

The Use of EOS Imaging to Assess Curve Magnitude Changes in Adolescent Idiopathic Scoliosis Undertaking Brace Management

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Abstract

This study aimed to investigate the use of EOS (bi-planer) imaging and SterEOS reconstruction software to study the efficacy of spinal bracing in adolescent idiopathic scoliosis (AIS).

EOS images of scoliosis patients being treated with bracing were obtained both in and out of their brace. These images were processed using SterEOS software to allow 3D representation, which was then compared to traditional coronal 2D parameters. Over a 12-month period 29 patients were recruited for participation. Of these participants, 25 had a single episode of EOS imaging out of and in their brace. Additionally, 19 of the 25 participants had further episodes of EOS imaging within the study period, separated by mean 144+/-44 days. This allowed a total of 44 EOS single scan episodes for parameter analysis out of, and in the brace. Longitudinal analysis was also performed on the 19 patients who had sequential scans.

Participants were mean 13.8 ± 1.1 years old at the first scan.

Coronal 2D parameters, specifically Cobb Angle measurement, were accurately reproducible with SterEOS 3D measurements.

Across all EOS scans (n = 44) the mean major coronal curve measurement was 42.3 ± 13.3° out of brace and 37.2 ± 13.8° in the brace. This produced a mean correction of 4.6 ± 4.4° (p < 0.05). The correction achieved in this cohort with bracing appeared more modest than those reported in previous studies using traditional 2D coronal curve measurements [1-3].

The mean axial vertebral rotation (AVR) was 10.6 ± 7.1° out of the brace and 9.6 ± 6.8° in the brace, with a mean correction of 1.4 ± 5.3° (p = 0.14). The current study results suggested no significant change in axial vertebral rotation with brace treatment. Notably, in 17 of the 44 AVR measured, the differences were negative. That is, the AVR worsened in the brace.

There was a significant moderate correlation between 3D coronal Cobb angle measured and AVR measured out of the brace for all curves. However, the change in Cobb and change in AVR with bracing did not correlate.

Over sequential EOS episodes (n = 19), there appeared no significant progression of 3D parameters.

There appeared to be a consistent reduction in the scoliosis Cobb angle of the major curve with brace treatment. AVR demonstrated no significant change with bracing, with instances of worsening of AVR in the brace, which was not reflected by Cobb angle measurement. Despite this, bracing appears to have limited curve progression in sequential scans, though not in the anticipated manner of immediate in-brace curve correction.

Keywords: Scoliosis; Adolescent Idiopathic Scoliosis (AIS); Bi-planer Imaging = EOS™ imaging = EOS Imaging; SterEOS™ = SterEOS; Spinal Bracing; Boston Brace; Vertebral Rotation; Axial Vertebral Rotation (AVR); Spine.

Abbreviations

AIS: Adolescent Idiopathic Scoliosis; EOS™: Bi-planer Collimated Beam x-ray; SterEOS™: Proprietary Software Used for Three-dimensional Reconstruction of EOS Generated x-rays

Introduction

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional (3D) curvature of the vertebral column, characterized by acquired abnormal development in the sagittal, coronal and axial planes. AIS is the most common spinal deformity of children and adolescents between 10 and 16 years, affecting 2-4% of the population [4,5].

Non-operative measures to control scoliosis during growth are limited. For curve magnitudes between 25-45°, in skeletally immature patients, bracing may be used to control curve progression [5-7]. Though bracing is common, its use is not universal, and the exact mechanisms by which it controls curve progression are not fully understood. Most braces are varied applications of the thoracic-lumbar-sacral orthoses (TLSO), commonly the “Boston brace” (Figure 1) [8]. Recent braces such as the Rigo-Chenaau [9,10], the PASB [11], and the Sforzesco brace [12,13] are being defined.

tion (AVR) at initial presentation identified as a key risk factor in the development of a progressive scoliotic deformity [15,16]. This may occur prior to scoliosis being evident on plane radiographs [17]. The sagittal 2D Cobb angle, though widely used, has been questioned by the SRS [18] as insufficient for complete assessment due to absence of transverse plan assessment [19-21].

