Spine

SPINE Volume 36, Number 20, pp E1306–E1313

Angle Measurement Reproducibility Using EOS Three-Dimensional Reconstructions in Adolescent Idiopathic Scoliosis Treated by Posterior Instrumentation

Brice Ilharreborde, MD,*† Jean Sebastien Steffen, PhD,† Eric Nectoux, MD,‡ Jean Marc Vital, MD,‡ Keyvan Mazda, MD,* Wafa Skalli, PhD,† and Ibrahim Obeid, MD‡

Study Design. A reproducibility study was conducted in preoperative and postoperative three-dimensional (3D) measurements for patients operated for adolescent idiopathic scoliosis (AIS).

Objective. To assess the reliability of preoperative and postoperative 3D reconstructions using EOS in patients operated for AIS.

Summary of Background Data. No prior reliability study of 3D measurements has been performed in the literature for severe scoliosis and for operated patients.

Methods. This series included 24 patients (62° ± 11) operated for Lenke 1 or 2 AIS, using either all-pedicle screw constructs (group 1) or hybrid constructs, with universal clamps at thoracic levels (group 2). All patients underwent low-dose standing biplanar radiographs, pre- and postoperatively. Three operators performed the 3D reconstruction process two times preoperatively and two times postoperatively (total 288 reconstructions). Intraoperator repeatability and interoperator reproducibility were calculated and compared between groups.

Results. The preoperative reproducibility was between 4° and 6.5° for parameters dedicated to scoliosis (Cobb and apical vertebral rotation), between 4° and 7° for kyphosis and lordosis values, and between 1° and 5° for pelvic measurements. The postoperative reproducibility was between 5° and 8° for values of kyphosis and lordosis, between 1° and 5.5° for pelvic parameters, and between 6.5° and 10.5° for the scoliotic parameters. The reproducibility of the scoliotic parameters was slightly better in the hybrid construct group, but the difference was not significant ($P = 0.8$). No difference was found between groups for the other parameters.

Conclusion. 3D postoperative reconstructions are as reproducible as preoperative ones. The reproducibility is not influenced by the type of implant used for correction. Mean difference between operator was higher than previously reported for the apical rotation measurement, but this difference can be explained by the severity of the curves and the lower visibility of the anatomical landmarks due to the implants.

Key words: three-dimensional reconstruction, scoliosis, vertebra. **Spine 2011;36:E1306–E1313**

The importance of analyzing scoliotic deformities in three dimensions has long been emphasized.[1,2] Based on the images obtained by using George Charpak's low-dose x-raystechnology (1992 Nobel Prize in Physics), Dubousset *et al*[3] proposed an innovative head to feet biplanar radiographic system, allowing for 3D reconstruction. Recent advances allowed to get fast and accurate three-dimensional (3D) reconstructions of the spine that can be used in a routine environment.[4] The resulting EOS system (EOS-Imaging, Paris, France) is a new slot-scanning x-ray imager that is used on patients in a weight-bearing position while reducing the radiation dose, which reduction has added importance when iterative examinations are required.[5]

The reliability of 3D reconstructions obtained by using semiautomatic transformation of biplanar x-rays has previously been reported in two series of patients with moderate adolescent idiopathic scoliosis (AIS).[4,6] The precision in the 3D parameters measured varied between 4° and 6° for spinal curves, between 1° and 4° for pelvic parameters, and between 2° and 4° for vertebral rotation. Although the range of precision was good, the mean Cobb angle of the patients was only 16° in one study[6] and 37° in the other,[4] which is less than the Cobb angles in AIS patients requiring surgery. To the best of our knowledge, the reliability of EOS 3D reconstructions has never been assessed in AIS patients treated by surgery. Regarding postoperative aspects, one might anticipate that the type of construct could influence the reliability of 3D reconstructions from biplanar imaging. Specifically, do all-pedicle screw constructs[7,8] hide anatomical landmarks necessary for semiautomated 3D reconstruction more than hybrid constructs that have radiolucent periapical sublaminar fixation?[9,10] The purpose of this study was to assess the reliability

From *Department of Pediatric Orthopaedics, Robert Debré Hospital, Paris 7 University, France; †Biomechanics Laboratory, Arts et Métiers Paris Tech, Paris, France; ‡Department of Orthopaedics, University Hospital of Bordeaux, Bordeaux, France.

Acknowledgment date: January 13, 2011. First Revision date: April 16, 2011. Acceptance date: June 12, 2011.

The manuscript submitted does not contain information about medical device(s)/drug(s).

