Upright Biplanar Slot Scanning in Pediatric Orthopedics: Applications, Advantages, and Artifacts

OBJECTIVE. Digital slot scanning is a relatively new technology that has been used for imaging of pediatric orthopedic conditions such as scoliosis and leg-length discrepancies. This article will review the clinical applications, advantages, and unique artifacts of this new technology.

CONCLUSION. Upright biplanar slot scanners acquire high-resolution radiographs simultaneously in two orthogonal planes with reduced radiation dose. Other advantages include a more physiologic weightbearing imaging position, improved Cobb angle measurements, and 3D modeling.

Pediatric skeletal disorders such as scoliosis and lower extremity deformities often require serial imaging for diagnosis, monitoring, surgical planning, and postoperative follow-up. Childhood scoliosis is one of the most common pediatric skeletal disorders that uses serial imaging, with approximately 1 in 300 adolescents requiring treatment [1–7]. Girls are more frequently affected than boys [3, 8–10]. Lower limb abnormalities—including femoral and tibial torsion, leg-length discrepancy, and angular deformities—also require frequent imaging for diagnosis and treatment.

The long-term effects of modern radiographic medical imaging on children are unknown, but radiation exposure to children should be minimized. Certain populations, such as those patients with early-onset scoliosis, may have very high cumulative radiation exposure from imaging studies ordered by multiple subspecialties [11]. On the basis of survivor data after nuclear catastrophes such as Hiroshima and Nagasaki, the risks of radiation-induced malignancy are higher in children and adolescents [12]. Additionally, Doody et al. [13] showed increased rates of subsequent thyroid and breast cancer in female patients treated for scoliosis in female patients treated for scoliosis between 1912 and 1965, with an average of 25 radiographs per patient; notably, in their study, breast radiation dosing per radiograph was estimated to be 4 mGy, whereas modern computed radiography (CR) dosing is substantially less, approximately 0.08 mGy [14]. Reduction in cumulative radiation dose is an important consideration in pediatric orthopedics and can be achieved by using pediatric dosing techniques [15, 16], substituting nonionizing imaging modalities such as MRI or ultrasound when appropriate [17, 18], and limiting the number of images taken [19, 20]. Additionally, lower doses can be achieved with advances in radiologic imaging technology, specifically through the use of biplanar slot scanners [21]. The EOS imaging system (EOS Imaging), an upright biplanar slot scanner, represents a relatively new technology that offers high-resolution images with reduced radiation dose and improved resolution compared with conventional radiography. The purpose of this report is to review the clinical applications, advantages and drawbacks, and unique artifacts and pitfalls of this new technology.

Introduction to Upright Slot Scanning

Kalifa et al. [21] first reported the clinical applications of a low-dose upright slot-scanning x-ray beam imaging system using multiwire proportional chambers. Based on the 1992 Nobel Prize–winning work in physics of Georges Charpak, the multiwire proportional xenon gas–filled chamber is capable of detecting single photons with high efficiency. A postpatient collimation slit results in rejection of scattered photons without use of a grid, allowing low-dose imaging [22]. In a study of 140 pediatric patients, Kalifa et al. reported substantial dose reductions compared with film-screen two-view radiography of the spine.
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Advantages of Upright Slot Scanning

Radiation Dose

A primary advantage of biplanar slot scanning is the overall reduction in dose to the pediatric patient, especially when serial imaging is required. Some of the first published clinical reports of biplanar slot scanning claimed a mean conventional film-screen-to-EOS entrance skin-dose ratio of 13:1, with a slight reduction in image quality [21]. More recent reports have cited a CR-to-EOS entrance skin dose range of 3:1 and 9:1 [23], with a skin entrance dose of 0.2 mSv for a posteroanterior and lateral scoliosis film pair [24]. Using current optimized CR techniques, we achieved approximately 50–60% reduction in effective dose compared with our standard CR technique.

Some cases of scoliosis or lower extremity length and rotational abnormalities may require CT to obtain accurate measurements for preoperative planning. The CT technique imparts a dose 4–23 times higher than that of biplanar techniques [25].

Image Quality and Accuracy

Despite using lower doses, biplanar slot scanners provide high-resolution images that have been shown to be slightly better than standard CR images [23]. Because the paired x-ray sources and detectors translate in the superior-inferior plane simultaneously, these images have no geometric magnification in the superior-inferior direction, in contrast to conventional projection imaging systems (Fig. 6).

