PhD Thesis

Investigation of Vertebral Rotations and Surgical Efficacy Based on 3D Reconstructions in Adolescent Idiopathic Scoliosis

Kristóf József, M.D.

University of Pécs, Medical School, Department of Orthopaedics
National Center for Spinal Disorders

Miklós Tunyogi Csapó, M.D., Ph.D.

supervisor

National Center for Spinal Disorders

Ádám Tibor Schlégl, M.D., Ph.D.

supervisor

University of Pécs, Medical School, Department of Orthopaedics

Péter Than, M.D., Ph.D., D.Sc.

program leader

Lajos Bogár, M.D., Ph.D., D.Sc.

head of doctoral school

University of Pécs, DCHCMPhS

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Introduction

Adolescent idiopathic scoliosis is a spinal deformity developing after the age of 10, characterized by the structural curvature of the spine with axial rotation. Radiologic imaging methods play a central role in the diagnostics of scoliosis – in addition to patient history and physical examination. Besides traditional X-rays, biplanar imaging techniques have appeared in the last decade. With the help of 3D reconstructions, EOS 2D/3D imaging can also obtain relatively accurate information about the axial plane of spinal deformity with low radiation exposure. The axial rotation of the apical vertebrae (apicalAVR) is prominent among the spinal rotation parameters, which is the only determining parameter of the axial plane in most of the studies.

Assessment of coronary plane correction is the most significant in determining surgical effectiveness of scoliosis surgeries, in which the reduction in Cobb angles achieved by surgery is given as a percentage of the preoperative Cobb angles. The correction rate can be influenced by several factors (e.g. spinal mobility, osteotomies, number of screws), The literature counts the average coronal correction efficiency between 63 % and 83 %, taking the above mentioned factors into account.

Correction in the axial plane is also of paramount importance since any substantial residual rib hump after surgery has a significant impact on postoperative quality of life.

The goals of the study

The basic aim of the study was to determine axial vertebral rotation (AVR) in the major and minor curves of adolescent idiopathic scoliosis using EOS 2D/3D imaging technology, and then to determine how the apical vertebrae relates to the maximal vertebral rotation (maxAVR). We planned a statistical comparison of maxAVR and apicalAVR parameters in all severity and Lenke classification groups.

As a secondary goal, we aimed to determine the three-dimensional effectiveness of scoliosis correction surgeries performed by our research group using EOS 2D/3D imaging. Our further goal was to examine the influence of the age of the patient on the correction rate. We paid special attention to differences with clinical relevance.

Examined population, and methods

In the retrospective part of our study, following the institutional ethical authorisation (file number: 7605 – PTE 2019), we reviewed the 9,872 EOS 2D/3D (EOS Imaging, Paris, France) images made between 2007 and 2018 during the routine patient care of the Orthopaedic Department, University of Pécs. We selected cases where adolescent idiopathic scoliosis was confirmed. Patients who had early onset or secunder scoliosis, or had previous spine surgery, or had associated musculoskeletal disorders, were excluded from the study. In addition, we excluded all patients where the images were not taken in the standard position, which may modify the spinal parameters. There were 267 females and 65 males in the patient population. The average Cobb angle was 37.7 degrees, between 10 and 122, covering the whole severity spectrum of adolescent idiopathic scoliosis.

In the second part of our study, we created a prospective patient register. We selected all patients who had adolescent idiopathic scoliosis with a surgical indication. Patients who had early onset or secunder scoliosis, had no surgical indication or previous spine surgery, or had associated musculoskeletal disease were excluded from the study. Patients who did not have EOS 2D/3D imaging before or close after surgery were also excluded from the study. Preoperative EOS images were taken on average 2 months before surgery, while postoperative imaging were made on postop day 5.

The enrolled 23 patients' correction surgery was performed during 2019-2020. The average age of the patients was 17.2 years on the day of the operation. There were 12 patients under the age of 17, and 11 patients were older than 17. The patient population consisted of 20 girls and 3 boys, with an average curve severity of 55 Cobb degrees.

