Emerging Techniques in Diagnostic Imaging for Idiopathic Scoliosis in Children and Adolescents: A Review of the Literature

Steven Girdler, Brian Cho, Christopher M. Mikhail, Zoe B. Cheung, Noor Maza, Samuel Kang-Wook Cho

Key words
- Diagnostic
- Idiopathic scoliosis
- Imaging
- Pediatric spine

Abbreviations and Acronyms
2D: 2-Dimensional
3D: 3-Dimensional
AIS: Adolescent idiopathic scoliosis
CT: Computed tomography

Department of Orthopaedic Surgery, Icahn School of Medicine at Mount Sinai, New York, New York, USA

To whom correspondence should be addressed: Samuel Kang-Wook Cho, M.D. [E-mail: samuel.cho@mountsinai.org]

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Traditionally, full spine standing radiographs have been the reference standard for diagnostic imaging in adolescent idiopathic scoliosis (AIS). However, recent advances in diagnostic imaging have the potential to reduce radiation exposure and preserve the image quality and utility. Recent advances in diagnostic imaging for AIS include the EOS imaging system, the DIERS formetric scanner, and ultrasonography. Moderate to strong evidence is available to support the interobserver reliability and validity of each of these modalities, even compared with the reference standard imaging techniques. As such, these emerging techniques might prove beneficial in diagnosing and monitoring AIS and its progression, without high levels of continued radiation exposure. To understand the historical perspective and current state of advanced imaging techniques for AIS, a search of PubMed electronic database was conducted to identify studies that had examined these new techniques in the diagnosis of idiopathic scoliosis in children and adolescents.

INTRODUCTION

Idiopathic scoliosis is a common spinal disorder in the pediatric population. Adolescent idiopathic scoliosis (AIS) is the most common type, with an incidence of 2%–4%.[1-3] Scoliosis is defined as a lateral curvature of the spine of ≥10° in the coronal plane. However, it is more accurately characterized as a 3-dimensional (3D) deformity in the coronal, sagittal, and axial planes.[4] The natural history and risk of progression of idiopathic scoliosis in children and adolescents depends on several factors, including skeletal maturity, sex, curve type, and curve magnitude at presentation. The goals of treatment are to prevent curve progression, prevent long-term pulmonary and cardiac sequelae, correct the deformity, restore trunk symmetry and balance, minimize pain and morbidity, and improve functional status.[5-7]

Routine imaging during adolescent growth is required to monitor deformity progression, with annual or semiannual full spine standing radiographs the traditional reference standard. Conventional radiographs, however, are limited in their ability to assess vertebral rotation and pelvic parameters. Computed tomography (CT) addresses these limitations by allowing for accurate 3D reconstruction. This advantage, however, is offset by the significantly greater radiation exposure and cost. A low-dose CT protocol with an effective dose that is 20 times lower than standard CT dose has been described that attempts to address this issue.[8] However, the issue of the altered spinal alignment and balance that results from the patient being in a supine position for the CT scan has remained.[9,10]

Previous studies have demonstrated that a patient with AIS could may undergo, on average, 12.2, 5.7, or 3.5 plain radiographs annually, equivalent to radiation exposure of 1400, 700, and 400 mrad annually, when treated with surgery, brace, or observation, respectively.[11] The concern regarding radiation exposure and the associated increase in the risk of malignancy has led to the development of new imaging modalities that reduce radiation exposure but preserve the image quality.[1,12-15] The reduction of radiation exposure should not come at the expense of valuable diagnostic information. Emerging imaging modalities that adhere to this principle include low-dose radiography, surface topography, and ultrasonography. The purpose of the present study was to review the reported data and discuss the role of these 3 emerging imaging techniques for idiopathic scoliosis in the pediatric population. First, we briefly discussed the development of each of these imaging modalities, followed by a discussion of recent reported studies that evaluated the efficacy of these imaging modalities in idiopathic scoliosis in children and adolescents.