No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

Address correspondence and reprint requests to Brice Ilharreborde, MD, Robert Debré Hospital, AP-HP, Paris 7 University, Department of Pediatric Orthopaedics, 48 Bd Sérurier, 75019 Paris, France; E-mail: i_brice@hotmail.com.

DOI: 10.1097/BRS.0b013e3182293548

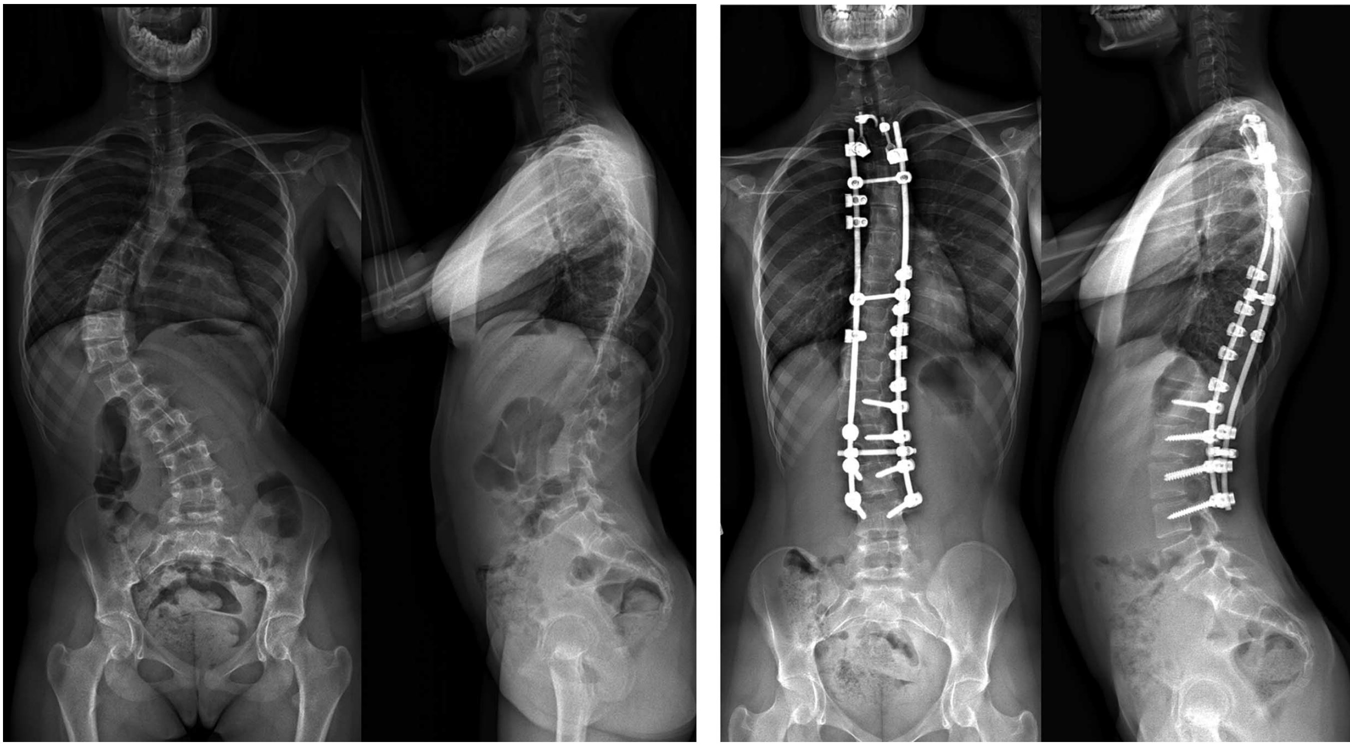

Figure 1. Preoperative and postoperative posteroanterior and lateral radiographs of a patient operated using hybrid construct.

of postoperative 3D reconstructions by using the low-dose biplanar x-ray system in patients operated for AIS and to evaluate the influence of two different thoracic implants on the reproducibility of postoperative measurements.

MATERIALS AND METHODS

Patients

After institutional review board approval, 24 consecutive patients operated for thoracic (Lenke 1 or 2) AIS were included. There were 20 girls and 4 boys (average age, 15 years; range, 13–18). Patients 1 to 12 (group 1) were operated in the same orthopedic department by using all-pedicle screw constructs (Figure 1). Patients 13 to 24 (group 2) were treated at another institution, in a pediatric orthopedic department, using hybrid constructs (Figure 2), combining lumbar pedicle screws and universal clamps (UC) at thoracic levels.[9]

In each group, one-third of the patients (n = 4) had a preoperative Cobb angle less than 50° (moderate curves), one-third had a preoperative Cobb angle between 50° and 65° (medium curves), and the other third had a preoperative Cobb angle greater than 65° (severe curves).