Recently EOS™ imaging has been utilized to enable 3D assessment of the spinal deformity, with significantly reduced radiation exposure [3,22] (Figure 2).

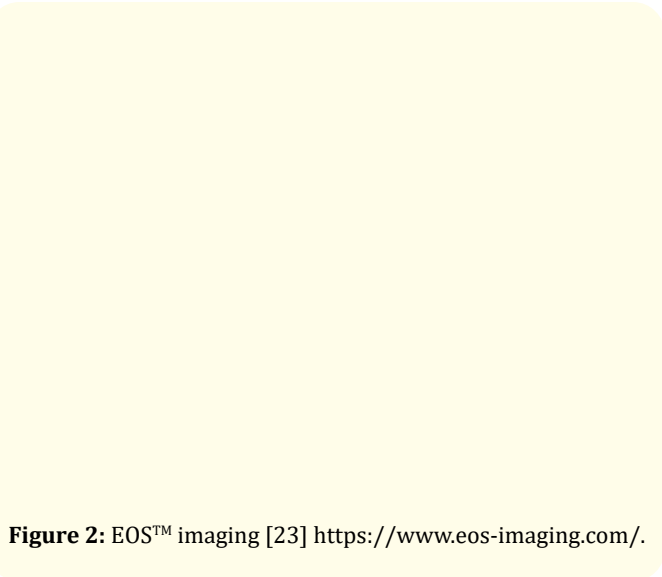


Figure 2: EOS™ imaging [23] <https://www.eos-imaging.com/>.

EOS™ allows the acquisition of two images in orthogonal planes simultaneously [24]. Utilizing this feature, with SterEOS™ software, this allows 3-dimensional reconstruction of bony structures [25]. Importantly, this is performed in the standing position in EOS™ with the effect of gravity demonstrated to be in the order of 11° of Cobb angle measurement [26-28].

Materials and Methods

This was a prospective study in patients undertaking brace management over a 12 month period. The patients typically had a scoliosis of greater than 25°, with growth potential defined by a Risser grading of 0-3.

Ethical approvals were obtained from both the Queensland Hospital and Health Service (HREC/18/QRCH/26) and the Queensland University of Technology Human Research Ethics Committee (QUT 1800000603).

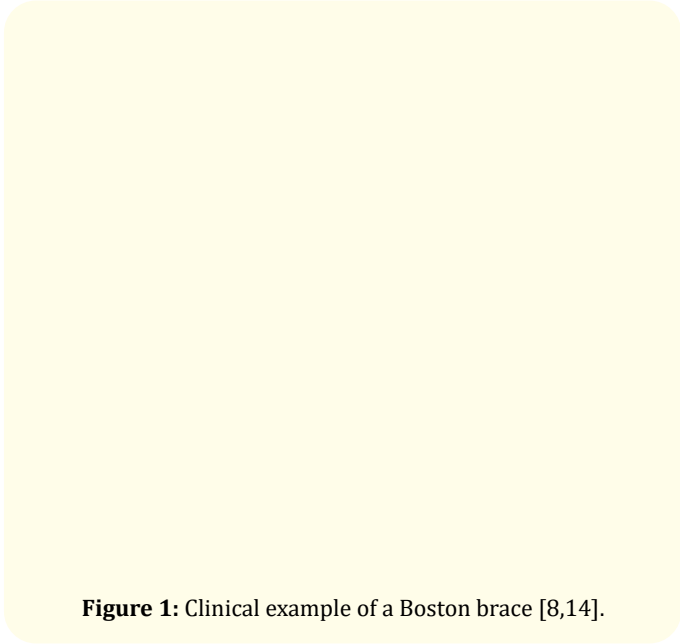


Figure 1: Clinical example of a Boston brace [8,14].

Conventionally a standing 2D radiograph is taken to assess the curvature. Understanding scoliosis as a 3D deformity in the axial plane, however, remains of importance, with axial vertebral rota-

AIS patients being treated with bracing at the Queensland Children’s Hospital (QCH) were invited to participate using the criteria outlined in table 1.