HISTORICAL PERSPECTIVE

Low-Dose Radiography

In 1992, the Nobel Prize in Physics was awarded to Georges Charpak for his work on multiwire proportional chamber systems that allow for precise detection of elementary particles that can be used to produce diagnostic radiographic images at very low radiation doses.[16] This vertical biplanar slot-scanning technology has been used to develop low-dose radiography that produces high-quality images with 50%–80% less radiation than required for conventional radiography.[17,18]

One system of low-dose radiography that has increased in popularity is EOS imaging (formerly, Biospace Med, Paris, France). The EOS imaging system consists of 2 pairs of x-ray tubes and detector units positioned in an orthogonal orientation that allows for simultaneous acquisition of anteroposterior and lateral x-ray images in a standing position (Figure 1).[19,20] Depending on the patient's height, EOS imaging can rapidly scan the spine in 8–15 seconds.[21] The software system, sterEOS (EOS Imaging, Paris, France), can then reconstruct a highly accurate 3D model of the spine from the EOS anteroposterior and lateral images.[19,20] The presence of spinal implants will not affect the reproducibility of EOS 3D reconstruction.[22] This approach reduces the radiation dose required to obtain a 2-dimensional (2D) image of the spine by 8–10 times and the dose necessary to obtain a 3D reconstruction compared with CT by 800–1000 times.[20,23] Additionally, Ilharreborde et al.[24] proposed an EOS "microdose" protocol that further reduces the radiation exposure by 5.5 times compared with the standard EOS protocol (i.e., a 45-fold reduction compared with conventional radiographs), without altering the quality of the images. Finally, the EOS imaging system also has the advantage compared with CT of acquiring images with the patient in an upright standing or seated position.[19,20]

Surface Topography

An early form of topographical assessment of the spine was Moiré topography, which has been used as a method of early identification of scoliosis since the 1970s. This method uses projections of light as patterns of shadow lines projected onto a physical surface. By knowing the distance from the light source and the camera, detailed differences in the subject's surface anatomy can be calculated. The benefits of this method include no radiation exposure and the ease of application. However, it is subject to limitations such as cost-effectiveness and variable accuracy.

Beginning with the use of the Scoliometer, many different systems that use surface topography to measure rotational deformity have been developed.[25-32] However, no system has achieved widespread acceptance. In 1996, Drerup and Hierholzer[33] developed an imaging method called rasterstereography that allows for 3D reconstructions of spinal deformities without radiation