Biplanar Radiographic System

Preoperative low-dose biplanar x-rays were taken within routine clinical procedures in both institutions. Patients were in weight-bearing position and arms folded at 45° to avoid superposition with the spine. Exposure parameters were 90 kV and 200 mA for the anteroposterior (AP) x-ray and 105 kV and 250 mA for the lateral view. All images included, at least, both the last cervical vertebra (C7) and the pelvis. Dose area product averaged 440 mGycm^2 (±143) for the AP radiograph and 682 mGycm^2 (±153) for the lateral x-ray. Patients were asked to hold their breath during the scan.

The EOS system is a slot-scanning radiologic device consisting of two x-ray sources, allowing simultaneous acquisition of two images.[5] The sources are coupled to linear detectors that are based on micromesh gaseous structure technology.[11] The two source-detector pairs are positioned orthogonally, so the patient's AP and lateral images are generated line by line, while the whole system is vertically translated. Scan time lasts from 8 to 15 seconds for a spine examination, depending on the patient's height.

Reconstruction Process

The 3D reconstruction of the spine from the biplanar radiographs used parametric models based on transversal and longitudinal inferences, as described by Humbert *et al*.[4]

Preliminary Step

The preliminary step was the digitalization of primary anatomical landmarks on the pelvis, as recommended by Baudoin *et al*.[12] The method required the identification of two spheres on the acetabuli and a segment on the sacral endplate, which permitted the creation of a "patient frame" that is compatible with the reference axis used by the Scoliosis Research Society for the classification of idiopathic scoliosis.[13]

First Estimate

The spinal curve, the T1 upper endplate, and the L5 lower endplate were first digitalized on both x-rays and used as predictors to statistically estimate the other descriptors of

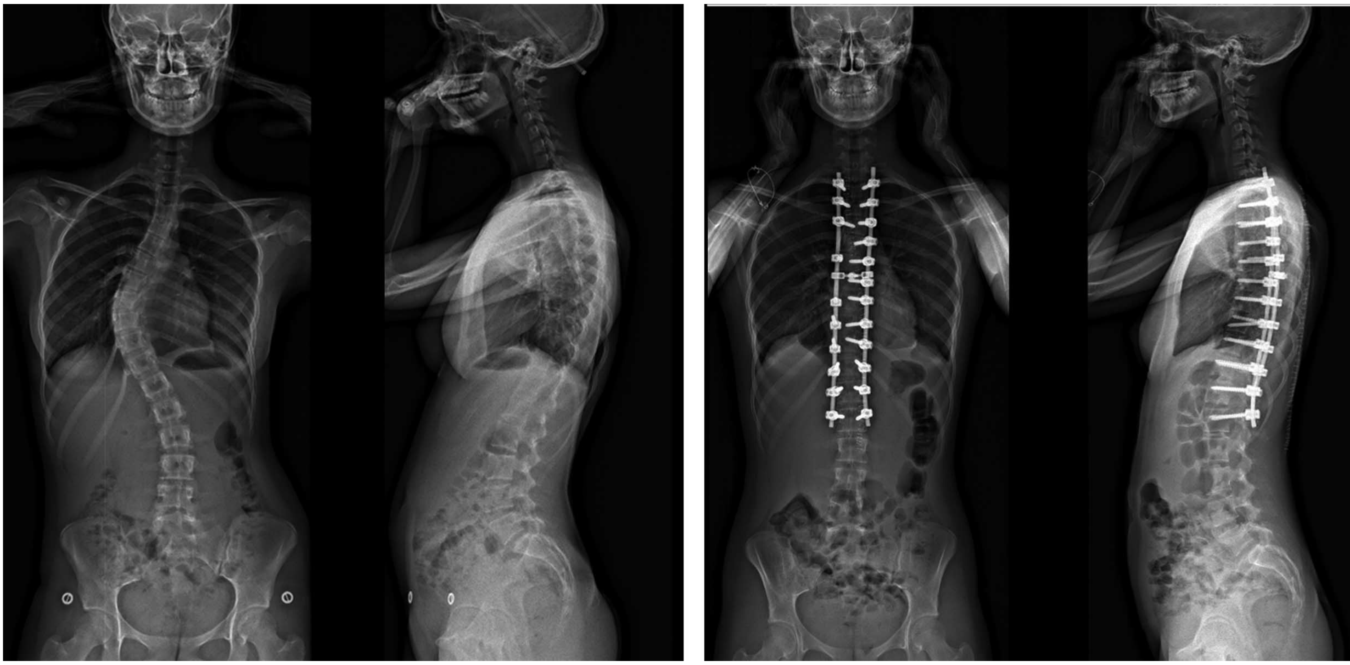

Figure 2. Preoperative and postoperative posteroanterior and lateral radiographs of a patient operated using all-pedicle screw construct.

the parametric spine. From the descriptors of the parametric spine model, a highly detailed model was generated and then projected on both x-rays so that the operator could visualize the 3D reconstruction.

