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Predicting 3D Thoracic Kyphosis Using Traditional 2D Radiographic Measurements in Adolescent Idiopathic Scoliosis

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Abstract

Study Design: Retrospective.
Objective: To develop and validate a prediction formula to estimate three-dimensional (3D) T5−T12 kyphosis in adolescent idiopathic scoliosis (AIS) from standard two-dimensional (2D) radiographic measurements.
Summary of Background Data: 2D measurements of thoracic kyphosis in AIS patients overestimate 3D kyphosis; however, there is a lack of widespread availability of 3D imaging technology.
Methods: Retrospective review was performed for AIS patients with right thoracic curves evaluated with EOS Imaging from January 2010 to June 2014. Standard 2D posteroanterior and lateral radiographic measurements, pelvic incidence, Nash-Moe grade, Perdriolle rotation, and ''3D T5−T12'' sagittal measures (reconstructed with sterEOS, analyzed with custom MatLab code) were input into a multivariate logistic analysis to create a prediction model for 3D T5−T12 sagittal alignment. An initial cohort of 66 patients (curves 14°−85°) was used to create a predictive model, and a separate cohort of 129 patients (curves 16°−84°) was used to validate the formula.
Results: 2D thoracic coronal Cobb and 2D T5−T12 kyphosis were the only significant predictors in the model. The prediction formula for estimating 3D T5−T12 sagittal measurement from standard 2D measurements, in degrees, was 18.1 + (0.81*2D T5−T12 sagittal Cobb) − (0.54*2D coronal Cobb), $r^2 = 0.84$. The average model error between predicted and measured 3D T5−T12 kyphosis was ±7°. The predicted 3D T5−T12 kyphosis (8.6° ± 12.1°) and measured 3D T5−T12 kyphosis (8.5° ± 13.0°) were not significantly different ($p = .8$). 3D kyphosis was less than standard measures of 2D kyphosis (8.5° ± 13.0° vs. 20.2° ± 12.6°, $p < .001$).
Conclusion: This simple validated formula to predict 3D T5−T12 sagittal alignment using routine 2D thoracic Cobb and T5−T12 kyphosis for thoracic AIS patients has great potential value in assessing historical data collected prior to the development of 3D imaging methods as well as understanding/planning surgical hypokyphosis correction in patients without access to 3D imaging.

Keywords: Adolescent idiopathic scoliosis; Kyphosis; 3D; 2D to 3D conversion

Level of Evidence: Level II

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Study conducted Rady Children's Hospital, San Diego.

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Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional (3D) deformity of the spinal column that necessitates radiographic imaging for appropriate diagnostic, prognostic, and operative decision making. Initial assessment includes posteroanterior (PA) and lateral radiographs to analyze deformity magnitude in the coronal and sagittal planes. 3D imaging is now possible utilizing upright biplanar slot scanning technology (EOS Imaging, Paris, France) combined with 3D image reconstruction software (sterEOS; EOS Imaging) [1,2]. Recent studies in which the 3D segmental evaluation of thoracic kyphosis was performed in patients with thoracic AIS suggest that the two-dimensional (2D) thoracic kyphosis measures obtained from lateral radiographs are often significantly greater than the 3D measures of kyphosis [3].

The importance of accurate evaluation of sagittal alignment cannot be overstated as current evidence suggests that curve progression may be affected by sagittal balance [4,5]. Moreover, advances in surgical instrumentation have focused on sagittal plane correction [6,7], mandating accurate preoperative assessment for direct comparison. Such studies highlight the need to improve the accuracy of radiographic sagittal plane assessment.

It is likely that 2D radiographic measurement errors are attributable to a combination of overshadowing by native thoracic anatomy, but more importantly vertebral axial plane rotation [8]. As vertebral rotation occurs in the transverse plane, lateral radiographs no longer allow for a true lateral assessment of the sagittal plane angulation between vertebrae. Péloux et al. proposed using oblique radiographs oriented perpendicular to the apical vertebra (the so-called plan d'election or Stagnara view) to improve accuracy [9]. This idea was expanded upon by Hayashi et al. who showed that orienting 3D reconstructions to a lateral plane of the apical vertebra with a kyphosis measure composed of the two vertebrae above and below the apical vertebra decreased rotational projection error [3].