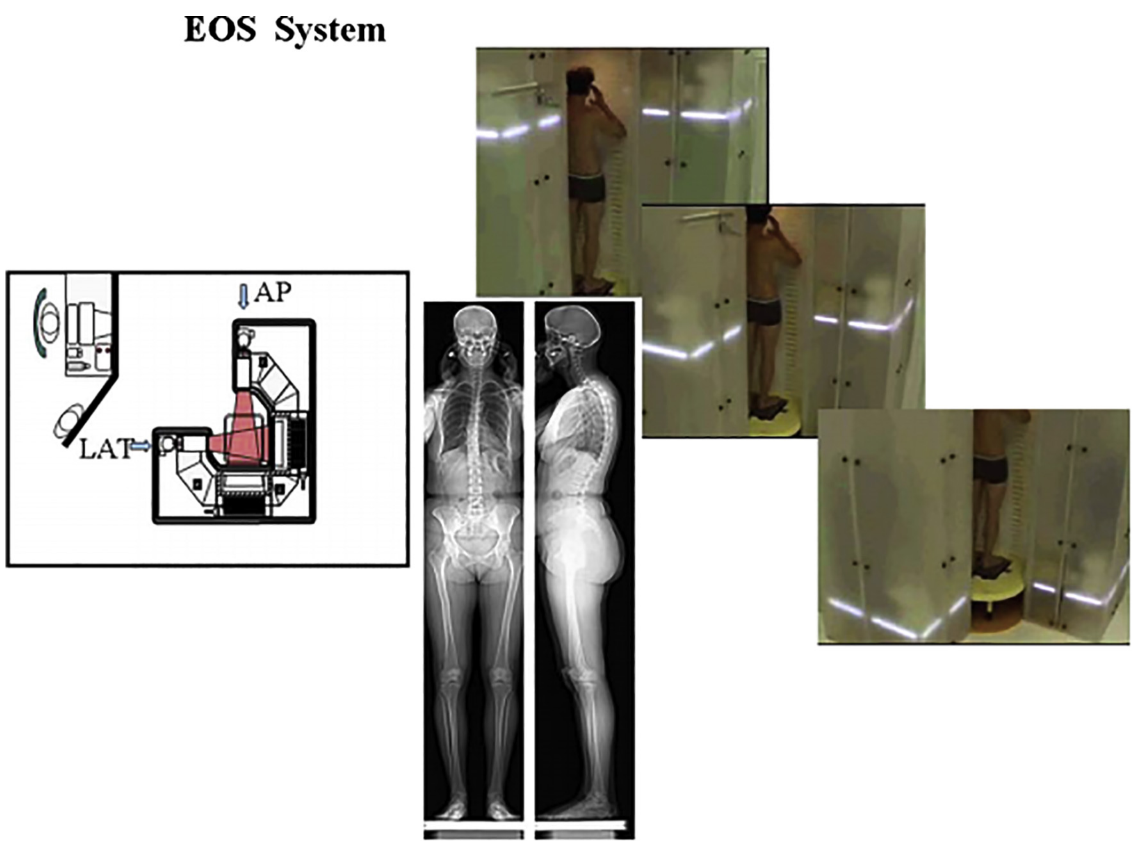

Figure 1. EOS imaging system. (**Left**) Overhead view of the system layout, highlighting the simultaneous anteroposterior and lateral total body radiographic acquisition process. (**Middle**) Radiographs generated by the system. (**Right**) Three images showing an example image acquisition process with vertical movement of the scanner. Reprinted, with permission, from Ilharreborde B, Dubousset J, Le Huec JC. Use of EOS imaging for the assessment of scoliosis deformities: application to postoperative 3D quantitative analysis of the trunk. *Eur Spine J.* 2014;23(suppl 4):S397-S405.

