusions:** The 3D changes with MCGR are mainly observed with initial rod implantation and no significant changes are observed with distractions. The MCGR can prevent deformity progression in the axial plane.

**Level of Evidence:** IV

**Key Points**

1. The rotational correction is greatest with the initial magnetically controlled growing rod implantation and is stable thereafter with distractions.

2. Patients with proximal junctional kyphosis had higher preoperative proximal junctional angles with flattening of the sagittal alignment with rod implantation followed by early rebound.

3. Patients without proximal junctional kyphosis had smaller preoperative proximal junctional angles that were preserved with rod implantation and stable thereafter with distractions.

4. No significant changes in coronal, sagittal or axial plane deformities occur with distractions up to 4 years follow-up.

# The effect of Magnetically Controlled Growing Rods on 3-dimensional changes in deformity correction

## Introduction

Early onset scoliosis (EOS) requires early treatment as they occur in young children with significant remaining growth potential. Left untreated, these deformities are at risk of rapid progression, cosmetic disfigurement and pulmonary insufficiency.[1-3] Growing rods is one of the most common treatment methods for EOS that allow for physiological spine growth while preventing spine deformity progression.[4-6] Traditionally, these rods require open distraction surgeries every 6 months. However, repeated surgeries in a growing child has significant drawbacks including increased risk for anesthestic and wound complications.[1,7] In response to these limitations, a remotely distractible, magnetically controlled growing rod (MCGR) has been developed to allow for outpatient gradual lengthening.[8] The MCGR allows for safe distractions and continuous neurological monitoring in an awake patient. Clinical and radiological outcomes have been shown to be similar to traditional growing rods[8-15] and it has also been used in safe gradual correction of severe spinal deformities.[16,17] The MCGR also allows for non-invasive radiation-free monitoring[18,19] and is an overall less costly option for EOS.[20-22]

In terms of curve correction, most studies have showed that the largest amount of coronal curve correction occurs at implantation with subsequent satisfactory control of the deformity.[8,9,12] Despite these coronal changes, assessment of vertebral rotation is important for prognosis as scoliosis is a 3-dimensional (3D) deformity.[23-25] The apical vertebral rotation (AVR) is particularly important with relevance to the rib hump which is a cosmetic concern. An increased rotational deformity may also lead to reduced chest cage area and thus pulmonary compromise.

However, the changes in the axial plane with MCGR treatment is unknown due to limitations in imaging availability. Computed tomography (CT) measurements are most useful for measuring vertebral rotation as they provide the true rotational profile of the spine.[26,27] However, it is not routinely performed in children due to high radiation exposure and lack of weight-bearing information.

Using the low-dose x-ray device EOS® (EOS® Imaging, Paris, France), we can obtain 3D reconstructed images of the spine based on biplanar images in posteroanterior (PA) and lateral standing views. The EOS® has already been shown to have good reliability for intraobserver and interobserver measurements for scoliosis curves with good precision (2-4 degrees variation only for vertebral rotation).[28-30] Verification of the reconstructed 3D images with CT has already been performed and is shown to be reliable.[31] Thus, it is timely at this stage to assess the effect of gradual distractions with the MCGR on correction of vertebral rotation. 3D models of the spine are created to monitor the change in vertebral rotation with each distraction. This technique can also observe for any relationship between frequent distractions, spine length gain and transverse vertebral growth. Hence, the objective of this study is to determine the 3D corrections of EOS with MCGR distractions.

## Materials and Methods

*Study design*

This was a prospective radiographic study of patients with EOS who underwent dual MCGRs. Patients were recruited consecutively from a tertiary spine referral center since October 2015. None of the patients had prior treatment for their spinal deformity. All patients had major thoracic deformities, at least 2 years follow-up after their primary insertion of MCGRs, and images

coupled with recorded body habitus parameters (body height, arm span, body weight). For all patients, dual MCGRs of 5.5 millimetres in diameter were placed in a standard and offset configuration. Ethics was approved by the local institutional review board. All patients underwent monthly 2mm distractions to both rods starting at 2 months after MCGR implantation.

*3D reconstruction*

Radiographic images were obtained of recruited subjects using EOS® imaging every 6-months of follow-up to assess for longitudinal changes in parameters. The EOS® system is a slot-scanning radiographic device that utilizes two x-ray sources to allow simultaneous capture of both the PA and lateral images. It reduces the radiation to up to 9 times compared to conventional radiographs.[32] Two pairs of detectors are positioned so that the images can be generated line by line as the scanning proceeds vertically. Patients stand in the machine so images are taken in weight-bearing position. Scan time lasts for 8 to 15 seconds according to the patient's height. The reconstruction of the spine is based on available models provided by the EOS® company.[29] The image reconstruction procedure is as follows: Firstly, the pelvic anatomical landmarks are accessed. The two spheres of the acetabuli are identified as well as the sacral endplate. Then, the spinal curve from the T1 upper endplate to the L5 lower endplate is identified. The approximate borders of the spine vertebra are identified and a preliminary model is created. Fine adjustment of the model is performed by manipulating the points on the four corners of the vertebral body, pedicles and posterior arches from T1 to L5.[33] Each modification improves the accuracy of the model. Finally, the accepted changes will create the 3D model with the necessary angles provided automatically (**Figure 1**). The two-dimensional images of the whole body had undergone 3-D reconstructions of the spine and lower limb using the validated SterEOS®software (EOS® Imaging, Paris, France).