Given the limited access for many patients to 3D imaging in AIS, we believe it is important to seek a means of comparing historical and future 2D images, known to underestimate the degree of sagittal plane deformity, to more accurate measures of 3D segmental sagittal alignment. Therefore, the purpose of this study was to develop and validate a prediction formula to more accurately estimate 3D T5–T12 sagittal alignment from standard 2D radiographic measurements.

Materials and Methods

A retrospective review of AIS patients at our institution was conducted following IRB approval. Our database was queried for patients with right thoracic curves who obtained EOS imaging between January 2010 and June 2014. Only patients without prior surgery or the preoperative images of those who had undergone surgery were included. Patients with major thoracic curves measuring between 10° and 90° were included. To provide a heterogeneous population, we included patients with minor upper thoracic and lumbar curves.

A summary of patient selection and randomization is shown in Figure 1. A total of 2,737 patients were identified in the query. A random sample of 195 patients from the query was selected for study analysis. All patients were initially placed into randomized groups according to their thoracic Cobb angle to ensure adequate representation of all curve magnitudes without gaps in the inclusion range. Groups spanned 10° thoracic Cobb increments sequentially from 10° to 90°. Approximately one-third of patients from each group were then randomly selected for the "development cohort" (n = 66) and the remaining two-thirds were placed in the "validation cohort" (n = 129).

Data collection included both age and radiographic measurements. All radiographic measurements were performed by an orthopedic research resident and two

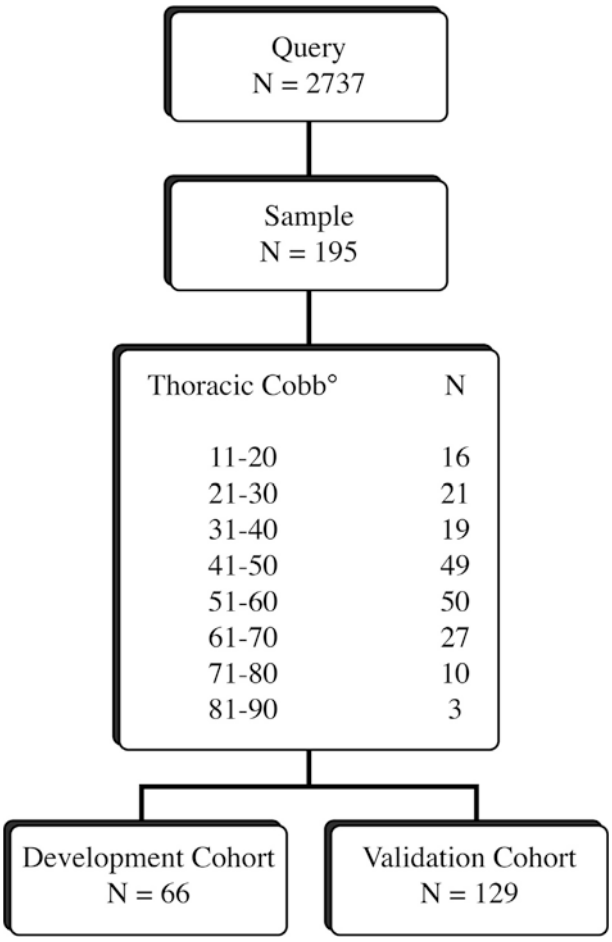

Fig. 1. Study enrollment and randomization.

orthopedic research specialists with extensive experience in the measurement of scoliosis radiographs. Standard 2D radiographic data were obtained via digital measurement of PA and lateral EOS images and included the following: 2D T5–T12 kyphosis, thoracic Cobb angle, curve direction, thoracic apex vertebra deviation, apex level, lumbar Cobb angle, lumbar apex deviation, pelvic incidence, coronal balance (C7 plumb line–center sacral vertical line distance), sagittal balance (C7 plumb line–sacral promontory distance) [10], Nash-Moe Grade [11], and Perdriolle [12] rotation. Measurement of 3D T5–T12 kyphosis was performed via customized sterEOS (EOS Imaging) and MatLab (Mathworks, Natick, MA) reconstructions with the summed segmental method previously described by Newton et al. [13]. This 3D method sums the segmental kyphosis/lordosis values for each level as measured in the local sagittal plane of each motion segment between T5 and T12 (Fig. 2). This yields a ''true'' lateral projection of each motion segment independent of the coronal or axial plane deviations. The individual sagittal measures for each segment were summed between T5 and T12. All data listed above were obtained for the development cohort whereas only those variables significantly correlated with 3D T5–T12 kyphosis were recorded for the validation cohort.