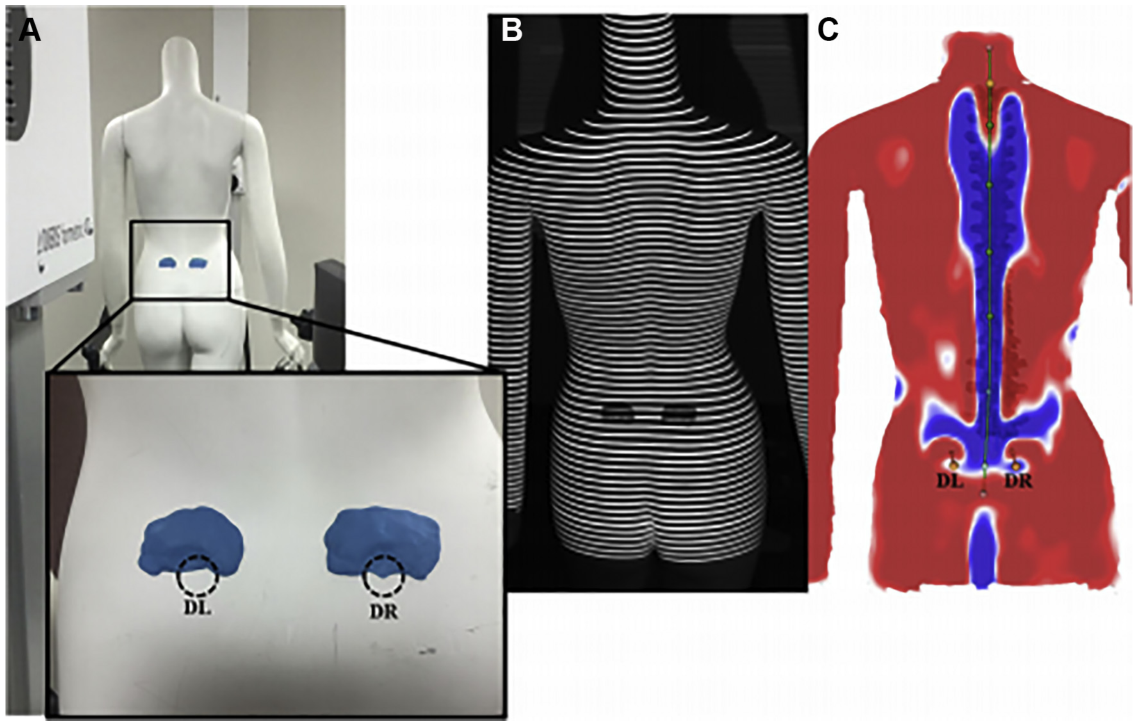

Figure 2. DIERS formetric 4-dimensional (4D) surface topography scans. (**A**) The left (DL) and right (DR) sacral dimples associated with the posterior superior iliac spine were added to the mannequin using modeling clay before scanning. (**B**) The DIERS formetric 4D system captures images as a grid of lines projected onto the surface of the back. (**C**) The DL and DR were verified to be clearly and accurately localized on the 3-dimensional model created by the DIERS formetric 4D system. Reprinted, with permission, from Degenhardt B, Starks Z, Bhatia S, Franklin GA. Appraisal of the DIERS method for calculating postural measurements: an observational study. *Scoliosis Spinal Disord.* 2017;12:28.

exposure. Rasterstereography is a method of stereophotogrammetric surface measurement of the back that has been demonstrated to produce reliable analysis and reconstruction of conservatively and surgically treated spinal deformities in patients with AIS with Cobb angles of ≤80°.[34] Based on this method, the DIERS formetric 4-dimensional (4D; DIERS Medical Systems, Chicago, Illinois, USA) is a radiation-free, no-contact scanner that produces a 3D reconstruction of the spine based on surface topography (Figure 2). It can be used to measure trunk rotation, spinal balance, and Cobb angles. The accuracy of mathematical models based on surface topography should continue to improve as the computing power improves over time.[28,35]

Ultrasonography

Ultrasonography is a nonionizing imaging modality that is low-cost, readily available, and provides real-time imaging findings. Spinal ultrasonography is based on the principle that the spinous processes and laminae are accurate landmarks for assessing spinal deformities.[36,37] Vertebral rotation can be determined by the rotation of the laminae relative to the inclination of the ultrasound transducer.[37] The use of ultrasonography in spinal imaging was first reported by Suzuki et al.[37] in 1989, when a hand-held transducer was used to measure the vertebral rotation in 25 pediatric patients with idiopathic scoliosis. More recently, Chen et al.[36,38] described the center of lamina method to estimate the curve magnitude and vertebral rotation in patients with scoliosis, which was comparable in terms of intra- and interrater reliability to the traditional measurements made using radiographs.[36,38] Although ultrasonography has been the focus of multiple studies, a widely accepted 3D ultrasound system for scoliosis assessment that is reliable and valid has not yet been established.

METHODS

The inclusion criterion for the present review was interventional studies that had evaluated the efficacy of EOS imaging, DIERS formetric 4D reconstruction, or ultrasonography for the assessment of AIS. We limited our literature search to studies reported in English in peer-reviewed journals from July 2008 to July 2018. A search using the PubMed database with controlled vocabulary and text word searches was performed. Our search strategy included 4 concepts, with the concepts linked together with the "AND" or "OR" operator: 1) adolescent idiopathic scoliosis; 2) EOS imaging; 3) ultrasonography; and 4) DIERS formetric 4D imaging. We used the search phrase "adolescent idiopathic scoliosis" AND ("eos" OR "ultrasound" OR "DIERS") to identify potential studies and performed a manual review of each studies references to identify additional studies for screening. The reports that did not meet the aim of the present study were excluded after the review. The remaining studies were included in the present review. Institutional review board approval was not required for the present study at our institution.