Full 3D Reconstruction of the Spine

The operator verified and, if necessary, performed fine adjustments of the position and shape of the vertebrae from T1 to L5, using control points on the vertebral bodies, pedicles, and posterior arches (Figure 3). This fine adjustment, described by Pomero *et al*,[14] was accelerated by the use of the parametric models based on longitudinal inferences reported by Humbert *et al*,[4] the model automatically improving with each correction of an anatomical feature.

Figure 3. Postoperative posteroanterior and lateral 3D reconstructions of a patient operated using all-pedicle screw construct.

Method Evaluation

Three operators performed the 3D reconstruction process two times preoperatively and two times postoperatively, for each of the 24 subjects (total, 288 reconstructions). Among these three operators, one was experienced with the method (operator 1) and two were senior spine surgeons (operators 2 and 3) who followed a practical course (3 days with examinations) to become familiar with the reconstruction process.

As described by Gille *et al*,[6] the following clinical measurements were calculated from the reconstructions and provided in each patient report: T1/T12 and T4/T12 kyphoses, L1/L5 and L1/S1 lordoses, Cobb angle, axial vertebral rotation (AVR) of the apical vertebra, pelvic incidence, pelvic tilt, and sacral slope. Only one of the operators (operator 1) determined which were the apical and the end vertebrae in each of the 24 subjects.

The time required for each of the 288 reconstructions was recorded.

Statistical Analysis

Two-tail paired *t* tests were used to compare preoperative and postoperative measurements. The intraoperator repeatability and interoperator reproducibility were evaluated, as recommended by the International Organization for Standardization, with an effect size of 1°.[15] To assess intraoperator repeatability, the variances of the two measurements for all operators were averaged. Interoperator reproducibility was calculated by using a cumulative factor that quantifies the variance of

TABLE 1. Mean Values (in Degrees) of the 10 Parameters Measured by the 3 Operators (24 Patients)

	Preoperative (Mean ± SD)	Postoperative (Mean ± SD)	*P*
Cobb angle	62 ± 11	20 ± 13	3.3 E-16
AVR	21 ± 7	16 ± 8	0.0014
T1–T12 kyphosis	33 ± 13	34 ± 10	0.57
T4–T12 kyphosis	23 ± 13	22 ± 10	0.69
L1–S1 lordosis	55 ± 9	48 ± 7	0.0025
L1–L5 lordosis	48 ± 9	42 ± 7	0.002
Pelvic incidence	48 ± 8	48 ± 9	0.59
Pelvic tilt	8 ± 6	10 ± 7	0.37
Pelvic angle	4 ± 4	4 ± 4	0.96
Sacral slope	39 ± 7	38±7	0.50

AVR indicates axial vertebral rotation of the apical vertebra.

the mean value obtained by each operator. Furthermore, an intraclass coefficient with 95% confidence interval was calculated. This coefficient expresses the proportion of the global variability that is because of the variability among subjects. An intraclass coefficient greater than 0.91, between 0.71 and 0.91, between 0.51 and 0.70, or less than 0.51 was considered to represent, respectively, very good agreement, good agreement, moderate agreement, or poor agreement. The design of this study was based on recent studies.[6]

Preoperative and postoperative reconstruction times were compared by using paired *t* tests and Mann-Whitney *U* tests. A $P < 0.05$ was considered to be significant. All statistical analyses were conducted by using the software Statview (SAS Institute Inc, Cary, NC).

RESULTS

Operative Procedures

The mean number of levels fused was 10 ± 1.2 in group 1. The number of implants used for all-pedicle screw constructs averaged 19 ± 1 (1.9 implants per vertebra).

The mean number of levels fused was 12 ± 1.5 in group 2. The number of implants used for hybrid constructs averaged 14 ± 2 (1.2 implants per vertebra).

The apical vertebra was instrumented with two implants (UCs or pedicle screws) in all cases.