Inclusion criteria	Exclusion criteria
Male and female patients aged 10 to 17 years	Patients of congenital, neuromuscular or other types of scoliosis
Diagnosis of idiopathic scoliosis	Patients who had already had corrective surgery
A minimum Cobb Angle required of 10°	The subject’s parent/guardian was cognitively impaired or unable to fully understand the study information sheet
Patients eligible for brace treatment as part of their standard clinical care	If consent was not given, participants were not be able to participate in this study

Table 1: Inclusion and Exclusion criteria for bracing study.

Informed consent was obtained from both the participant and their legal guardian. All research was performed in accordance with the relevant guidelines established with Declaration of Helsinki.

EOS imaging was taken both in and out of the brace at each review appointment during the study period (every 4 - 6 months). For each review appointment, the brace was removed the evening prior to allow a minimum 12 hours ‘out of brace’. The brace was then reapplied after the initial EOS image and a further EOS image taken in the brace to allow comparison. Follow-up continued until the completion of brace treatment.

The EOS images obtained were processed using SterEOS™ software on a Windows Operating System workstation.

Coronal Parameters recorded were 2D and 3D Cobb angle measurements. Sagittal Parameters recorded were Pelvic Incidence (PI), Pelvic Tilt (PT), Sacral Slope (SS), Thoracic Kyphosis and Lumbar Lordosis. The single Intervertebral Orientation of Axial vertebral rotation (AVR) was recorded in 17 vertebrae from T1 to L5 using SterEOS™. AVR was referenced in both the ‘patient plane’ (pelvic orientation) and ‘radio plane’ (device orientation). The apex of the curve and the apical vertebra were used for comparative analysis.

EOS and SterEOS derived curve parameters were interpreted in the context of standard coronal 2D curve angle (Cobb angle [29]) measured from the PA radiograph obtained from EOS.

The Risser sign was recorded from the frontal plane EOS view. The scoliosis curve classification was determined according to Lenke [8].

Statistical analysis was performed using IBM SPSS™ (Version 25) analysis software. Statistical testing was performed using paired sample t-tests and Pearson’s correlation.

Results and Discussion

Between January 2019 and January 2020, 29 patients were recruited. Three patients were prescribed bracing but were non-compliant and one patient did not attend their appointment. This provided a cohort of 25 patients having at least one single episode of EOS imaging out of and in their brace over a 12 month period. 19 patients had two episodes of EOS imaging, separated by mean 144+/-44 days, allowing longitudinal analysis of parameters.

There were a total of 44 EOS scan episodes available for immediate parameter analysis, out of and in the brace (Table 2).

	n	Mean Age (yrs +/- SD.)	Mean Risser Grade	Lenke Type [30] (n)
Number of Participants	25	13.8+/-1.1	1.5+/-1.6	1 (15) 2(1) 3(2) 4(0) 5(5) 6(2)
All EOS Scans	44	13.8+/-1.1	1.5+/-1.6	
1 st scan	25	13.5+/-1.1	1.3+/-1.6	
2 nd scan	19	13.9+/-1.1	1.7+/-1.6	
Average time between 1 st and 2 nd scan 144+/-44 days				

Table 2: EOS episode demographics including Lenke curve type [30].

Results

3D versus 2D coronal Cobb angle measurements on all Scoliosis curves

The coronal 2D Cobb angle measurements, taken from the PA EOS radiographs were compared to the 3D reconstruction Cobb angle measurement from SterEOS (n = 44). The mean 2D coronal Cobb angle out of brace was 42.3+/-13.3°. The mean SterEOS 3D coronal Cobb angle out brace was 41.1+/-12.8°. The mean difference was 1.3+/-3.4°. This produced a significant (p < 0.05) strong correlation of values (r = 0.96).