DISCUSSION

Despite the development of new imaging modalities for idiopathic scoliosis in the pediatric population, a relative paucity of reported data has compared these modalities with reference standard radiographs, with only 13 studies meeting the criteria for review for the 3 imaging modalities: 4 for low-dose radiography, 4 for surface topography, and 5 for ultrasonography.

Low-Dose Radiography

In a 2016 study by Hirsch et al.,[39] standing and bending EOS imaging studies were compared with traditional supine side bending radiographs to assess patients' preoperative flexibility. Bending images of 50 patients were taken with the patient in the standing position for EOS and the standard supine position for radiographs. No significant differences were noted in the side-bending Cobb angles between the EOS imaging studies and radiographs in the upper thoracic, main thoracic, and lumbar spine. Also, no significant differences were found in the iliolumbar angle between the 2 imaging modalities.[39] Subsequent subgroup analysis using the Lenke curve classification also showed no significant differences in the spinal and pelvis measurements between EOS and radiographs for the different Lenke curve types. Therefore, assessment of preoperative flexibility using side bending EOS imaging studies with the patient in the standing position was found to be comparable to the reference standard supine side bending radiographs, with the additional benefits of decreased radiation exposure and ease of image acquisition for the patient and radiograph technician.

The role of sterEOS 3D software for surface 3D reconstructions has also been a topic of interest in recent studies. In 2012, Somoskeoy et al.[40] compared the correlation and reliability of coronal and sagittal curvature measurements using EOS 2D imaging and sterEOS 3D reconstruction. Coronal and sagittal curvature measurements in 201 patients were taken either manually with traditional 2D methods or automatically with sterEOS 3D reconstruction. No significant differences were found in the measurements between the manual 2D methods and the automatic sterEOS 3D-based methods. The intraobserver reliability was excellent for both methods, and interrater reproducibility was higher for the sterEOS 3D methods. Overall, the findings demonstrated accurate, reliable, and reproducible measurements for spinal curvature using the EOS 2D/3D system with sterEOS 3D software.

A similar study in 2013 by Illés et al.[41] evaluated EOS 3D reconstruction in patients with AIS undergoing surgical correction and compared them with measurements made using EOS 2D imaging studies. A total of 95 patients who had undergone surgical correction were included. The pre- and postoperative EOS imaging studies were reviewed to compare the correlation between the vertebral vector-based spinal parameters on the 3D reconstructions and conventional 2D measurements. Close correlations were found between the 3D and 2D measurements for coronal curves, with a correlation coefficient of 0.950 preoperatively and 0.935 postoperatively. Good correlation was also found for thoracic kyphosis, with a correlation coefficient of 0.893 preoperatively and 0.896 postoperatively. Therefore, the investigators proposed that vertebral vector analysis using EOS 3D imaging studies can help simplify and facilitate the characterization and analysis of complex spinal deformities.

In 2009, Sangole et al.[42] developed the da Vinci representation based on EOS studies, which was a new, clinically useful method used to characterize 3D spinal deformities with Lenke 1 main thoracic curves. This da Vinci representation identified 3 subgroups of main thoracic curves. All 3 subgroups had similar coronal plane deformities. However, 1 group had small nonsurgical curves, and the remaining 2 groups had major curves that differed in the sagittal plane (i.e., 1 group with normokyphotic deformities and 1 group with hypokyphotic deformities). EOS technology has, therefore, helped shape the modern understanding of thoracic scoliosis and helped to guide treatment.

Although the financial investment required to purchase, install, and run low-dose radiography systems such as the EOS imaging system is substantially greater than that for standard digital radiography systems, it produces radiographs with lower radiation exposure without distortions and also enables secondary 3D reconstruction.[43,44] Cost/benefit analyses have suggested that the EOS imaging system requires a higher number of examinations annually to be cost effective, despite the lower labor costs per examination resulting from the shorter examination times.[45,46] Therefore, it might be more suitable for institutions that perform a high volume of spinal imaging in children and adolescents.