Spinal and Pelvic Parameters

The anatomic landmarks were clearly distinguishable by varying the luminosity and contrast to optimally reveal the vertebrae and pelvis. In particular, the superior endplate of T1 and the femoral heads were visible in all cases. Consequently, the 10 radiologic parameters were measurable in all 24 patients.

The mean values of the spinal and pelvic parameters of the series are summarized in Table 1. The Cobb angle, AVR, and lordosis values were significantly changed by the operation.

Reproducibility and Repeatability

The preoperative measurement repeatability (intraoperator) and reproducibility (interoperator) are reported in Table 2. Values were lower than 7° for all frontal and sagittal spinal parameters and under 5° for pelvic measurements.

The postoperative measurement repeatability and reproducibility are summarized in Table 3. The reproducibility was 6.9° and 10.4° for the two scoliotic parameters (Cobb angle and AVR) and under 5.5° for pelvic parameters. The intraoperator repeatability was better than interoperator reproducibility (0.3°–3.6°) for all parameters. The agreement was very good for all clinical measurements (both preoperative and postoperative). Differences between preoperative and postoperative reproducibility of each clinical parameter was less than 1° in all cases, except for the AVR (4.3°) (Figure 4).

TABLE 2. Preoperative Clinical Measurement Repeatability and Reproducibility (in Degrees)

	Intraoperator Repeatability (N = 24)	Interoperator Reproducibility (N = 24)	Humbert *et al*[4] Severe Scoliosis >40°	Intraclass Correlation Coefficient
Cobb angle	4.8	6.2	3.5	0.99
AVR	5.3	6.1	3.9	0.97
T1–T12 kyphosis	5.9	7	5.6	0.99
T4–T12 kyphosis	4.4	5.7	4.3	0.99
L1–S1 lordosis	5.1	5.9	4.2	0.99
L1–L5 lordosis	5.7	6.7	5.4	0.98
Pelvic incidence	4.6	4.7	3.5	0.99
Pelvic tilt	1.0	1.4	0.8	1.00
Pelvic angle	1.5	1.9		0.99
Sacral slope	4.3	4.3	3.2	0.99

AVR indicates axial vertebral rotation of the apical vertebra.

TABLE 3. Postoperative Clinical Measurement Repeatability and Reproducibility (in Degrees)

	Study Group (N = 24)		Group 1 (N = 12)		Group 2 (N = 12)		Intraclass Correlation Coefficient
Cobb angle	4.6	6.9	5.1	6.4	3.9	7.3	0.99
AVR	7.5	10.4	8.8	10.1	5.9	11.4	0.94
T1–T12 kyphosis	5.2	7.7	5.3	8	5.1	7.9	0.98
T4–T12 kyphosis	4.2	5.4	4.4	6	4.0	5.2	0.99
L1–S1 lordosis	4.4	5.6	4.0	5.1	4.8	6.0	0.98
L1–L5 lordosis	3.8	5.4	3.6	5.1	4.0	5.7	0.98
Pelvic incidence	4.5	5.2	4.4	5.2	4.5	5.2	0.99
Pelvic tilt	1.2	1.5	1.5	1.8	0.8	1.1	1.00
Pelvic angle	1.3	1.6	1.1	1.5	1.4	1.7	0.99
Sacral slope	4.0	4.6	3.8	4.3	4.3	4.9	0.98

AVR indicates axial vertebral rotation of the apical vertebra.

The postoperative reproducibility of the parameters specific to scoliosis was not influenced by the implant type used for correction ($P = 0.8$) (Figure 5).

Reconstruction Time

The mean reconstruction times evaluated from the 24 subjects are reported in Table 4. There was no difference between groups regarding preoperative reconstruction times ($P = 0.9$). Reconstructions of postoperative x-rays, with instrumentation, were significantly longer (average difference 1 minute 20 seconds) than the preoperative ones. However, no difference was found between the two groups regarding postoperative reconstruction times ($P = 0.217$).

Reconstruction times were significantly longer when the operator was novice (operators 2 and 3) ($P = 9.3E-13$). The mean difference in reconstruction times between experienced and recently trained operators was 2 minutes 45 seconds (±1 minute 40 seconds).