Scoliosis surgery

In the prospective part of our study, in the patients who got the surgical indication, spondylodesis were performed after transpedicular screwing, which is the gold standard surgery of adolescent idiopathic scoliosis. The corrective manoeuvres included rod derotation, vertebral translation, distraction, compression, in situ rod bending, and direct vertebral derotation, supplemented with osteotomies, if necessary. Each time, a chromium-cobalt rod was used on the concave side, while on the convex side we used a titanium rod implant. The average surgical time was 436±124 minutes, with blood loss of 1437± 597 ml.

EOS 2D/3D imaging

EOS 2D/3D imaging was part of the routine diagnostics in our clinic. A standing posture, low-radiation, 3D reconstruction capable scanning can be performed with biplanar imaging. In each case, the imaging was carried out in a special "knuckles on clavicles" position, without forward step, to allow accurate 3D vertebral reconstructions.

A full spine 3D reconstruction was made based on X-ray images using the streEOS software (V1.4.4.5297, EOS Imaging Ltd, Paris, France), which follows the contours of all thoracic and lumbar vertebrae. An initial model is created based on anatomical reference points (e.g. sacrum plateau), which is perfected by an operator to the actual bone morphology of the patient. The reliability of the parameters calculated from the final 3D model has also been proven in comparison with CT scans.

Based on the 3D model, the sterEOS software automatically calculated the following spinal parameters:

- Cobb angle
- Th.I-Th.XII. kyphosis,
- Th.IV-Th.XII. kyphosis,
- L.I-L.V. lordosis
- L.I-S.I. lordosis
- Axial vertebral rotation (AVR) in the Th.I-L.V. vertebrae
- End vertebrae of the major curve
- Apical vertebrae of the major curve and apical vertebral rotation (apicalAVR).

The Cobb angle and AVR values were calculated in both the positive and negative ranges, depending on the direction of curvature and rotation. The absolute value of these parameters was used for subsequent calculations. The apical vertebrae are automatically identified by the sterEOS software in the major curves, but we manually determined them in the minor curves. From the axial vertebral rotation dataset, we determined the maximal vertebral rotation (maxAVR), which we compared to the automatically defined apical vertebral rotation (apicalAVR).

Statistical analysis

The statistical analysis was performed using SPSS v.23 (IBM Corp., Armonk, NY, USA).

We used descriptive statistics to test demographic data and describing the distance of the vertebrae from each other. Shapiro-Wilk test was used to examine the normal distribution. Wilcoxon test was used to compare apicalAVR and maxAVR values. Linear regression analysis was used to clarify the relationship between apicalAVR/maxAVR and Cobb angles. We examined the difference between the pre- and post-operative data series with paired sample t-test and a Wilcoxon test. Our results were considered significant at $p<0.05$.

Results

Investigating axial vertebral rotations using 3D method

In the retrospective part of our study, we compared the apicalAVR to the maxAVR. Of the 332 selected cases, in the case of 198 patients (59.6%) the apical vertebra did not have maximal rotation in the major curves. A difference between the apical vertebrae and the maximal vertebral rotation was experienced in 69 cases (67.6%) out of 102 cases in minor curves (in Lenke 2, 3, 4, 6 patients). The difference between the apicalAVR and maxAVR parameters is shown in Table 1.

maxAVR-apicalAVR difference	equal	0-3°	3-5°	5-10°	>10°	**Sum**
Major curve	134	124	39	30	5	**332**
Minor curve	34	43	16	8	1	**102**

Table 1 — Differences between apicalAVR and maxAVR values in major and minor curves

The average apicalAVR in the major curves was 12.53±9.15 degrees, compared to an average of 14.33±9.68 degrees for the maxAVR ($p < 0.001$). The maximally rotating vertebrae may have deviated by 1-2 segments from the apical vertebrae. The segment differences and the calculated apicalAVR and maxAVR parameters are shown in Table 2.