Trained individuals blinded to the clinical information performed all image reconstructions. The time spent on 3D modelling was 31.7±6.1 minutes per reconstruction.

*Study parameters*

Demographic data including patient gender, age at MCGR implantation, and diagnosis (congenital, neuromuscular, syndromic, idiopathic) was recorded. Changes in body height (cm), body weight (kg), arm span (cm), and body mass index were recorded. Images were obtained preoperatively, immediate postoperatively, and from postoperative 6-months to postoperative-48 months at 6-monthly intervals. Details regarding the primary surgery included levels of instrumentation and anchor-type (pedicle screw or hook). Any complications such as infection, anchor loosening, and proximal junctional kyphosis (PJK) were recorded. The number of rod exchanges was also recorded.

Specifically for the 3D imaging parameters, in addition to the gross morphology of the 3D model, the SterEOS® software provided the usually quoted spinopelvic alignment parameters.[34] These included the coronal Cobb angle, T1-T12 kyphosis, T4-T12 kyphosis, L1-S1 lordosis, L1-L5 lordosis, pelvic incidence, sagittal and lateral pelvic tilt, pelvic rotation and sacral slope. The rotational profile was also studied through the measurement of apical vertebral rotation at the thoracic apex, the proximal thoracic apex and the lumbar apex. PJK was identified by an increase in the proximal junctional angle (caudal endplate of the UIV to the cephalad endplate of two vertebrae proximally) of 10 degrees or more and at least 10 degrees greater than the preoperative measurement.[35]

*Statistical Analysis*

Descriptive statistics were calculated in mean, standard deviation (SD) and percentage. Mean values were plotted against follow-up time-points, enabling comparison between parameters. The timing of rod exchanges was also taken into account and was expressed using bar graphs within the dual-axis plot. Normality tests using Shapiro-Wilk tests were run and found that data was not normally distributed. One-way analysis of variance (ANOVA) was used to study the changes in radiographical parameters with time. Spearman correlation test was used to assess for any correlation between changes of the axial, coronal and sagittal parameters. Spearman's rank correlation coefficient ($r_s$) depicts the direction and strength of any relationships detected, with a value of 0.10 to 0.29 suggesting a small association, whereas a coefficient of 0.30 to 0.49 and ≥ 0.50 indicating a medium and a large association respectively.[36] Statistical analyses were conducted using SPSS Windows 23.0 (IBM SPSS Inc., Chicago, Illinois, USA) and charts were created by Excel (Microsoft, Redmond, Washington, USA). A p-value of <0.05 was considered statistically significant.

## Results

A total of 10 (2 males, 8 females) EOS patients (**Table 1**) were studied. Their diagnoses were juvenile idiopathic (n=5), infantile idiopathic (n=1), neurofibromatosis (n=1), neuromuscular (n=1), Sotos syndrome (n=1) and Arthrogryposis (n=1). The mean age at index surgery was 8.2±3.0 years and mean postoperative follow-up of 34.3±9.5 months. Six patients had rod exchanges. The baseline profile of the patients is listed in **table 2**. The preoperative body height was 122.7±10.2cm, preoperative arm span was 118.8±12.8cm, preoperative body weight was 20.8±7.1 kg, and preoperative body mass index was 13.0±2.9 kg/m$^2$. The pelvic incidence and

lumbar lordosis was well-matched preoperatively. No significant proximal thoracic deformity was observed in coronal, sagittal or axial planes.

Consistent gains in body height, body weight, and arm span were observed with follow-up (**Table 3**). The main changes in coronal Cobb angles only occurred at the initial rod implantation surgery with only small changes that occurred at subsequent follow-ups. For the sagittal plane, the spine was flattened with initial surgery with reductions in T1-T12 and T4-T12 kyphosis, and L1-S1 and L1-L5 lordosis. There was rebound increases in kyphosis and lordosis within the two years of follow-up followed by minimal changes thereafter. The lateral pelvic tilt maintained its position throughout follow-up while sagittal pelvic tilt gradually reduced to more retroversion especially in the first two years of follow-up. When comparing preoperative, immediate postoperative and final follow-up data (**Table 4**), the main changes only occurred for thoracic and lumbar Cobb angles, L1-S1 lordosis.

For the axial plane, the apical vertebral rotation also had its largest change in the initial rod implantation without significant changes following subsequent distractions (**Figure 2**) despite increasing body height. There was minimal change overall in the rotational profiles, even after rod exchanges. For the thoracic apex, which had the largest changes, besides the initial surgery, the maximum mean change was only 3.4±3.5 degrees thereafter. Similarly, the lumbar apex and proximal thoracic apex had maximal mean changes of 4.3±6.8 degrees and 3.4±3.5 degrees, respectively. Further analyses performed comparing the three parameters showed no significant correlations between coronal, sagittal and axial plane changes except for changes in coronal parameters and T1-12 kyphosis and L1-L5 lordosis (**Table 5**).

There were three patients who developed PJK (**Table 5**). These patients had preoperatively larger proximal junctional angles than those without PJK, and their kyphotic angles were flattened

with initial rod implantation (**Table 6**). PJK occurred as early as postoperative 6 months (**Figure 3**) but was sustained throughout follow-up without deterioration.