DISCUSSION

Preoperative Measurements

Several authors have emphasized the limitation of 2D radiological measurements and the clinical interest of measurements obtained from 3D reconstruction.[16,17] Hong *et al*[18] recently found significant correlations between 3D parameters, such as

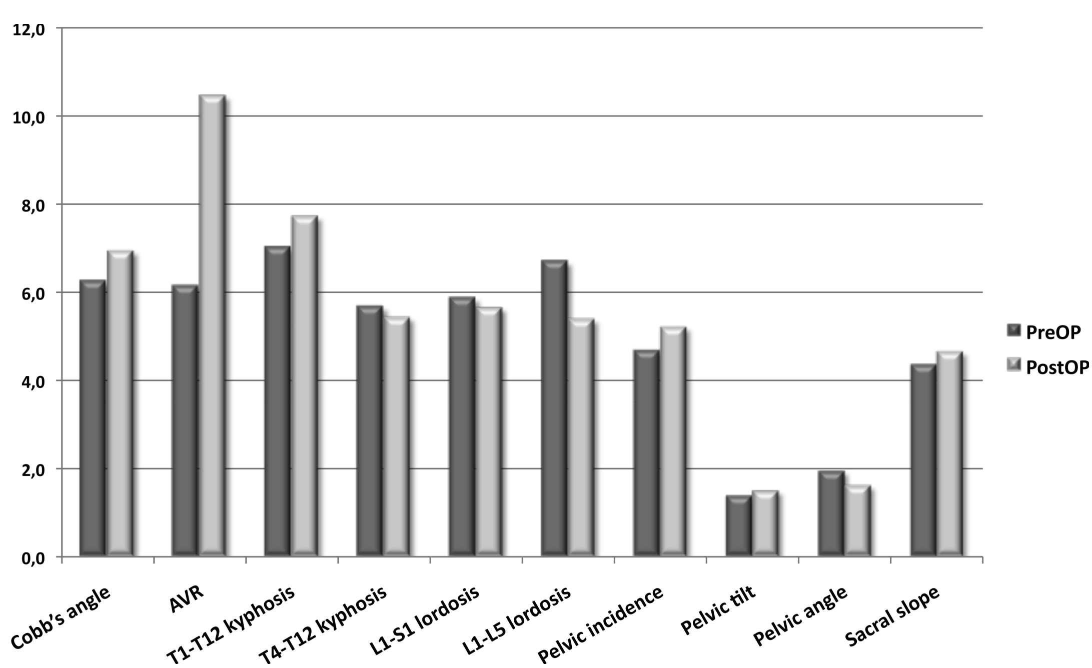

Figure 4. Preoperative and postoperative angle measurement reproducibility.

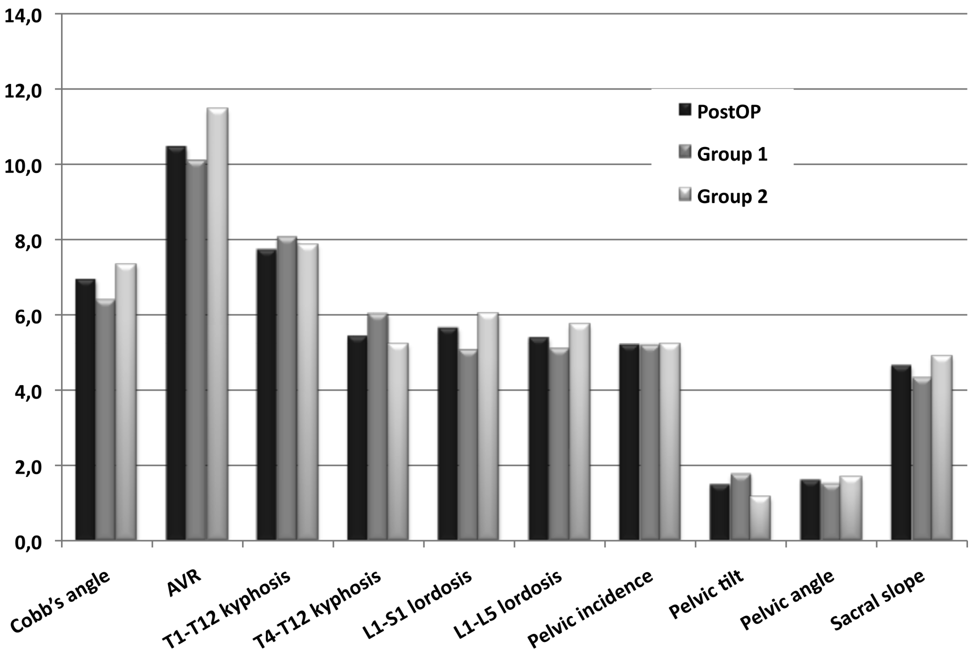

Figure 5. Differences in postoperative angle measurement reproducibility between groups.