In summary, EOS imaging has been shown to be as effective in the assessment of scoliosis deformity as traditional 2D evaluation with standard radiographs and has the added benefit of decreased radiation exposure. In some cases, such as the DaVinci representation, EOS technology has added benefits, including characterization of deformities in the axial and sagittal, as well as coronal, planes. However, implementation of this new technology can entail an initial cost burden, decreased cost-effectiveness, and limited accessibility.

Surface Topography

In 2012, Frerich et al.[47] compared DIERS formetric 4D surface topography and standard radiography as a safer option for evaluating patients with AIS. The association between Cobb angles in 64 patients measured using the DIERS formetric 4D system and standard radiography was strong, with a correlation coefficient of 0.758 and 0.872 for the lumbar and thoracic curves, respectively. The average difference in the Cobb angles measured using the 2 methods was 9.42° and 6.98° in the lumbar and thoracic curves, respectively. The reproducibility of 30 repeated DIERS formetric 4D measurements taken on 14 patients was found to be very high, with a reliability coefficient of 0.996. Therefore, the DIERS formetric 4D system was shown to be comparable to standard radiography in terms of test–retest reproducibility. However, the investigators also noted that the DIERS formetric 4D system does not predict the curve magnitude exactly but can be reliably used for curve surveillance, given the strong correlation with the radiographic Cobb angles.[47]

Another study comparing the reliability and reproducibility of DIERS formetric 4D scanning to reference standard radiographs was performed by Knott et al.[48] in 2016. A total of 193 pediatric patients with scoliosis underwent standing radiographs and surface topography scans with the DIERS formetric 4D system. The reproducibility of the thoracic curve, lumbar curve, and thoracic kyphosis measurements using DIERS formetric 4D surface topography was strong, with interclass correlations ranging from 0.855 to 0.944. The association between the DIERS formetric 4D measurements and standard radiographic measurements was also strong for the thoracic curve magnitude with a correlation coefficient of 0.7, moderate for the lumbar curve magnitude with a correlation coefficient of 0.5, and strong for thoracic kyphosis with a correlation coefficient of 0.8. The average difference in the thoracic curve magnitude and lumbar curve magnitude between the DIERS formetric 4D measurements and radiographic measurements was 5.8° and 8.8°, respectively. With these promising results, the investigators proposed that the utility of the DIERS formetric 4D system is in its reproducible quantification of deformity after the initial radiographs have been taken, with the potential of performing serial assessment of deformity progression without the use of serial radiographs.[48]

A more recent study by Tabard-Fougere et al.[49] in 2017 compared the validity and reliability of the DIERS formetric 4D system with 2D EOS radiography in patients with AIS and a major curve Cobb angle of 10°–40°. Measurements of 35 patients demonstrated a strong correlation and no significant difference between the Cobb angle using 2D EOS radiography and the scoliosis angle using DIER formetric 4D rasterstereography, with a correlation coefficient of 0.70. The intra- and interobserver reliability were excellent, with an intraclass correlation coefficient >0.75. The results of their study, as well as those from previous studies, support the use of surface topographic analysis with the DIERS formetric 4D system as a noninvasive method of monitoring curve progression in idiopathic scoliosis. This has the potential to decrease the use of serial radiographs, which would reduce both radiation exposure and costs.

In addition to the DIERS formetric 4D system, other surface topography mapping systems have been developed and are being investigated as an alternative method for scoliosis surveillance. One study by Komeili et al.[50] in 2014 used VIVID 910 3D laser scanners (Konica Minolta Sensing Inc., Ramsey, New Jersey, USA) to assess the reliability and reproducibility of assessing torso asymmetry using surface topography in 46 patients with AIS. The intraobserver reliability was excellent, with a mean kappa coefficient of 0.85. The interobserver reliability among 4 observers had a mean kappa coefficient of 0.62. The test–retest reliability of this method was also assessed, with a mean kappa value of 0.83–0.99. Therefore, similar to the DIERS formetric 4D system, this novel surface topography technique shows promise as a noninvasive tool for assessing and monitoring deformity progression in patients with AIS.[50]