## Discussion

Understanding changes in 3D is crucial for proper management of patients with EOS. Rotational malalignment may aggravate the rib hump, which is a major concern for cosmesis. Increasing rotational deformities may also reduce the area of the chest cage thereby compromising pulmonary function. In this study, we explored the potential 3D changes that occur with MCGR treatment for EOS. Like the coronal Cobb angle, the main changes occur in the initial rod implantation without significant variations with distractions. Hence, the rotational profile is also be maintained with MCGR treatment.

Axial plane rotation is commonly measured on plain radiographs by Perdriolle and Vidal's method.[37,38] However, 3D assessment based on a single 2-dimensional image is inherently inaccurate as each scoliosis is unique with complexities that are not easily identified.[39] 3D reconstruction using the EOS® is accurate to within 4-6 degrees for the coronal deformity and 2-4 degrees for vertebral rotation in scoliosis.[28,29] Verification of these reconstructed 3D images has been performed with CT and is proven to be reliable.[31] It is important to note that the time required to complete each 3D reconstruction was 31.7±6.1 minutes. Despite the advantages of reduced radiation exposure, major drawbacks of using EOS® reconstructions is the manpower requirement and lack of automation which we hope will be solved in the future. Nevertheless, this is the best 3D assessment tool available currently.

The changes in the axial plane concerning growing rods are not well understood. Kamaci *et al*[38] suggested that the apical vertebral rotation improves with traditional growing rod treatment

by comparing the preoperative and final follow-up assessments. However, this does not reflect the changes occurring with distractions and the interplay with events like rod complications or rod exchanges. The 10 degree improvements reported in their study is similar to our findings of mean 13.6 degree reduction in rotation after MCGR implantation.[38] With the previous reports of similar initial corrections in the coronal plane after traditional growing rod and MCGR implantation[4,9,12-15], we speculate that the reported improvements elsewhere was contributed by the initial surgery rather than with distraction. Nevertheless, it is important to note that no deterioration in the rotational profile was observed during the course of the treatment. Hence, MCGR is successful in preventing axial plane deformity progression despite no anchors around the apex of the deformity.

The comparable changes found with rod implantation and with distractions in 3D is representative of spinal coupling.[40-42] During MCGR implantation, no particular maneuver was performed to correct the apical rotation as there are only two sets of anchors placed at the proximal and distal foundations without any instrumentation in the intervening spinal segments or attempt to derotate the spine. Hence, effectively only the coronal deformity is planned for correction with rod insertion and intraoperative distraction maneuvers. The spontaneous reduction of the rotational deformity is achieved through coupling.

An interesting phenomenon is observed for the sagittal plane. Proper contouring of the MCGR is not easily achievable due to the straight actuator segment.[12,30] This has been attributed to the high-risk of PJK after growing rod surgery.[30,43,44] The ability of the spine to compensate for sudden flattening of the sagittal alignment is highlighted by the early rebound in thoracic kyphosis and lumbar lordosis after rod implantation. PJK may occur and in our series, it is apparent for those with preoperative higher proximal junctional angles. The recruitment of more cranial spinal

segments to reproduce the thoracic kyphosis is clearly represented by a rebound increase in proximal junctional angle as early as postoperative 6 months. There is also greater T1-T12 kyphotic change as compared to T4-T12. The inclusion of T1-4 in addition to the T4-T12 better incorporates the kyphotic changes occurring in the proximal thoracic spinal segments. In our series, the increase in kyphosis was only observed in the early postoperative follow-up and the overall kyphosis did not change thereafter. There is no further deterioration in the proximal junctional angle after the early change. This may be a reason why we only observed three patients developing PJK, which is a relatively low rate (30%) as compared to previous reports (~40%).[15,43]

There are several limitations to this study that must be discussed. Firstly, we report the results of a small number of patients with variable ages at rod implantation. The lack of significance reported by the correlation analyses may be related to these limitations. However, it may also represent the variations in 3D curve types that have been reported.[39] For example, not all scoliosis curves are hypokyphotic and as correlation analyses are uni-directional, this tool may not be most representative of interactions between coronal, sagittal and axial planes. Nevertheless, our results will need to be validated in a larger study. For the purposes of this study, despite the presence of implants superimposing onto the vertebral bodies, measurements using the EOS® is still possible for postoperative images with reproducible data.[34] However, in one study investigating 3D reconstructions of the spine with posterior instrumentation in-situ, the reported precision may vary from 2.8 to 10 degrees for Cobb angles and 6.8 to 10.4 degrees for apical vertebral rotation calculations. At present, we unfortunately have no other more accurate 3D assessment available for children that also avoids the high radiation exposure associated with CT.

This is the first study to assess 3D changes in scoliosis correction with MCGR distractions. The corrections in rotational deformity are seen only with initial rod implantation and no significant changes are observed with distractions thereafter. Hence, the MCGR is successful in controlling the deformity and prevents its progression in the coronal, sagittal and axial planes. Understanding 3D changes in the deformity is important as it provides insight into how growth-sparing distraction devices can be tailored towards different patients with variable curve types. Further study can examine whether transverse plane growth deviates with MCGR treatment and whether this influences the correction outcomes achieved at final fusion surgery, as well as correlation with respiratory function.