Statistics

The development cohort was used to create a prediction formula for estimated 3D T5–T12 kyphosis. Pearson's univariate analysis was performed to identify all variables correlated with 3D T5–T12 kyphosis. A stepwise multivariate regression was performed on all significantly correlated variables to create the final prediction model. The validation cohort was utilized to verify the accuracy and reproducibility of the prediction formula. ANOVA was performed to check for significant differences between the development and validation cohort predictions of 3D T5–T12 kyphosis. A linear regression was done to evaluate the formula in the validation group. Finally, mean absolute errors (the absolute value of the difference between the actual and predicted values of 3D T5–T12 kyphosis) of the cohorts were compared to ensure validity. All data were analyzed using the SPSS 11.0 (SPSS, Chicago, IL) statistical software program.

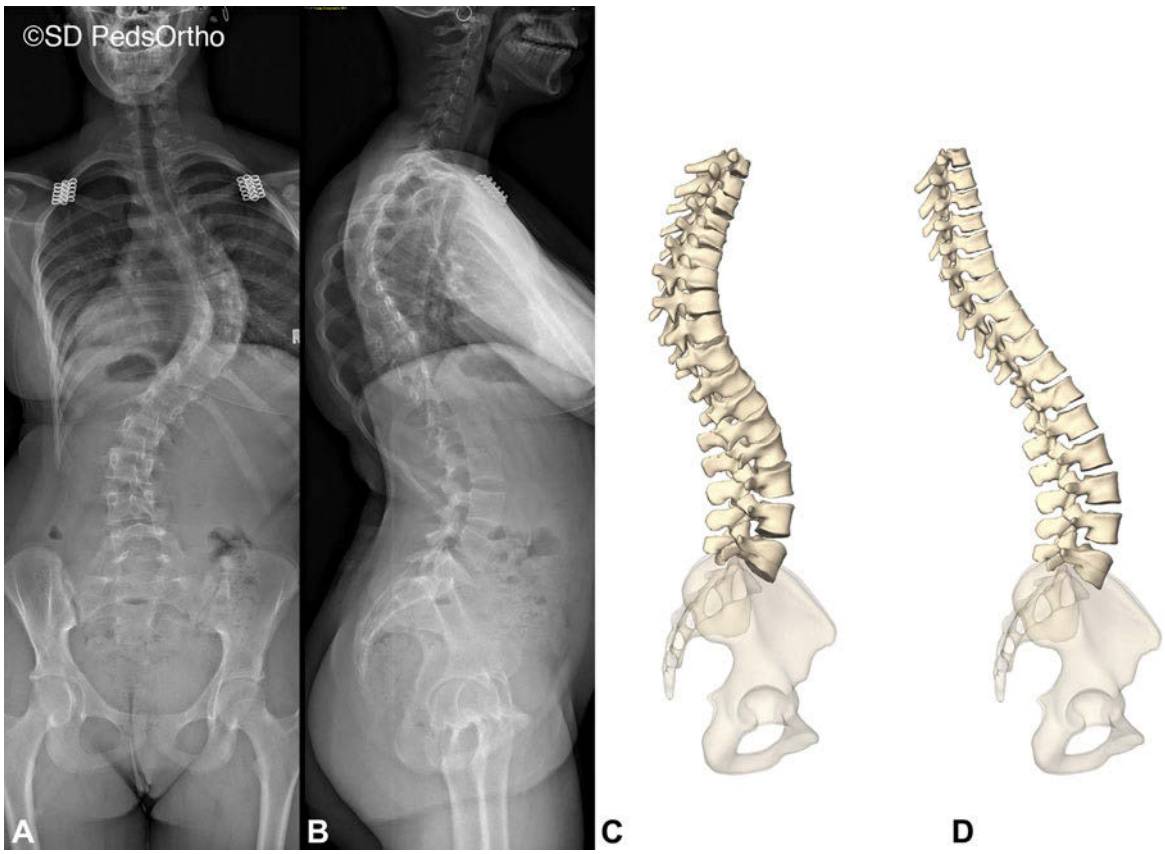

Fig. 2. The 2D radiographs (A, B) and the 3D reconstructed lateral image in the traditional global reference frame (C) underestimate the hypokyphosis that is observed with the 3D reconstructed model using the summed segmental method (D) that ''restacks'' each motion segment in its respective plane, eliminating the influence of the coronal and axial deformities on the sagittal plane.