The results from these studies suggest that although surface topography has a test–retest reproducibility comparable to that of standard radiographs, it underestimates the magnitude of most spinal parameters compared with conventional radiography.[47,48,51] Therefore, surface topography could be useful for 1) the initial assessment when the need for radiographs is uncertain; 2) serial examinations to determine whether the deformity has progressed; and 3) quantifying the magnitude, 3D shape, and rate of progression of a spinal deformity.[48] Because serial surface topography studies could be useful in reducing the frequency of radiographic examinations to monitor AIS curve progression, interest has ensued in maximizing the efficacy and timing of these studies. Some investigators have recommended a rasterstereographic examination every 3–6 months, with a conventional radiographic examination only every 12–18 months to reduce radiation exposure.[52] Despite this, currently no data are available to recommend the appropriate frequency to effectively use surface topography at this time. Finally, standardizing the use of surface topography, such as using surface markers, could be helpful in improving the accuracy of mathematical models when additional features such as skin or subcutaneous lesions or surgical scars are present.[53]

In summary, surface topography can be used as a method of radiation-free assessment of spinal alignment, with benefits that include the potential for interval monitoring with decreased radiation exposure in adolescents with scoliosis. The limitations include the initial cost burden, cost-effectiveness, and the potential for underestimation of the curve magnitude compared with standard radiographs.

Ultrasonography

Multiple recent studies have investigated the use of ultrasonography to estimate the Cobb angles in patients with scoliosis. In a recent 2018 study by Brink et al.,[54] the reliability and validity of ultrasonography for measuring coronal deformity in 33 patients with AIS was examined. They used the spinous processes and transverse processes as landmarks.[54] Although the ultrasound angles were 15%–37% smaller than the standard Cobb angles, the correlations between the ultrasound angles and Cobb angles were excellent, with a coefficient of determination of ≥0.970. The ultrasound angles were also reliable, with an intraclass correlation coefficient of ≥0.84.

The ability of ultrasonography to detect curve progression was also studied in patients with AIS by Young et al.[55] in 2015. The Cobb angles were approximated using the center of lamina method, and the reliability and accuracy of ultrasonography for measuring coronal curves was compared between observers who had the aid of a previous radiograph and those who did not. With the aid of a previous radiograph, stronger correlation with the Cobb angle measurements on the standard radiographs was found. The specificity and sensitivity of ultrasonography for detecting curve progression was 0.91 and 0.83, respectively.[55] These results have shown that using a previous radiograph as a baseline measurement can improve the assessment of the coronal curvature using ultrasonography. Further support for the use of previous radiographs as an adjunct to the ultrasound measurements was reported by a subsequent study by Zheng et al.[56] in 2016. With the aid of previous radiographs, the reliability and accuracy of coronal curve measurements on ultrasound images were significantly improved.

Despite the demonstrated correlation between the ultrasound and standard radiographic measurements of scoliotic curves, the use of ultrasonography is not without limitations. In a recent 2018 study by Zheng et al.,[57] the operator-dependent nature of ultrasonography was examined. The correlation and accuracy between the ultrasound and radiographic measurements were assessed. The ultrasound measurements were also compared between 1 experienced operator and 3 trainees.[57] The experienced operator was found to have fewer curves with a large discrepancy between the ultrasound and radiographic measurements and a greater correlation with the radiographic measurements compared with those performed by the trainees. These results illustrated the highly operator dependent nature of ultrasonography and highlighted the importance of a well-trained and experienced operator take the measurements to optimize the accuracy of ultrasonography in assessing scoliotic curves.