3D coronal Cobb angle out of brace versus 3D coronal Cobb angle in brace

Difference in 3D Cobb angle measurements were analyzed for changes between the out of and in brace condition (n = 44). The mean coronal Cobb angle measurement out of the brace was 42.3+/-13.3°. The mean coronal Cobb angle measurement in the brace was 37.7+/-13.8°. This resulted in a mean difference of 4.6+/-4.4° (p < 0.05). Curves with a magnitude of less than 40° were separated (n = 18), as to reflect a more common bracing population, with a similar mean difference of 4.3+/-6.9° (p < 0.05).

Change in 3D coronal Cobb angle in brace versus 3D Cobb angle out of brace

There was no significant correlation (p = 0.63; r = 0.06) between the absolute 3D coronal Cobb angle and the change in coronal Cobb angle with bracing in all curve types (Figure 3). This indicated the magnitude of the reduction in coronal Cobb angle when measured in-brace was independent of curve severity.

Figure 3: Change in Cobb versus 3D Cobb for all curve.

AVR out of brace versus AVR in brace

Difference in AVR were analyzed for the changes between out of and in brace conditions (n = 44). The mean AVR out of the brace was 10.6+/-7.1°. The mean AVR in the brace was 9.6+/-6.8°. The mean difference in AVR was 1.7 +/- 5.3°, demonstrating no significant difference (p = 0.14).

Notably, in 17 of the 44 measurements the AVR were negative. That is, the AVR worsened in brace. These 17 patients were separated for further analysis. For worsening AVR in brace the mean out of brace was 9.7+/-5.45°. The mean AVR in brace was 13.1+/-5.13°. The mean difference in AVR was 3.1+/-3.3° (p < 0.05). Out of the 17 patients for whom AVR was recorded to have worsened, only 2 had a worsening of Cobb angle measurement, with 15 still recording an improvement in Cobb angle in brace.

The AVR results were separated out for curve magnitudes less than 40° (n = 18), with mean AVR out of the brace of 7.7+/-3.7° and in the brace of 6.9+/-4.7°. This was a mean difference of 2.6+/-4.9°, demonstrating no significant difference (p = 0.25).

AVR out of brace versus 3D Cobb angle out of brace

There was a significant (p < 0.05) moderate correlation (r = 0.47) between 3D major coronal Cobb angle measured out of brace and AVR measured out of the brace in all curve types (Figure 4).

Figure 4: AVR out of brace versus major coronal Cobb angle out of brace.

Change in AVR in Brace versus 3D Cobb angle out of brace

The change in AVR measurement with bracing was compared to the 3D coronal Cobb angle out of brace (Figure 5). There was no significant correlation ($p = 0.55$; $r = 0.1$) between the absolute 3D coronal Cobb angle measurement and the change in AVR measurement with bracing.

Figure 5: Change of AVR versus 3D coronal Cobb angle Out of the brace.

Results were separated for curve magnitudes of less than 40° ($n = 18$) (Figure 6). Although there appeared to be a trend for smaller magnitude changes in in-brace AVR with increasing 3D coronal Cobb angle, there was no significant correlation ($p = 0.25$; $r = 0.29$) between these measurements.

Figure 6: Change in AVR in brace versus 3D coronal Cobb angle out of the brace for curves $<40^\circ$.

Sequential 3D coronal Cobb angle and Axial Vertebral Rotation Measurements

Measurements were analyzed over sequential EOS episodes in the same patient group. This was performed in 19 patients over a 12 month study period with a mean time between imaging of 144 ± 44 days.

The major coronal Cobb angle out of the Brace were compared over sequential EOS episodes. The mean Initial Cobb angle ‘out of brace’ for the first episode was $41.8 \pm 12.8^\circ$. The mean Cobb angle ‘out of brace’ for the second episode was $43.2 \pm 14.6^\circ$, demonstrating no significant difference $1.5 \pm 6.8^\circ$ ($p = 0.36$).

The major coronal Cobb angle measurements ‘in brace’ were compared over sequential EOS episodes. The mean Cobb angle in the brace for the first episode was $38.7 \pm 12.2^\circ$. The mean Cobb angle ‘in brace’ for the second episode was $38.0 \pm 15.1^\circ$, resulting in a mean difference of $0.7 \pm 6.3^\circ$ ($p = 0.65$).