Distance from the apical vertebrae	n		apicalAVR	maxAVR	p-value
same	134		14.94±10.17°	14.94±10.17°	-
1	182		10.89±8.16°	13.91±9.59°	<0,001*
2	16		10.87±6.24°	14.23±6.16°	<0,001*
Sum	**332**		**12.53 ± 9.15°**	**14.33 ± 9.68°**	**<0,001***

Table 2 — Distance of the maximally rotating vertebrae from the apical vertebrae in the major curves (Average ± standard deviation). P-values are the results of Wilcoxon's ranking test, $p<0.05$ values were considered significant (*).

The maximal thoracal vertebral rotation (in Lenke 1, 2, 3 and 4 curves) was measured between vertebrae Th.IV. and Th.XI. with an average of 14.75±11.12°. The thoracolumbar/lumbar vertebral rotation (in Lenke 4, 5 and 6 curves) was maximal between Th.XII. and L.IV. vertebrae with an average of 13.72±7.16°.

ApicalAVR and maxAVR parameters showed significant differences from mild to severe scoliotic patients and in the different Lenke classification groups. Whether we measured the apical vertebrae or the maximally rotating vertebrae, axial rotation values are increasing in parallel with Cobb angle (both $p<0,001$ with linear regression analysis; Beta1=0.663; Beta2=0.685). The apicalAVR was measured at an average of 9.29±6.95° in structural minor curves, compared to the maxAVR average of 11.21±7.44° ($p<0.001$).

Investigation of surgical efficacy using 3D method

A surgical correction rate was 78.2% in the major curves (from an average of 55.1 Cobb degrees to 12.0 Cobb degrees; $p<0.001$). Depending on the method of measurement in the axial plane, 56.7% (average apicalAVR from 21.0 degrees to 9.1 degrees; $p<0.001$) or 55.2% (average maxAVR from 24.1 degrees to 10.8 degrees; $p<0.001$) of axial correction was reached.

There was a significant difference between the preoperative apicalAVR and maxAVR values both in the major ($p<0.001$) and minor curves ($p=0.003$). A similar significant difference was found in the evaluation of postoperative data (major curves: $p<0.001$; minor curves: $p<0.001$).

In our experience, most of the patients' deformities become inflexible at the end of adolescence, reaching the age of 17. We found a significant difference in our surgical results before and after the age of 17 years at the time of the operation, supporting this observation. In patients operated after the age of 17, nearly the same coronal curve correction was achieved with those under the age of 17 (on average 79.2% versus 77.0%; $p=0.614$), but the derotation of the deformity was significantly less successful (apicalAVR correction averaged 38.1% versus 68.5%; $p=0.016$, and maxAVR correction averaged 42.4% versus 64.4%; $p=0.020$).

Conclusions

In the retrospective part of our study, we determined the axial vertebral rotation of patients with adolescent idiopathic scoliosis using 3D imaging. The next part in our study we assessed the effectiveness of surgical correction rate, using the EOS 2D/3D method in our prospective patient register. The age of the patients was considered as a potential influencing factor.

Investigating axial vertebral rotations using 3D method

We analysed the axial parameters of the thoracolumbar spine using EOS 2D/3D imaging in a large number of patients with adolescent idiopathic scoliosis. In accordance with the literature, we have treated the axial rotation of the apical vertebrae as a priority, which we compared to the maximally rotating vertebrae. We analysed also the major and minor curves in the case of double and triple structural scoliotic deformities.

Significant differences were found between apicalAVR and maxAVR values both in the major and minor curves. Our result means that the apical vertebrae are not considered to be maximally rotating in a significant number of cases. This contradicts the general belief from the early 1990s that the apical vertebra has the highest rotation.