Results

Demographic and radiographic data for both cohorts are shown in Table 1. Thoracic Cobb angles ranged between 14° and 85° in the development group and between 16° and 84° in the validation group. There were no significant differences between the development and validation groups in terms of thoracic Cobb angle ($p = .357$), 2D T5–T12 kyphosis ($p = .183$), or 3D T5–T12 kyphosis ($p = .134$).

Nearly all measured 2D variables were significantly correlated with 3D T5–T12 kyphosis (Table 2). The only variable not significantly correlated was lumbar apex deviation. There was a trend toward correlation for sagittal and coronal balance, with both approaching significance at $p = .05$. Of all the variables significantly correlated with 3D T5–T12 kyphosis, only 2D T5–T12 kyphosis was positively correlated; all others were negatively correlated.

The stepwise multivariate regression showed that 2D T5–T12 kyphosis and 2D thoracic Cobb were the only two significant independent predictors of 3D T5–T12 kyphosis (Table 3). The final prediction formula for 3D T5–T12 kyphosis was the following: 3D T5–T12 kyphosis = 18.1 + (0.81*2D T5–T12 kyphosis) − (0.54*2D thoracic Cobb) degrees. The average model error between predicted and actual measured 3D kyphosis was ±7°. 2D T5–T12 kyphosis accounted for 47% of the variability while 2D thoracic Cobb accounted for 38% for an R^2 of 0.84.

The findings for the formula testing in the validation cohort were similar to the development cohort (Fig. 3). The mean predicted 3D T5–T12 kyphosis (8.6° ± 12.1°) and measured 3D T5–T12 kyphosis (8.5° ± 13.0°) were not significantly different ($p = .8$). However, both were significantly less than the measured 2D T5–T12 kyphosis (20.2° ± 12.6°, $p < .001$, $p < .001$). The model

Table 1
Demographic and radiographic data for the development and validation cohorts.

Variable	Development (mean ± σ)	Validation (mean ± σ)	Significance (p)
Thoracic Cobb (°)	45.6 ± 19.8	47.8 ± 13.6	.357
2D T5–T12 kyphosis (°)	22.8 ± 14.0	20.2 ± 12.6	.183
3D T5–T12 kyphosis (°)	11.8 ± 17.4	8.5 ± 13.0	.134
Thoracic apex deviation (cm)	3.7 ± 2.5		
Thoracic apex level	8.6 ± 0.9		
Lumbar Cobb (°)	29.4 ± 12.9		
Lumbar apex deviation (cm)	−1.1 ± 1.1		
Pelvic incidence (°)	52.7 ± 12.9		
Coronal balance (cm)	0.0 ± 1.6		
Sagittal balance (cm)	0.6 ± 2.5		
Nash-Moe grade	1.5 ± 0.6		
Perdriolle rotation (°)	15.0 ± 11.3		
Age (years)	13.1 ± 2.3		

Only those variables significantly correlated with 3D T5–T12 kyphosis were recorded for the validation group.

Table 2
Results of Pearson correlation between measured variables and 3D T5–T12 kyphosis.

Variable	Correlation	Significance (p)
Age	−0.309	.012
2D T5–T12 kyphosis	0.682	<.0001
Thoracic Cobb	−0.651	<.0001
Thoracic apex deviation	−0.559	<.0001
Lumbar Cobb	−0.519	<.0001
Lumbar apex deviation	0.055	.661
Pelvic incidence	−0.259	.036
Coronal balance	−0.242	.050
Sagittal balance	−0.243	.050
Nash-Moe grade	−0.504	<.0001
Perdriolle rotation	−0.535	<.0001

Table 3
Results of the stepwise multivariate regression.