vertebral rotation, rib hump index, or sternal shift, and clinical outcomes. They concluded that computed tomographic (CT)-based measurements of 3D deformities could provide useful information in planning and predicting the outcome of corrective surgery. The reconstruction process and clinical parameters evaluated in the current study have specific practical clinical applications. Indeed, getting a low-dose weight-bearing 3D reliable morphological analysis of scoliosis, with a reasonable time of acquisition and processing, would be of particular interest. In the thoracoabdominal region, the reported average dose of ionizing radiation is six to nine times less than that in conventional radiographic imaging, thus limiting its harmful effects, especially in children and adolescents followed for scoliosis.[5]

The reliability of this 3D reconstruction process has previously been reported by Gille *et al*[6] and Humbert *et al*[4] in subjects with scoliosis who did not require surgical management, but the mean Cobb angle in those groups was lower than in the present patients. The present spinal deformities were not only more severe but also led to surgery in every case. Regarding the preoperative measurements of kyphosis, lordosis, and pelvic parameters, one might have expected poorer reproducibility in our series, because the severity of the scoliosis involved was greater than that in previous studies. This was not the case; the intraoperator repeatability and interoperator reproducibility differed from the corresponding values reported by Gille *et al*[6] and Humbert *et al*[4] by no more than 1°. Furthermore, the present reproducibility results for lordosis and kyphosis measurements were even comparable with those obtained by using lateral radiographs in volunteer subjects without scoliosis.[19,20] This finding in our patients with an average Cobb angle of 62° confirms the reliability of the two previous reports in patients with less-severe scoliosis[4,6] and illustrates one of the advantages of 3D reconstructions over conventional 2D imaging. On conventional lateral views of patients with scoliosis, lordosis and kyphosis are more difficult to measure than in subjects without scoliosis because of the vertebral rotation and angle of the endplates with regard to the horizontal plane in scoliotic spines.[21]

Concerning the preoperative scoliosis Cobb angle and AVR, the reproducibility of the measurements was also quite satisfactory, roughly between 4° and 6.5°, consistent with the slightly superior precision reported previously using the same method but in patients with much lower Cobb angles (average, 16°[6] and 37°[4] *vs.* 62°). Abul-Kasim *et al*[22] recently described an alternative method to assess vertebral rotations while reducing patients' radiation. They showed that low-dose CT in prone position were reliable in the perioperative workup of AIS, with effective dose 20 times lower than that of a standard CT for trauma. The advantage of EOS is that patients are in weight-bearing position and that the method does not require additional examination to measure vertebral rotations. The device is expensive, but the cost of an examination remains the same as one of the conventional full-spine radiograph in our institution.

TABLE 4. Mean Reconstruction Times (±SD) for the Three Operators

	Study Group (N = 24)	Group 1 (N = 12)	Group 2 (N = 12)
Preoperative	11 min 31 s (±1 min)	11 min 33 s (±1 min 8 s)	11 min 30 s (±1 min)
Postoperative	12 min 50 s (±50 s)	13 min (±45 s)	12 min 35 s (±1 min)
P	4.6 E-05 (s)	0.002 (s)	0.013 (s)

(s) indicates significant.

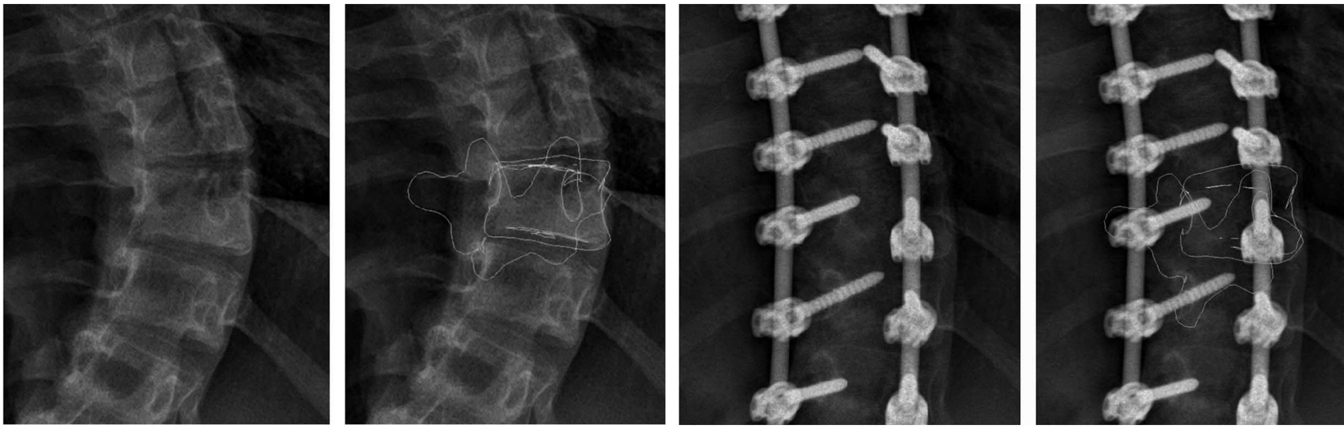

Figure 6. Preoperative and postoperative posteroanterior radiographs of a 62° scoliotic curve treated using all-pedicle screw construct, showing the difficulty of identifying anatomical landmarks due to pedicle screws.