The Scolioscan (model SCN801 [Telefield Medical Imaging, Ltd., Hong Kong Special Administrative Region, People's Republic of China]), was the focus of a 2016 report by Zheng et al.[57] Scolioscan is a 3D ultrasound imaging system that uses a volume projection imaging method to form coronal images of the spine to make measurements of the spinal curvature. Compared with the Cobb angles using reference standard radiography, the Scolioscan angle was noted to slightly underestimate the magnitude of the spinal deformity. However, moderate to strong correlations were found between the Scolioscan angles and Cobb angles in the thoracic and the lumbar spine (r^2 >0.72). The intra- and interobserver reliability was also very good, with an intraclass correlation >0.87. Scolioscan, therefore, appears to be a promising 3D ultrasound imaging system for scoliosis screening and monitoring curve progression.[57]

The reported studies on the use of ultrasonography to assess AIS curves have been limited in that only patients with mild to moderate AIS with a major Cobb angle of <45° were included.[38,55,57] The limitation of ultrasonography is that when patients have more severe curves and associated vertebral rotation, some of the areas behind the spinous processes will not be visualized using ultrasonography because the side of the spinous process facing toward the transducer will block the emitted ultrasound signals.[58] Therefore, it remains unclear whether ultrasonography will have the same accuracy and reliability for assessing AIS in patients with more severe deformities. In addition, although ultrasonography might be appropriate for monitoring scoliosis progression in patients with mild to moderate curves who have undergone a previous radiographic examination, it is not reliable in preoperative planning for determining the appropriate levels for surgical fusion.[55]

In summary, ultrasonography is an extremely accessible modality that can be widely applied in clinical practice by trained individuals. It has the benefits of low cost and no radiation, unlike the other imaging modalities previously discussed. The limitations of its use include the greater potential for human error and the limited detection of low magnitude curves. Nonetheless, it can be used to safely monitor curve progression over time without the need for repeated short-interval radiographic assessments.

CONCLUSIONS

Despite recent advances in diagnostic imaging for idiopathic scoliosis in the pediatric population, standard radiographs remain the reference standard for deformity assessment at presentation and for subsequent routine monitoring. However, emerging concerns regarding the risks of radiation exposure and future malignancy have led to the development of new imaging modalities, including low-dose radiography, surface topography, and ultrasonography. Low-dose radiographic systems such as EOS imaging have been proved to be good, albeit expensive, alternatives to standard radiographs with comparable image quality, allowing for accurate and reliable spinal measurements with decreased radiation exposure. In contrast, surface topography and ultrasonography offer the benefit of eliminating radiation exposure completely but have been shown to be less accurate in quantifying the exact magnitude of the curvature. However, both imaging modalities have demonstrated strong correlations with standard radiographic Cobb angles and, therefore, could play a role in curve surveillance after an initial radiograph has already been obtained. It is important to continue to develop new protocols that combine these imaging modalities to effectively use the advantages of each modality and provide a widely accessible, efficacious, and cost-effective imaging protocol for diagnosing and monitoring scoliosis in the pediatric population.

As new technology in diagnostic imaging for idiopathic scoliosis in the pediatric population continues to develop, several issues warrant more attention and should be addressed in future studies. First, although low-dose radiography has the potential to be an ideal alternative to standard radiography for evaluating scoliosis, its high cost and lack of availability have made it prohibitive at many institutions. The cost-effectiveness of low-dose radiography should, therefore, be investigated further to develop strategies to improve the accessibility to this technology. Second, the limitations of surface topography and ultrasonography in quantifying the exact magnitudes of spinal curvatures should be addressed. Existing studies have demonstrated the utility of surface topography and ultrasonography with the aid of a previous radiograph as a baseline. Future directions should focus on developing standardized protocols for the combined use of baseline radiographs and serial surface topographic or ultrasound imaging for curve surveillance to decrease the overall radiation exposure. It would also be of interest to further investigate and develop techniques that can use surface topography and ultrasonography in preoperative planning and selecting fusion levels. Pending these future directions, it remains to be seen whether low-dose radiography, surface topography, or ultrasonography will gain widespread usage in the deformity assessment of idiopathic scoliosis in the pediatric population.

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