Variable	R^2	Significance (p)
2D T5–T12 kyphosis	0.47	<.001
2D thoracic Cobb	0.38	<.001
Combined	0.84	

2D T5–T12 kyphosis and 2D thoracic Cobb were the sole significant predictors that accounted for 84% of the variability of the model.

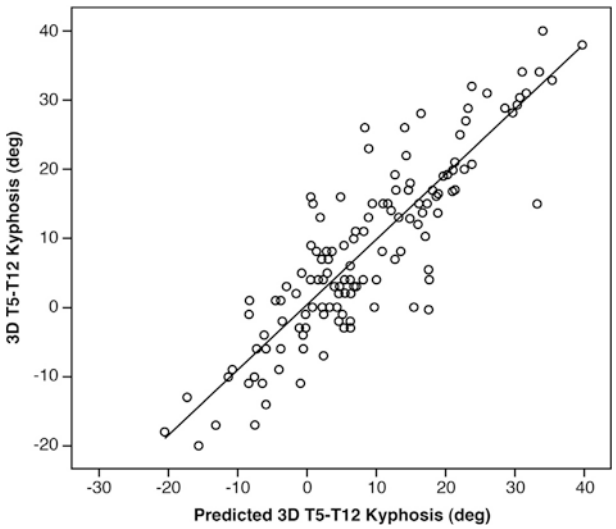

Fig. 3. Predicted 3D T5–T12 kyphosis versus 3D EOS measured T5–T12 kyphosis in the validation cohort.

Table 4
Results of formula validity testing.

Cohort	Mean absolute error (°)	Standard deviation	n	Significance (p)
Development	5.48	4.07	66	.283
Validation	4.83	3.98	129	
Total	5.05	4.01	195	

Mean absolute errors between the development and validation cohort were not significantly different.

accounted for 77% of the variability between predicted and measured 3D T5–T12 kyphosis in the validation cohort. The average model error in the validation cohort was ±6.3°.

The mean absolute errors of the formula in the development and validation cohorts were not significantly different (Table 4). Mean absolute error for the development cohort was 5.5° ± 4.0° and the validation cohort was 4.8° ± 4.0°. In all patients combined, the mean absolute error was 5.1°.

Discussion

Curve morphology in AIS patients is complex and renders radiographic assessment difficult and, occasionally, inaccurate. There is significant variation in the sagittal profile, and obscuring native anatomy in the thoracic region has led to low inter- and intraobserver reliability for measuring 2D thoracic kyphosis [3,14]. Accurate recognition of 3D alignment is crucial to the management of scoliosis and may be useful for comparing prior and current research findings [15,16]. As such, a method for more accurately assessing thoracic sagittal alignment may have great current and future clinical utility for patients with AIS. The EOS Imaging system allows 3D reconstructions of the scoliotic spine to be generated and has permitted surgeons to clearly identify substantial abnormalities of the thoracic sagittal plane in patients with AIS [5,17-21]. However, there is no universal access to these advanced 3D imaging methods and historical plain radiographic measurements have also been limited to planar measurements.

Our results show that a prediction formula exists that is accurate and valid for estimating 3D T5–T12 kyphosis in AIS patients based solely on standard thoracic coronal Cobb angle and sagittal T5–T12 kyphosis measurements from PA and lateral images. The formula was created using a validated imaging system that is accurate and reproducible [14,22]. The prediction formula requires only two simple, common measurements that can readily be obtained from 2D radiographs. As the formula was developed in a large number of AIS patients equally spanning thoracic Cobb angles ranging from 10° to 90°, it may be clinically utilized for patients with smaller Cobb angles who may be observation or bracing candidates as well as those with larger operative size curves. Accordingly, it also applies to the majority of patients presenting clinically as well as to the vast number of studies previously published in the scientific literature.

The measured error value of 7° in the prediction formula is similar to other measurement error values reported in the literature for thoracic kyphosis measurements. Carreau et al. found an average digital 2D T4–T12 kyphosis measurement error of 7.06° ± 6.55° [14]. In another study, Kuklo et al. reported an average digital 2D T5–T12 kyphosis measurement error of 6.68° (95% confidence interval 5.74°–7.61°) [23]. The similar magnitudes suggest that the present study provides a reasonably accurate means of estimating 3D thoracic kyphosis for patient populations.