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## Figure Legends

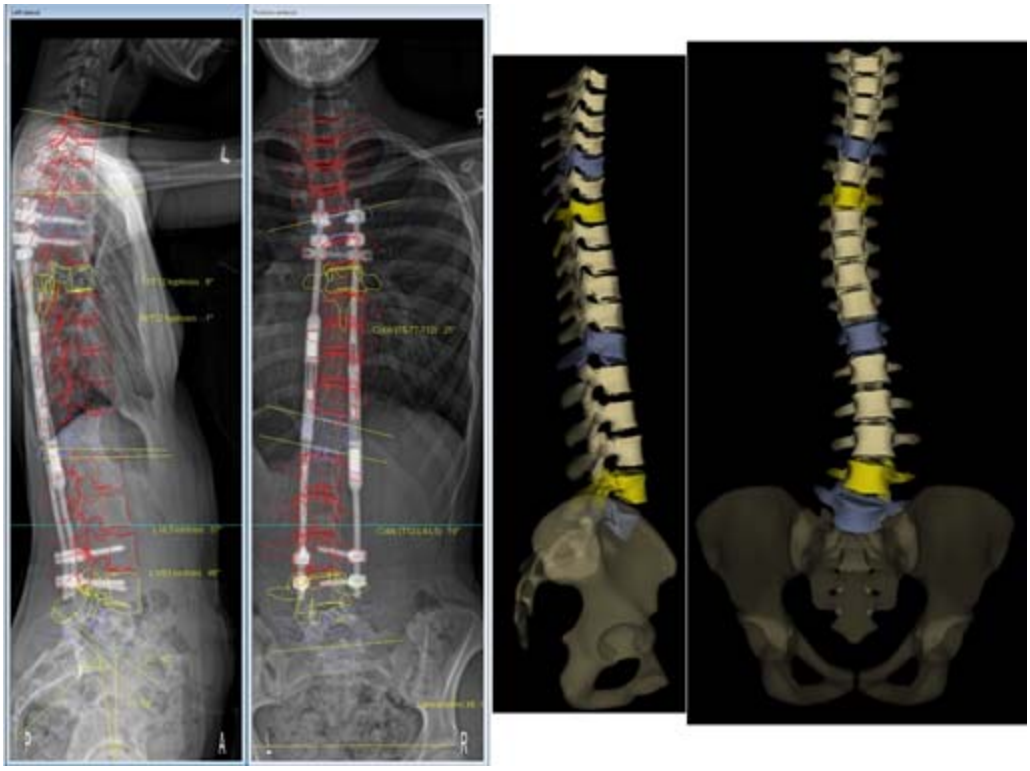

**Figure 1:** 3D reconstruction output created from SterEOS®.

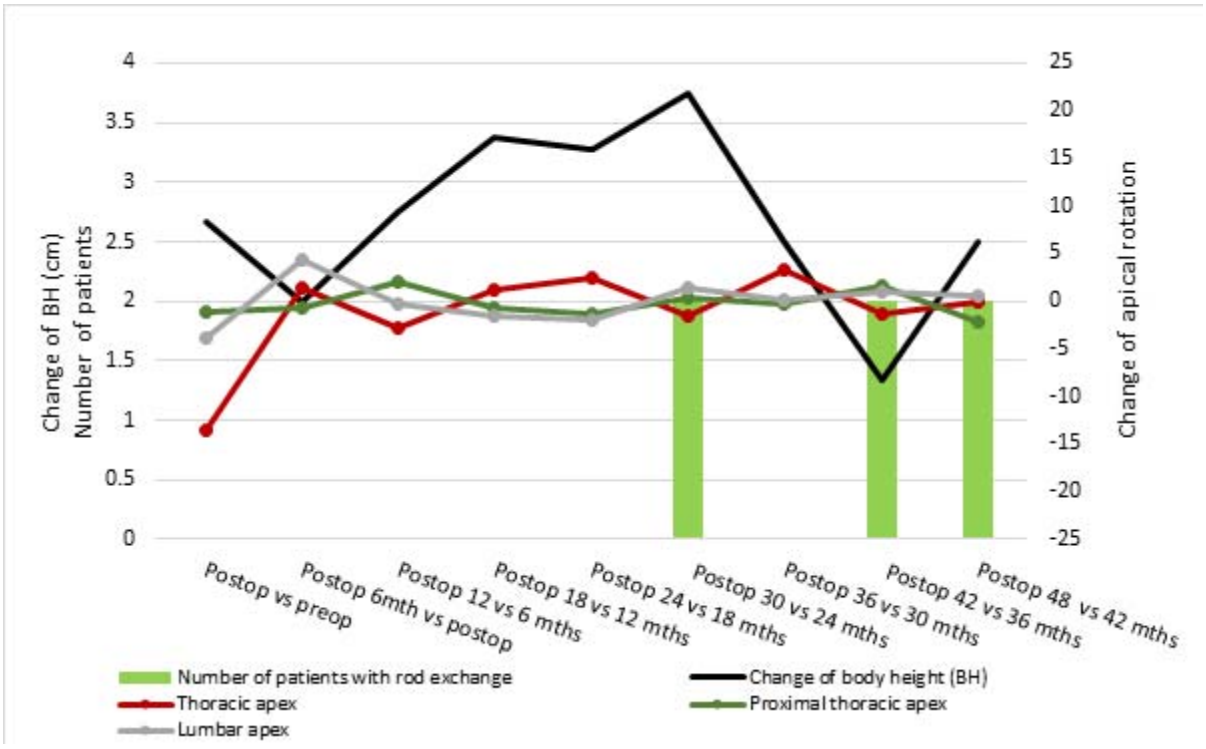


**Figure 2:** Graph of the changes in rotational profile at the proximal thoracic, thoracic and lumbar apices with initial implantation and at every 6 months follow-up. The main change occurs at initiation implantation and no significant deviations are observed thereafter despite growth or with rod exchange.

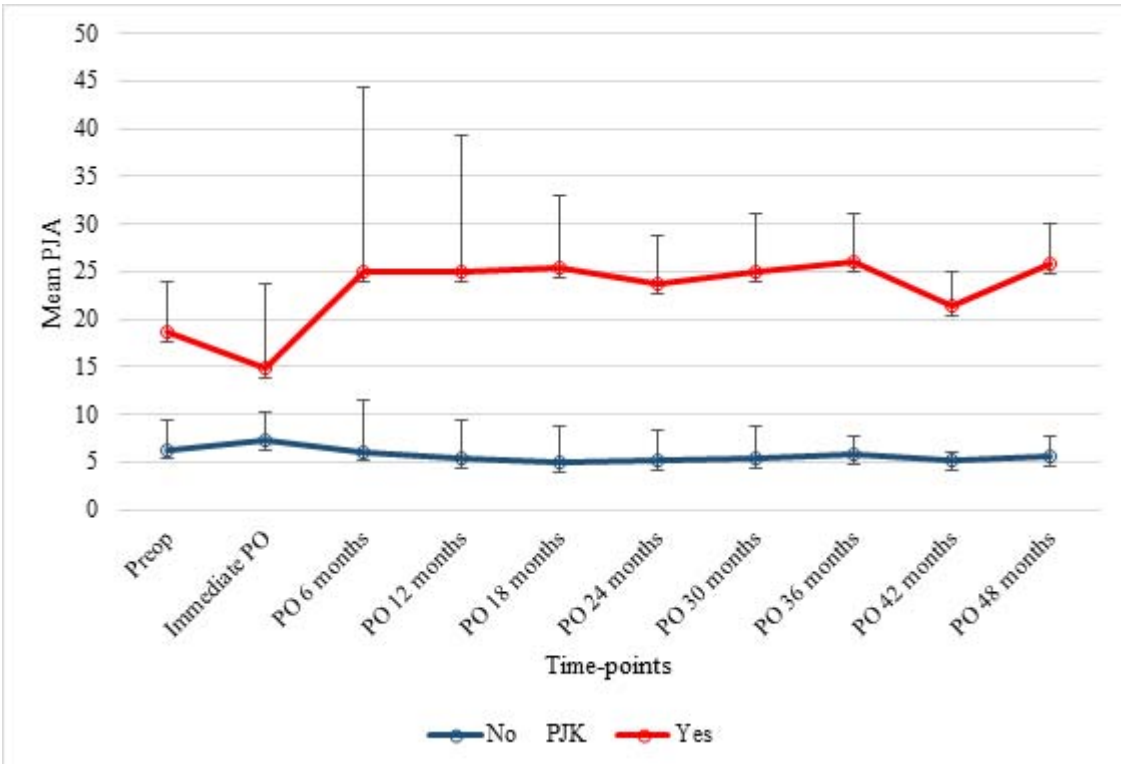


**Figure 3:** Mean changes with standard deviation bars for proximal junctional angle (PJA) in degrees at preop, immediate postop (PO), PO 6 months, PO 12 months, PO 18 months, PO 24 months, PO 30 months, PO 36 months, PO 42 months and PO 48 months between patients with and without proximal junctional kyphosis (PJK).

## Table Legends

**Table 1:** Patient profiles.

**Table 2:** Baseline radiological parameters.

**Table 3:** Changes of growth and clinical parameters between time-points.

**Table 4:** Correlation tests of changes of Cobb angles, changes of sagittal parameters and changes rotational profiles at all time-points.