The adjacent vertebrae also had maximal rotation in addition to the apical vertebrae in the studied patient population. The maximal rotation was measured at a distance of two segments from the apical vertebrae in 4.8% of the major curves, and in 10.3% of the minor curves. This is consistent with the results of Stokes at al., which show that the vertebrae within two levels of the apical vertebrae may have the highest rotation.

We consider the axial rotation difference above 5° to be clinically relevant between the apical vertebrae and the maximally rotating vertebrae. This difference detected in preoperative planning can have a significant impact on the axial direction of the inserted screws. If the surgeon does not notice a difference above 5° in such a situation, there is a hypothetical possibility of complication due to improper axial screw directions (too medial or lateral screw position). On the same basis, the axial rotation difference above 10° is considered to be a particularly significant difference between the apical vertebrae and the maximally rotating vertebrae, which is definitely recommended to be detected during the preoperative examination.

Although we treat specially the axial rotation differences above 5° due to their clinical relevance, we must not forget about the differences between axial rotations below 5°, but still measurable. We see primarily the scientific relevance of such differences in highlighting the importance of maxAVR in addition to the commonly used apicalAVR parameter in describing the axial dimension of scoliosis.

ApicalAVR and maxAVR differed significantly in all severity groups, therefore the apical vertebrae cannot considered to be maximally rotating any of the severity groups. There was significant difference between apicalAVR and maxAVR values in each statistically evaluable Lenke classification groups.

The close relationship between apical vertebral rotation and Cobb angle has already been described, that we were able to confirm with our data. The maxAVR values were also significantly correlated with the Cobb angle. Our data give an additional evidence that an increasing axial rotation can be experienced during the higher coronal deformation.

We measured maximal rotation also at Th.IV-Th.V., Th.XI-Th.XII. and L.IV vertebrae compared to previous studies. On this basis, the maximally rotating vertebrae can occur any of the Th.IV-L.IV. segments.

The apical vertebra had the highest rotation in 40.4% of the major curves and in 31.7% of the minor curvatures. This difference may be caused by only the last few vertebrae cross the central sacral vertical line (CSVL) in the structural minor curves, when the rotation of the vertebrae decreases. If we focus on clinically relevant axial rotation differences (more than 5°) between the apical vertebrae and the maximally rotating vertebrae in the minor curves, the above-mentioned difference in relation to the major curves disappears (difference more than 5° difference in major curves: 10.5% compared to the minor curves: 8.8%).

Consequently, apicalAVR is even less suitable for scientific evaluation of the axial dimension of minor curves.

The retrospective structure of the study is a fundamental limiting factor. However, we believe that radiological analysis has been carried out in a standard position what would give the same results in a prospective study. It can be considered as a limitation that the software we use identifies vertebrae even in cases where there is an intervertebral disc in an apical position. This can increase the maxial rotations measured on the non-apical vertebrae and raise the need for further clarification of the method. Our values in the rare (Lenke 4) group were not statistically evaluated due to the low number of patients.

Investigation of surgical efficacy using 3D method

In the prospective part of our study, we analysed pre- and post-operative EOS 2D/3D images in idiopathic adolescent scoliosis. We measured an average of 78.2% surgical efficiency in the coronal plane by analysing the 3D reconstructions of the spine and pelvis, which corresponds to the values in the literature. We found a clinically significant corrective efficiency difference of more than 10% compared to previous surgical techniques. We experienced milder hypokyphosis (normokyphosis) than previous studies in the preoperative values of our patients (thoracal kyphosis 24.9±12.6° versus 13.2±7.9°), which was not significantly affected by the surgical correction. We found a statistically significant difference in pre- and postoperative values in the lumbar lordosis between the L.I. and L.V. vertebrae. This difference of a few degrees is not clinically relevant in our opinion.