Postoperative Measurements

The clinical measurements were possible in all patients, because the biplanar radiographs system enhances overall image quality, as reported by Deschenes *et al*,[5] and the optimization tools provided by the software allowed extensive adjustments of luminosity and contrast. The postoperative intraoperator repeatability and interoperator reproducibility observed for kyphosis, lordosis, and pelvic parameter determinations remained comparable with those obtained preoperatively and were not influenced by the type of posterior instrumentation.

Although postoperative 3D reconstructions were less straightforward to obtain than the preoperative reconstructions, due to the superposition of implants with anatomical landmarks, and the Cobb angle measurement remained equally reproducible (6.9° *vs.* 6.2° preoperatively). These results are consistent with conventional methods of measurement, in which reported precision values vary from 2.8° to 10°, according to intraobserver and interobserver studies and depending on the severity of the deformity.[23–25]

The clinical parameter most affected by the implants was the AVR. The repeatability and reproducibility, which were between 5° and 6.1° preoperatively, dropped off to between 6.8° and 10.4° on postoperative reconstructions. However, the interoperator reproducibility remained better than the results reported in the literature with the Perdriolle torsion meter.[26,27] Values in the current study were slightly superior to those previously reported with the same method by Humbert *et al*,[4] who found a precision of 3.9° in AVR measurements in nonoperated patients with scoliotic curves greater than 40°. We believe that this difference is likely due to the presence of implants at the apex of the deformity in our patients (Figure 6). Both intra- and interoperator measurements were slightly more precise in the hybrid construct patients, who had UCs in the thoracic spine, but the difference with the all-pedicle screw constructs did not reach statistical significance (intraoperator, $P = 0.71$; interoperator, $P = 0.93$).

Reconstruction Times

Reconstruction time averaged 11.5 minutes preoperatively, which is comparable with the time observed by Humbert *et al*[4] in severe scoliosis. All three operators had a different level of experience, but the mean difference in reconstruction times between the most experienced observer and the other two was only 2 minutes 45 seconds ± 1 minute 40 seconds, reflecting the straightforwardness of the computer tool. While we did not evaluate the learning curve of this method, the small difference in reconstruction times between the recently trained and experienced users suggested that the learning curve was short.

Postoperative reconstruction times were significantly longer in both groups (all-screw group, $P = 0.002$; UC group, $P = 0.013$), because implants made the identification of anatomical landmarks more difficult. There was no difference in reconstruction time between the UC and pedicle screw groups ($P = 0.217$).

Limitations of the Study

Although the orthogonal scanning image acquisition technique used in the present report may also provide more accurate measurements than conventional 2D imaging, only the repeatability and reproducibility of these measurements could be tested in the present study. In the current series, the "full spinal" 3D reconstruction method was the only one assessed. This method is still time consuming, and the clinical measurements precision of the "fast" 3D reconstruction method, as described by Humbert *et al*[4] (average 3 minutes preoperatively in severe scoliosis), warrants further investigation, including analysis of postoperative images. Such studies could be compared to the current results in anticipation of routine clinical use. In addition, the reproducibility of 3D measurements of intervertebral rotation, especially in nonfused segments, needs to be evaluated in future clinical studies, including other Lenke-type AIS.

CONCLUSIONS

In conclusion, this study confirmed the reliability of 3D parameter measurements in patients with severe scoliosis and showed for the first time the good reproducibility of these measurements on postoperative images in a context of routine clinical use of low-dose biplanar radiographic system.

The second important finding of the present report was that the type of instrumentation used at thoracic levels did not significantly alter reconstruction times or influence the reproducibility of clinical measurements.

➢ Key Points

- ❑ This study confirms the reliability of 3D parameter measurements in patients with severe scoliosis, considered for surgery.
- ❑ Low dose biplanar x-rays can be performed in a context of routine clinical use.
- ❑ The type of instrumentation used at thoracic levels did not significantly alter reconstruction times or influence the reproducibility of clinical measurements

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