**Table 5:** Proximal junctional angle (mean values ± SD) at specific time-points.

**Table 6:** Changes of Proximal junctional angle (mean values ± SD) at specific time-points.

Table 1: Patient profiles

| Subject Number | Gender | Diagnosis | Age at MCGR Implantation (years) | Foundations | Complications | Number of rod exchanges (years after first surgery) | Unplanned Reoperation |
|---|---|---|---|---|---|---|---|
| #01 | F | Juvenile idiopathic scoliosis | 8.5 | T4/5 upgoing pedicle hooks, L2/3 pedicle screws | Nil | 1 (3yrs) | |
| #02 | F | Juvenile idiopathic scoliosis | 12.7 | T3/4 claw construct, L2/3 pedicle screws | Nil | 0 | |
| #03 | F | Infantile idiopathic scoliosis with Marfanoid features | 4.1 | T4/5, L3/4 pedicle screws | Nil | 1 (3yrs) | |
| #04 | F | Arthrogryposis | 9.4 | T3/4 upgoing pedicle hooks, L2/3 pedicle screws | Nil | 0 | |
| #05 | F | Juvenile idiopathic scoliosis with Marfanoid features | 7.4 | T4/5, L3/4 pedicle screws | Proximal foundation nonunion, anchor loosening, bone formation at expandable portion of rod, PJK | 1 (2yrs) | 2 (proximal foundation nonunion and anchor loosening) |
| #06 | F | Sotos syndrome | 4.3 | T5/6 claw construct, L3/4 pedicle screws | Bone formation at expandable portion of rod, metallosis, PJK | 1 (4yrs) | |
| #07 | F | Juvenile idiopathic scoliosis | 11.4 | T5/6, L3/4 pedicle screws | Broken rod, metallosis | 1 (2yrs) | 1 (broken rod, metallosis) |
| #08 | M | Neurofibromatosis scoliosis | 4.8 | T3/4, L3/4 pedicle screws | Infection, PJK | 2 (2yrs, 4yrs) | 1 (infection) |
| #09 | F | Neuromuscular scoliosis | 10.4 | T1/2, L1/2 pedicle screws | Nil | 0 | |
| #10 | M | Juvenile idiopathic scoliosis | 9.0 | T5/6 upgoing pedicle hooks, L2/3 pedicle screws | Nil | 0 | |

Table 2: Baseline radiological parameters

| Parameters | Mean ± SD |
|---|---|
| Imaging parameters | |
| Preoperative curve magnitude - Cobb angle (degrees) | |
| Thoracic | 68.7 ± 18.3 |
| Proximal thoracic | 15.9 ± 20.6 |
| Lumbar | 39.7 ± 4.0 |
| Proximal junctional angle | 8.1 ± 4.6 |
| Preoperative sagittal profile | |
| T1-T12 kyphosis | 31.3 ± 13.3 |
| T4-T12 kyphosis | 29.0 ± 15.4 |
| L1-S1 lordosis | 58.0 ± 6.2 |
| L1-L5 lordosis | 41.5 ± 7.0 |
| Preoperative pelvic profile | |
| Pelvic tilt - Sagittal | 4.7 ± 14.8 |
| - Lateral | 7.0 ± 4.4 |
| Pelvic incidence | 48.6 ± 13.2 |
| Sacral slope | 43.9 ± 5.8 |
| Pelvis rotation | -1.0 ± 4.4 |
| Preoperative rotational profile – apical vertebral rotation | |
| Thoracic apex | -13.7 ± 10.5 |
| Proximal thoracic apex | 0.9 ± 1.4 |
| Lumbar apex | 5.2 ± 12.1 |