This indicated no significant out of, or in brace magnitude progression of the major coronal Cobb angle.

AVR measurements out of the Brace were compared over sequential EOS episodes. The mean AVR ‘out of brace’ for the first episode was $10.4 \pm 6.4^\circ$. The mean AVR ‘out of brace’ for the second episode was $11.4 \pm 8.3^\circ$, resulting in a mean difference of $1.0 \pm 6.8^\circ$ ($p = 0.53$).

The mean AVR ‘in brace’ for the first episode was $11.1 \pm 6.7^\circ$. The mean AVR ‘in brace’ for the second episode was $9.2 \pm 7.4^\circ$, resulting in a mean difference of $1.9 \pm 5.4^\circ$ ($p = 0.15$).

This indicated no significant out of, or in brace AVR progression.

Discussion

Brace treatment is a common measure used to control scoliosis during growth and is commonly employed at curve magnitudes of $20-40^\circ$, with growth remaining [7,31]. The use of EOS imaging for scoliosis surveillance presents an attractive tool to minimize cumulative radiation exposure during this period. Additionally, due to the simultaneous acquisition of frontal and lateral imaging, it has facilitated software, SterEOS™, to allow 3D reconstruction.

In clinical practice, scoliosis is most commonly characterized by 2D curve values as determined by the Cobb method [32]. This

method has been shown to exhibit good intra and inter-observer reliability [33-35]. The traditional 2D parameter measurements recorded in our study are reproduced in our SterEOS 3D measurements, with a strong correlation.

The biomechanics of brace correction has the potential to be further defined in 3D planes with SterEOS™ [13]. Measurement beyond the 2D coronal plane is leading to the development of varied brace systems looking to address the rotatory or torsional component of the vertebral deformity [9,11,12,36]. Our study attempted to measure specific parameters of scoliosis correction, including AVR, ultimately to be used to predict the 'in use' effect of the braces rather than relying on the effect of the brace empirically [17].

Across all EOS scans there was a mean 3D Cobb angle correction with bracing of $4.6 \pm 4.4^\circ$ ($p < 0.05$). Curves of $<40^\circ$ ($n = 18$), reflecting a more common magnitude for bracing, demonstrated a clinically similar mean difference of $4.3 \pm 4.92^\circ$. This would indicate that curve type and magnitude did not appear to influence the degree of correction. This immediate correction appeared more modest than previous studies using 2D Cobb angle measurements [1-3].

Though the exact mechanism of the bracing effect is not known, it has been suggested that a greater immediate curve correction may lead to greater ultimate success [2,5,37]. It is postulated that this may relate to the effect on the bending moment at the apex of the curve. Using finite element modeling, it has been suggested that greater than 20% correction is required to nullify the bending moment [1,38].

Therefore, though 3D Cobb angle measurements in this study demonstrated statistical improvement when imaged in the Brace, from a clinical perspective this appeared more modest. The sample size is relatively small compared to previous multicenter bracing outcome studies and the sample is curve heterogeneous. A larger cohort may have allowed further separations to be made. The time taken for the brace to take effect may also be questioned. The participants were requested to take the brace off the night prior. This appears adequate given previous studies demonstrating loss of correction 2 hours after brace removal [39]. Lastly, spinal flexibility is another factor demonstrated to influence scoliotic curve correction in brace and secondarily, to influence bracing outcome [2,40,41]. Some authors have suggested aiming for 40% or more correction

of the initial coronal curvature [37,42,43]. Patient's enrolled in this study did not have flexibility x-rays prior to brace application due to ethical considerations. Flexibility films are, at this point are not accurately attained in the EOS.