These data supplement prior knowledge that 2D measures of thoracic kyphosis in patients with thoracic AIS are often overestimated when measured on the lateral radiograph compared with the more sophisticated 3D summed segmental measurement technique [13]. Depending on the method used and the magnitude of the deformity, thoracic kyphosis may be measured up to 10°–20° greater on a standard lateral radiograph than the more precise 3D methods that account for variations in spinal axial plane rotation [3,14]. Moreover, the significant negative correlations found with variables associated with 3D T5–T12 kyphosis support prior observations that these variables are responsible for the measurement differences between the 2D and 3D methods of kyphosis measurement. Specifically, increases in thoracic Cobb, thoracic apex deviation, lumbar Cobb, pelvic incidence, coronal imbalance, sagittal imbalance, and rotation may increase overestimations of T5–T12 kyphosis. This finding is particularly valuable as it further illustrates that many patients are more hypokyphotic segmentally at the apex than previously recognized and reported in the literature using 2D measures of thoracic kyphosis. Although this study does not evaluate curve progression, these findings are in line with current data that suggest when properly measured, hypokyphotic sagittal imbalance may play a role in curve progression [16,24].

Although other modalities such as computed tomography (CT) can also provide accurate 3D data, the concerns regarding radiation exposure and the possibility of late radiation sequelae in this vulnerable population [25] prevent their use for the numerous evaluations AIS patients require. As previously described by Carreau et al., the EOS system has high inter- and intraobserver reliability and accuracy [14]. Although the number of scoliosis centers offering EOS Imaging is increasing, access to this low-dose radiation imaging technique with 3D reconstruction capabilities remains limited across the world. The majority of facilities continue to instead rely on standard PA and lateral 2D radiographs for clinical evaluation. As a result, this prediction formula may have significant clinical applicability worldwide by allowing an accurate estimation of 3D T5–T12 kyphosis solely based on standard 2D imaging.

More recent research on operative outcomes in AIS has focused on obtaining and maintaining correction of thoracic kyphosis [26-30]. The majority of studies used preoperative thoracic kyphosis data obtained from measuring standard radiographs [6,7]. As previously mentioned, the inaccuracy of such measurements makes comparisons between pre- and postoperative values particularly problematic. Although such measurements are more accurate on postoperative films in which the spinal curvature has been corrected (especially with axial derotation), the comparison of these pre- and postoperative measurements may lead to

incorrect conclusions primarily because of the inaccuracy of the preoperative measurements. It is our hope that this prediction formula will help standardize such comparisons by both reevaluating prior outcomes and assessing current and future 2D data.

The study is not without limitations; the formula is only for patients with AIS and right major thoracic curves, and thus should not be used in patients with left curves, patients with scoliosis due to nonidiopathic causes, or major lumbar curves. Although the average error term is small and on par with prior measurement variations, the prediction should not be expected to exactly match the true 3D sagittal alignment measurement for individual patients. This formula is best suited for the purpose of aggregated data within larger patient populations and may not be as accurate if applied to determining an individual patient's estimated 3D kyphosis. Finally, the model was specifically created for kyphosis measured between the levels of T5 and T12 in order to match much of the previously published data [7,13,23,26,28] and thus should not be extrapolated to other levels. Nevertheless, we find the validity and simplicity that the prediction model provides as a valuable tool for clinical assessment of the thoracic sagittal alignment in patients with thoracic AIS.

Conclusion

This study utilized a broad range of AIS patients with right thoracic curves to develop an accurate and valid method for predicting 3D thoracic kyphosis between T5 and T12 based on standard 2D posteroanterior and lateral radiographs. Thoracic Cobb angle and 2D T5–T12 kyphosis were the sole significant predictors for estimating 3D T5–T12 sagittal alignment. This simple formula has great potential value in assessing historical 2D data collected before 3D imaging methods as well as helping with surgical planning for patients without access to 3D imaging. The 3D kyphosis prediction formula created in this study will allow surgeons to better assess their AIS patients' sagittal deformities both pre- and postoperatively in hopes of improving the outcomes and understanding of this condition.

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