Table 3: Changes of growth and clinical parameters between time-points

| Parameters (Mean ± SD) | Immediate postop vs preop | Postop 6 months vs immediate postop | 12 vs 6 months | 18 vs 12 months | 24 vs 18 months | 30 vs 24 months | 36 vs 30 months | 42 vs 36 months | 48 vs 42 months | p-value |
|---|---|---|---|---|---|---|---|---|---|---|
| Changes of growth parameters mean ± SD) | | | | | | | | | | |
| Body Height (cm) | 2.7 ± 1.5 | 2.0 ± 1.4 | 2.8 ± 0.5 | 3.4 ± 2.4 | 3.3 ± 1.2 | 3.8 ± 1.0 | 2.5 ± 0.6 | 1.3 ± 1.2 | 2.5 ± 2.1 | 0.371 |
| Body Weight (kg) | 0.5 ± 0.7 | 2.0 ± 1.7 | -0.2 ± 1.0 | 1.5 ± 0.4 | 1.4 ± 2.2 | 1.4 ± 1.3 | 1.5 ± 1.9 | 1.6 ± 1.9 | 1.3 ± 1.5 | 0.765 |
| Arm span (cm) | 1.0 ± 0.0 | 4.0 ± 2.2 | 2.9 ± 0.9 | 2.8 ± 1.8 | 3.1 ± 1.1 | 3.3 ± 1.7 | 3.1 ± 1.5 | 1.0 ± 0.9 | 3.0 ± 0.0 | 0.004* |
| BMI | -0.4 ± 0.6 | 0.7 ± 0.8 | -0.8 ± 0.6 | 0.1 ± 0.8 | 0.0 ± 0.9 | 0.1 ± 0.9 | 0.3 ± 0.9 | 0.4 ± 0.7 | 0.2 ± 0.4 | 0.785 |
| Changes of Cobb angles (degree, mean ± SD) | | | | | | | | | | |
| Thoracic | -45.7 ± 24.4 | 3.5 ± 5.4 | 0.1 ±1.3 | 1.3 ± 2.3 | 0.4 ± 4.0 | -2.2 ± 1.2 | -1.6 ± 3.5 | 0.6 ± 1.2 | 0.4 ± 1.6 | <0.001* |
| Proximal thoracic | -12.7 ± 17.9 | -2.0 ± 3.0 | -0.4 ± 3.8 | 1.0 ± 3.8 | 0.2 ± 3.0 | 4.4 ± 3.1 | 0.5 ± 5.5 | 2.3 ± 4.4 | 3.6 ± 0.4 | 0.158 |
| Lumbar | -26.7 ± 7.1 | 2.3 ± 7.8 | 1.5 ± 3.5 | -1.7 ± 2.7 | -1.4 ± 0.4 | -1.8 ± 2.4 | 1.8 ± 3.3 | -0.5 ± 0.7 | -2.5 ± 3.5 | <0.001* |
| Proximal junctional angle | -0.8 ± 3.6 | 2.6 ± 8.2 | -0.3 ± 4.0 | 0.0 ± 4.0 | -0.6 ± 3.6 | 0.4 ± 3.1 | 0.5 ± 2.7 | -1.8 ± 2.4 | 2.0 ± 2.8 | 0.532 |
| Sagittal Profile changes | | | | | | | | | | |
| T1-T12 kyphosis | -3.3 ± 1.4 | 8.2 ± 12.8 | 4.6 ± 7.8 | 2.8 ± 6.9 | -1.4 ± 5.0 | -3.2 ± 9.8 | -3.2 ± 6.4 | 4.7 ± 1.3 | -2.2 ± 5.7 | 0.393 |
| T4-T12 kyphosis | -6.2 ± 10.8 | 5.3 ± 8.0 | 4.5 ± 3.7 | -5.0 ± 2.0 | 1.6 ± 8.0 | 1.1 ± 2.5 | 0.9 ± 2.8 | 0.7 ± 4.5 | 1.5 ± 1.3 | 0.282 |
| L1-S1 lordosis | -10.4 ± 14.1 | 5.7 ± 10.3 | 6.6 ± 9.8 | 4.5 ± 4.8 | -2.6 ± 4.6 | 6.9 ± 8.0 | -3.9 ± 9.0 | 2.0 ± 3.3 | 1.0 ± 3.8 | 0.256 |
| L1-L5 lordosis | -7.3 ± 9.3 | 7.3 ± 4.2 | 2.8 ± 4.8 | 2.5 ± 4.0 | -0.2 ± 2.3 | 3.8 ± 4.0 | -1.1 ± 8.0 | 2.2 ±1.6 | 0.6 ± 1.9 | 0.167 |
| Rotational profile changes | | | | | | | | | | |
| Thoracic apex | -13.6 ± 11.4 | 1.5 ± 5.2 | -2.7 ± 5.1 | 1.2± 4.5 | 2.5 ± 5.6 | -1.6 ± 3.1 | 3.4 ± 3.5 | -1.3 ± 1.5 | -0.1 ± 1.1 | 0.042* |
| Proximal thoracic apex | -1.1 ± 1.5 | -0.6 ± 7.3 | 2.1 ± 4.6 | -0.6 ± 5.2 | -1.4 ± 3.1 | 0.4 ± 9.5 | -0.2 ± 7.5 | 1.6 ± 2.3 | -2.1 ± 3.0 | 0.991 |
| Lumbar apex | -3.8 ± 2.0 | 4.3 ± 6.8 | -0.2 ± 5.4 | -1.6 ± 3.6 | -1.9 ± 5.1 | 1.4 ± 3.7 | 0.2 ± 2.6 | 1.0 ± 2.7 | 0.5 ± 0.7 | 0.574 |
| Pelvic parameters (mean ± SD, degrees) | | | | | | | | | | |
| Sagittal pelvic tilt | 7.4 ± 10.7 | -4.0 ± 7.8 | -2.7 ± 10.3 | -2.4 ± 7.9 | -1.7 ± 7.1 | -0.6 ± 8.4 | 0.9 ± 8.8 | 0.3 ± 3.4 | -0.1 ± 6.8 | 0.903 |
| Lateral pelvic tilt | 2.0 ± 4.2 | 0.8 ± 1.7 | -0.3 ± 2.6 | -0.7± 1.2 | 0.3 ± 0.5 | -0.5 ± 2.1 | 0.0 ± 3.5 | -1.7 ± 1.2 | 2.5 ± 2.1 | 0.664 |
| Pelvis rotation | 6.3 ± 0.6 | -2.1 ± 9.0 | 0.5 ± 5.9 | -1.9 ± 1.4 | 2.4 ± 1.7 | 0.8 ± 1.5 | 0.2 ± 4.0 | -0.9 ± 2.2 | 3.0 ± 0.3 | 0.602 |

BMI: body mass index

Table 4: Changes between preoperative, immediate postoperative and final follow-up measurements