The change in the 3D Cobb angle in the brace was also compared to the absolute 3D Cobb angle out of the brace. It was thought that with increasing Cobb angle, there may be less correction of the curve. However, there appeared no significant correlation ($r = 0.06$; $p = 0.63$) between the absolute 3D coronal Cobb angle and the change in Cobb angle with bracing in all curve types. There was a weak, but not significant ($r = -0.18$; $p = 0.48$), negative correlation with curves analyzed of magnitude less than 40° ($n = 18$). From clinical experience, and previous literature, this trend for a negative correlation was expected, but the lack of significance was not. As curve magnitude increases, the curve proportionately becomes stiffer [44]. It was therefore anticipated that there would have been less change in Cobb angle measurement with brace treatment as the curve magnitude increased.

The transverse plane assessment, in the form of AVR, is relevant for complete deformity a assessment [18-21]. When comparing 3D Cobb angle measurement to AVR, there was a significant ($p < 0.05$) moderate ($r = 0.47$) correlation measured out of the brace in all curve types. This would reflect clinical experience with greater rotation observed with increasing curve severity with the deformity related to vertebral rotation within the curvature limits [20,45-48]. This result reinforces other reconstructive methods such as CT and MRI [26,47].

The AVR out of and in the brace were compared. Results for the mean difference in AVR out- vs in-brace suggested no significant change with brace treatment. This is despite a significant change in Cobb angle measurement as seen above. The change in AVR was also not influenced by the severity of the curve, as measured by the out of brace 3D coronal Cobb angle. Notably, in 17 of the 44 AVR measurements, the differences were negative. That is, the AVR was measured greater, or worsened, in brace, with a mean difference of $3.1^\circ \pm 3.3^\circ$ ($p < 0.05$). Previous literature evaluating change in AVR between the out of and in brace condition is limited. Recently, Courvoisier, *et al.* [49] has performed an analysis of biplaner imaging and the effect of bracing in 30 patients. The AVR was improved ($>5^\circ$) in only 26% of cases, worsened in 23% and unchanged in

50%. A greater than 5° difference was required in order to state a significant difference, which would be consistent with our confidence interval. In Courvoisier's [49] discussion, "the main finding is the high variability of the effects on bracing on all 3D parameters". It is suggested that given the population is heterogeneous and that the cohort small (n = 30), this may represent a limitation to interpretation of these results.

Given the results of our current study, AVR however does not appear to exhibit significant improvement with orthotic bracing and in some cases worsens.

The fundamental aim of bracing, however, is to prevent curve progression and avoid the curve reaching a magnitude that will continue to progress through skeletal maturity, or require surgical correction. The effectiveness of brace treatment has been established in clinical studies using 2D Cobb angle progression measured from radiographs at the time of bracing to final curve magnitude or progression to surgery as outcomes [17,36,50,51]. Success may be defined as less than 5° major curve progression between episodes, final curve magnitude of less than 50° and/or not requiring surgical intervention [50,51]. Coronal Cobb angle measurements out of the Brace were compared over sequential EOS episodes, and demonstrated no significant change. Clinically, this result may be seen as successful for this cohort, as curve progression had been less than 5° over an interval of 4 months.

Notably this occurred despite what may be considered a modest immediate improvement in coronal Cobb angle measurement when in the brace.

Again, though the AVR appears to correlate with absolute Cobb angle measurement, the changes that occurred in bracing do not appear consistent across Cobb angles and AVR. This is not able to be explained from the results obtained. Correlation with more detailed anatomical imaging may be useful in the future.

Conclusions

The present study investigated the function of spinal bracing in treating scoliosis patients utilizing bi-planer imaging, EOS™ imaging and SterEOS™.

The traditional 2D parameters were accurately reproducible in SterEOS 3D measurements. Across all EOS scans the coronal Cobb angle correction achieved in this cohort with bracing appeared

more modest than previous studies [1-3]. This is postulated to be due to curve flexibility and the curve magnitude of the cohort. With respect to the difference in the axial plane that results from bracing, the current study results suggested no significant change in AVR, and in some cases worsening. Notably, in 17 of the 44 AVR measured, the differences were negative. This warrants further investigation.

Over sequential EOS episodes there appeared no significant progression of 3D parameters. This appears to be occurring through predominantly coronal plane correction.

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