We examined surgical efficacy in the axial plane by two different methods. We achieved a 56.7% derotation efficiency based on apicalAVR values, which is concurrent to the literature data. We measured a derotation rate of 55.2% using the maxAVR method. There is no significant difference in the percentage of the two methods because maxAVR was significantly higher than apicalAVR in both preoperative and postoperative cases, evening the degree of surgical efficacy calculated out of the two. Consequently, both methods are suitable for evaluating surgical efficacy with axial plane. However, it should be noted that maxAVR is demonstrably higher in both pre- and postoperative measurements.

We did not find any significant differences in corrective efficiency in the coronal plane among our patients who operated before or after the age of 17, but we achieved significantly higher derotation efficiency in the younger age group. Zhu at al. found a significant difference in corrective efficiency in the coronal plane of an average of 8 Cobb degrees among almost the same age groups, which is not supported by our results. A large residual rib hump after surgery has a significant effect on postoperative quality of life what makes the axial plane correction important. From a rotational point of view, Huitema at al. studied patients who underwent anterior fusion surgery before and after the age of 21. They achieved an average of 3 degrees more effective derotations in the younger age group (from 26 to 11 degrees vs. 33 to 21 degrees). Compared to their results, we found a higher difference in derotation efficiency between the age groups. However, we would note that there was a difference in age grouping and surgical techniques in the referred Dutch study, therefore the comparison between the two studies is limited.

The 23 patient enrolled in the study were found to be sufficient to detect clinically significant differences, but our results are limited by the relatively low number of cases. We found values between 80-90% with post hoc statistical power analysis for the age group tests, and the statistical power of our other results was over 99%.

Summary

We studied vertebral rotations with the help of EOS 2D/3D spinal reconstructions in adolescent idiopathic scoliosis. We have proven in all severity groups and in the statistically evaluable Lenke groups that apical vertebral rotation and maximal vertebral rotation are two different parameters. This result may provide a basis for the reassessment of many studies where only apicalAVR was used to describe the axial component. We consider the use of maxAVR instead of apicalAVR to evaluate completely the axial dimension of idiopathic scoliosis, especially in the examination of minor curves.

We assessed the effectiveness of our research group's surgical corrections with a prospective study. We examined the three dimensions of deformities and our results meets international standards. We could demonstrate the greater axial effectiveness of scoliosis correction surgeries performed before the age of 17. Based on our results, it is recommended to perform spinal correction surgery before the age of 17 from the rotational aspect in adolescent idiopathic scoliosis.

Summary of novel results

- The apical vertebrae have the highest axial rotation in 40% of cases in adolescent idiopathic scoliosis.
- ApicalAVR and maxAVR are considered two different parameters in the major curves in adolescent idiopathic scoliosis.
- In the case of the minor curves of double and triple curves, apicalAVR and maxAVR are considered two different parameters in adolescent idiopathic scoliosis.
- The difference between apicalAVR and maxAVR can be detected in all severity groups, from mild to severe scoliosis.
- The difference between apicalAVR and maxAVR can be measured in all statistically evaluable Lenke groups in adolescent idiopathic scoliosis.
- The maximally rotating vertebrae can occur anywhere from Th.IV to L.IV. vertebrae in adolescent idiopathic scoliosis.

- There may be a clinically significant difference between the axial rotation of the apical vertebrae and the maximally rotating vertebrae in adolescent idiopathic scoliosis.
- In addition to apicalAVR, maxAVR is also significantly related to the Cobb angle in adolescent idiopathic scoliosis.
- Axial plane surgical efficacy can be calculated from maxAVR parameter as well in adolescent idiopathic scoliosis.
- It is recommended to perform spinal correction surgery before the age of 17 from the rotational aspect in adolescent idiopathic scoliosis.

Publications related to this thesis

Scientific papers

József K., Schlégl, Á. T., Burkus, M., Márkus, I., O'Sullivan, I., Than, P., Tunyogi Csapó, M. (2020). Maximal Axial Vertebral Rotation in Adolescent Idiopathic Scoliosis: Is the Apical Vertebra the Most Rotated? Global Spine Journal, 2192568220948830. IF: 2,915; SJR:1,398 (D1)

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