Determination of the Cobb angle is a key step in the assessment of scoliosis, and an angle greater than 55° is often considered an indication for surgical intervention for idiopathic scoliosis. The Cobb angle varies with pelvic rotation, which is present in nearly all cases of idiopathic scoliosis owing to an associated rotary component of the vertebral bodies [26], and varies with patient positioning (Fig. 7). The automated Cobb angle determination with the EOS imaging system corrects for the degree of pelvic rotation, resulting in more accurate Cobb angle measurements and in improved precision when comparing follow-up examinations. Automated Cobb angle measurements provide less inter- and intraobserver variability and have been shown to be comparable to CT-derived measurements [24, 27, 28].

Along with lower doses than CT, EOS provides comparable precision and reliability in measurements in both pre- and postoperative patients. Multiple studies have shown its accuracy and reproducibility for Cobb angle assessment compared with CT [24, 27, 28]. Al-Aubaidi et al. [27] found no significant difference in measurements of vertebral rotation and Cobb angles with EOS versus CT. Rousseau et al. [29] showed EOS to have overall favorable reproducibility in reconstructing cervical vertebrae with little interobserver variability. Ilharreborde et al. [24] showed accurate angle measurement reproducibility with 3D reconstructions—in both pre- and postoperative patients—that were not affected by the type of surgical correction. Lower limb lengths and torsion values measured with EOS were found to correlate closely with CT values without significant bias or interobserver variability [30–33].

Because the slot scanner can acquire full-length images, the need to “stitch” multiple images together to produce a full-length view of the limb or spine is not needed, eliminating stitching errors [34]. Finally, the abnormalities of scoliosis and lower limb abnormalities are processes affected by weightbearing; thus, the nonweightbearing position of CT and MRI may alter anatomic relationships.

Workflow and Efficiency

Compared with standard digital radiography, EOS examinations generally require less time and labor of the radiology technologists [35, 36]. Dietrich et al. [35] showed statistically significant reductions in examination times, with biplanar radiography requiring only 248 seconds to complete versus 449 seconds for standard digital radiography. This suggests the potential for lower labor costs for radiology technologists per examination and a higher throughput of patients per day, thereby increasing efficiency.

Surgical Implications and Planning

As mentioned, a Cobb angle greater than 55° is well established as a surgical indication for children with idiopathic scoliosis. With reference to an anteroposterior or posteroanterior spinal radiograph, the Cobb angle is measured from the superior and inferior endplates of the most maximally tilted proximal and distal vertebral bodies. With the advent of pedicle screw fixation and complex corrective maneuvers, the surgical correction of scoliosis has significantly advanced over past decades [37–39]. First-generation implants, such as Harrington rods, focused primarily on distraction across the spine, which resulted in a high incidence of flat-back deformity and loss of normal sagittal plane alignment, and were found to be associated with poor health-related quality-of-life outcomes [40–43]. Scoliosis entails coronal, axial, and sagittal deformation of the spine and requires an individualized surgical approach to achieve balanced, safe, and acceptable correction. With scoliotic deformities, multiple vertebral segments are translated in both the coronal and sagittal planes and show varying degrees of rotation about the long axis of the spine. Biplanar orthogonal imaging with 3D reconstructions provide a novel top-down orientation (termed the “da Vinci view”) in which the surgeon can better assess individual vertebral body translation and rotation (Fig. 8) and plan surgical manipulation of individual vertebral segments. Such techniques hold the promise of improved outcomes, such as restoration of the normal thoracic kyphosis with a lower incidence of flat-back syndrome and derotation of the spine to reduce residual chest wall or pelvic asymmetry [44].

In addition to scoliosis, pediatric orthopedic surgeons frequently treat leg-length discrepancies and angular deformities of the long bones of the lower extremities. Im-
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Aging can show the location and severity of leg-length discrepancies and the underlying causes such as tumor, infection, physseal arrest, or idiopathic deformities. Imaging is typically obtained with a supine scanogram and is an accurate method for leg-length discrepancy measurement. Because of the geometry of conventional radiography with an x-ray point source and a 2D detector at a distance from the source, geometric magnification will result in inaccuracies in length measurements. Because it uses parallel linear sources and detectors that move in tandem during the image acquisition, geometric magnification does not occur with biplanar slot scanning (Fig. 6). Upright biplanar imaging allows additional assessment of femoral or tibial torsion, which is another common indication for pediatric orthopedic evaluation.