| Parameters | Mean pre-operative (±SD) | Mean immediate postoperative (±SD) | Mean final follow-up (±SD) | Preoperative vs Final p-value | Immediate postop vs Final p-value |
|---|---|---|---|---|---|
| Cobb Angle | | | | | |
| Thoracic | 68.7±18.3 | 23.8±10.7 | 19.2±9.6 | 0.005* | 0.543 |
| Proximal thoracic | 15.9±20.6 | 15.6±13.8 | 18.5±1.2 | 0.851 | 0.692 |
| Lumbar | 39.7±4.0 | 9.1±7.6 | 9.0±8.2 | 0.002* | 0.979 |
| Proximal junctional angle | 8.1±4.6 | 7.3±4.8 | 12.9±8.7 | 0.359 | 0.322 |
| Sagittal Profile | | | | | |
| T1-T12 kyphosis | 31.3±13.3 | 33.5±20.4 | 44.1±16.7 | 0.327 | 0.451 |
| T4-T12 kyphosis | 29.0±15.4 | 29.9±17.2 | 33.3±20.1 | 0.772 | 0.806 |
| L1-S1 lordosis | 58.0±6.2 | 42.9±18.8 | 44.1±6.4 | 0.034* | 0.912 |
| L1-L5 lordosis | 41.5±7.0 | 30.3±13.5 | 31.6±7.3 | 0.130 | 0.876 |
| Rotational Profile | | | | | |
| Thoracic apex | -13.7±10.5 | -11.2±16.6 | 1.9±15.5 | 0.197 | 0.292 |
| Proximal thoracic apex | 0.9±1.4 | 1.5±1.5 | 2.0±5.4 | 0.748 | 0.864 |
| Lumbar apex | 5.2±12.1 | -1.6±5.3 | 8.6±7.7 | 0.664 | 0.072 |
| Pelvic parameters | | | | | |
| Sagittal pelvic tilt | 4.7±14.8 | 8.3±13.7 | 6.8±8.2 | 0.816 | 0.862 |
| Lateral pelvic tilt | 7.0±4.4 | 5.3±6.7 | 3.8±1.3 | 0.325 | 0.673 |
| Pelvis rotation | -1.0±4.4 | 0.7±6.0 | 0.3±4.9 | 0.742 | 0.916 |

**Commented [PC1]:** Paired samples t-test

Table 4: Correlation tests of changes of Cobb angles, changes of sagittal parameters and changes rotational profiles at all time-points

| Changes between time-points | $r_s$ | p-value | $r_s$ | p-value | $r_s$ | p-value | $r_s$ | p-value |
|---|---|---|---|---|---|---|---|---|
| | Coronal parameters | | | | | | | |
| | Thoracic Cobb angle | | Proximal Thoracic Cobb angle | | Lumbar Cobb angle | | Proximal junctional angle | |
| Vertebral rotation at thoracic apex | 0.191 | 0.320 | 0.278 | 0.145 | 0.228 | 0.235 | -0.094 | 0.626 |
| Sagittal Parameters | | | | | | | | |
| T1-T12 kyphosis | 0.496 | 0.006** | -0.210 | 0.274 | 0.116 | 0.550 | -0.198 | 0.304 |
| T4-T12 kyphosis | 0.174 | 0.368 | -0.359 | 0.056 | 0.286 | 0.133 | 0.184 | 0.339 |
| L1-S1 lordosis | 0.406 | 0.029* | 0.042 | 0.831 | -0.080 | 0.681 | 0.138 | 0.475 |
| L1-L5 lordosis | 0.330 | 0.081 | -0.074 | 0.701 | -0.098 | 0.613 | -0.370 | 0.048* |

Table 5: Proximal junctional angle (mean values ± SD) at specific time-points

| PJA | Preoperative | Immediate PO | PO 6 months | PO 12 months | PO 18 months | PO 24 months | PO 30 months | PO 36 months | PO 42 months | PO 48 months |
|---|---|---|---|---|---|---|---|---|---|---|
| >10° (n=3) | 12.3 ± 5.3 | 7.7 ± 8.8 | 18.8 ± 19.4 | 19.5 ± 14.4 | 20.3 ± 7.6 | 18.5 ± 5.0 | 19.6 ± 6.1 | 20.2 ± 5.1 | 16.1 ± 3.6 | 20.3 ± 4.2 |
| <10° (n=7) | 6.3 ± 3.0 | 7.2 ± 3.1 | 6.1 ± 5.3 | 5.4 ± 3.9 | 5.0 ± 3.8 | 5.2 ± 3.1 | 5.3 ± 3.5 | 5.8 ± 1.8 | 5.2 ± 0.8 | 5.5 ± 2.3 |
| p-value | 0.067 | 0.667 | 0.517 | 0.183 | 0.033* | 0.024* | 0.024* | 0.024* | 0.024* | 0.100 |

PJA: proximal junctional angle; PO: postoperative

Table 6: Changes of Proximal junctional angle (mean values ± SD) at specific time-points

| PJA | Preop vs Immediate PO | PO 6 months vs Immediate PO | PO 12 vs 6 months | PO 18 vs 12 months | PO 24 vs 18 months | PO 30 vs 24 months | PO 36 v 30 months | PO 42 vs 36 months | PO 48 vs 42 months |
|---|---|---|---|---|---|---|---|---|---|
| >10° (n=3) | -4.6 ± 3.7 | 11.1 ± 10.8 | 0.7 ± 6.4 | 0.8 ± 6.8 | -1.8 ± 6.5 | 1.1 ± 6.0 | 0.6 ± 3.3 | -4.1 ± 1.5 | 4.2 ± 0.6 |
| <10° (n=7) | 0.9 ± 2.1 | -1.1 ± 3.3 | -0.7 ± 3.1 | -0.4 ± 2.8 | 0.0 ± 1.8 | 0.1 ± 0.9 | 0.5 ± 2.7 | -0.6 ± 1.8 | -0.2 ± 2.4 |
| p-value | 0.033* | 0.033* | 0.517 | 0.833 | 0.714 | 1.000 | 1.000 | 0.048* | 0.100 |

PJA: proximal junctional angle; PO: postoperative