**Potential Drawbacks**

**Postprocessing**

A major drawback of the EOS imaging system is the need for extensive postprocessing of the posteroanterior and lateral radiographs to generate the 3D images and the derived angles and lengths. Using the proprietary software, the technologist must mark multiple anatomic landmarks on the posteroanterior and lateral image pair. For the spine, these landmarks include the sacral promontory, the center of the acetabular roofs, and the T1 superior and L5 inferior endplates on the posteroanterior and lateral images. From these landmarks, the outer contours of the thoracic and lumbar spine are generated, which then have to be manually corrected on a level-by-level basis in both views. The software then generates ROIs for each vertebral level, which the technologist translates and rotates to better align with the margins of the individual segments on the radiograph. Typically, two or three iterations of the process are required for each image analyzed. On nearly every examination, portions of the contours of at least several of the vertebral segments may be obscured, and the alignment is only a rough approximation. Additionally, segmentation anomalies are difficult to manage with the predetermined levels generated with the postprocessing software. For a typical spine study, the postprocessing requires between 90 and 120 minutes. The cost for the technologist’s time, as well as training and software and equipment upgrades, can be considerable and need to be accounted for in cost-benefit analyses of the EOS imaging system. Last, the additional postprocessing of the images usually results in an increased cost to the patient for the examination.

**Artifacts**

Despite eliminating the stitching artifact of the traditional CR flat-panel detector, the biplanar slot scanner system has its own set of image artifacts. These include patient motion artifacts, edge enhancement, potential underestimation of leg-length discrepancy, and the “off-center” artifact [36]. Because images are acquired in a vertical sequential fashion over approximately 15 seconds, patient movement during the examination causes motion artifacts. Because of the sequential image acquisition and construction used with biplanar slot scanning, motion during a portion of the acquisition results in only a portion of the image appearing shifted or wavy but sharp and without blurring (Fig. 8). Cardiac motion often produces an undulating left-heart border because the image is acquired during systole and diastole [36] (Fig. 8).

With upright frontal imaging, the measured leg-length discrepancy may be reduced owing to slight flexion of the knee of the longer leg. For avoidance of this artifact, a biplanar acquisition with 3D postprocessing is recommended whenever there is suspected hip, knee, or ankle flexion to facilitate complete assessment of rotational profile, angular deformity, and leg-length discrepancy.

The EOS imaging system requires the technologist to enter the distance from the x-ray source to reference plane on the acquisition monitor. This is used to specify whether if the patient is at isocenter within the EOS unit or standing against the back wall. If this distance entry is incorrect or if the patient is not positioned isocenter, then distortion of the image similar to the effect of a fun-house mirror can occur, causing the patient to look either shorter and wider or taller and thinner (Fig. 9). A potential solution for this includes taping a round metallic marker to the patient’s skin to serve as a reference [36]. When the object appears not round but is distorted on the radiograph, the distance from x-ray source to reference plane has not been entered properly. If recognized, this artifact can be corrected with postprocessing by the technologist. Alternatively, a measurement of the image width can be used to verify that the appropriate distance value has been entered. When the patient is at isocenter and the distance from source to reference plane has been entered correctly, the image width will be 340 mm.

**Cost-Effectiveness**

The initial cost of the machine with setup and training is estimated to be $400,000–$600,000. A 2013 U.K. study suggested EOS is not cost-effective for dose reduction alone but acknowledged that the potential for better surgical outcomes and higher throughput could make it cost-effective [45]. With lower labor costs from faster examinations, Dietrich et al. [35] estimated the number of examinations required to break even was approximately 4100 per year; however, this is 50% greater than the number of CR or digital radiography examinations per year required to break even. This study does not take into account improved image quality (with a reduction in repeat radiographic studies or CT) or potential cost savings from improved surgical outcomes.

**Conclusion**

Biplanar slot scanning offers a significant advancement in low-dose imaging technology for patients with scoliosis and lower limb deformity. Advantages include lower dose, precise measurements, and 3D modeling for improved diagnostics and surgical planning. There is a high initial cost and extensive postprocessing required to generate the computer-derived data and 3D models. Awareness of unique imaging artifacts and pitfalls is important for radiologists and orthopedic surgeons to minimize misinterpretation.

**References**

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34. Supakul N, Newbrough K, Cohen M, Jennings SG. Diagnostic errors from digital stitching of scoliosis images: the importance of evaluating the source images prior to making a final diagnosis. Pediatr Radiol 2012; 42:584–598


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Fig. 1—Upright biplanar radiography system. 
A, Schematic shows paired orthogonal sources and detectors. (Modified and reprinted with permission from EOS Imaging, Cambridge, MA)
B, Photograph shows installed unit. Biplanar acquisition is shown on workstation console. Note position of arms with fingers on clavicles.

Fig. 2—Upright surface-rendered images obtained from paired posteroanterior and lateral radiographs. 
A, Orthogonal view of spine is shown.
B, Slight offset positioning is notable on lateral projection of lower extremities, permitting separate long-bone measurements. Colored lines show computer-generated leg-length measurements.
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**Fig. 3**—Computer-derived measurements obtained from paired frontal and lateral radiographic views obtained simultaneously. (Courtesy of Mayo Clinic, Rochester, MN)

**A,** Automated Cobb measurement, vertebral body rotation, and kyphosis assessment are shown on computer-derived measurements of spine.

**B,** Segment lengths and torsion angles are shown on computer-derived measurements of lower extremities. HKS = angle between femoral mechanical axis and femoral anatomic axis.

#### Spine parameters

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#### Sagittal Balance

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#### Knee parameters

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<td>Femorobial rotation</td>
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Fig. 4—Surgical planning with virtual 3D spine model generated from orthogonal frontal and lateral spine radiographs. 
A, Virtual 3D spine model shows apical vertebral segments (yellow) and superior and inferior vertebral segments (blue).
B, Top-down preoperative view of spine shows splayed spinous processes (arrows), indicating rotary component of scoliosis. (Courtesy of Mayo Clinic, Rochester, MN)
C, Software-generated graph shows curvature and axial rotary components of individual vertebral segments.
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Fig. 5—Surgical planning and patient education with 3D models created using 3D printer.  
A, Virtual 3D preoperative (lavender) and postoperative (teal) spine models. (Courtesy of Mayo Clinic, Rochester, MN)  
B, Actual 3D printed spine model.  
C, In top-down orientation, printed model shows splaying of spinous processes indicating rotary component of scoliosis.

Table: Pelvic parameters

<table>
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<td>Sacral slope</td>
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<td>Pelvis axial rotation</td>
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<td>Sagittal pelvic tilt</td>
<td>$-3^\circ$</td>
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Parameters calculated in the patient frame (based on a vertical plane passing through the center of the cotyles), which corrects the effect of a potential axial rotation of the pelvis during acquisition. A pelvis axial rotation is positive when the pelvis is rotated toward the patient left side.

Fig. 6—Conventional radiography system (left) with point source and stationary detector results in geometric magnification, whereas EOS system (right) has x-ray source and detectors that move in tandem, eliminating geometric magnification. (Modified and reprinted with permission from EOS Imaging, Cambridge, MA)

Fig. 7—Variation of Cobb angle with pelvic rotation, which can affect accuracy of Cobb angle. From biplanar orthogonal plane information, pelvic rotation and tilt are calculated and corrected for in Cobb angle assessment. (Courtesy of Mayo Clinic, Rochester, MN)
**Fig. 8**—Artifacts due to patient motion shown on images from EOS system (EOS Imaging).

A, Spinal hardware appears bent (arrow) on EOS-acquired image. This is an artifact of patient motion during lateral acquisition, and this rod was shown to be normal on conventional radiograph obtained later same day.

B, Motion during acquisition creates wiggly appearance of mid femurs. Note how remainder of image is sharp and not blurred as would be typical appearance with motion artifacts with conventional radiography.

C, Cardiac motion creates undulating left-heart border (arrow).

**Fig. 9**—Distortion artifact.

A, Off-center acquisition results in distorted widening of patient, including vertebral bodies.

B, Normal body and vertebral proportions are shown on previous scan acquired 8 months earlier.