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Diagnostic Imaging of Spinal Deformities

Reducing Patients Radiation Dose With a New Slot-Scanning X-ray Imager

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Study Design. Clinical trial comparing image quality and entrance dose between Biospace EOS system, a new slot-scanning radiographic device, and a Fuji FCR 7501S computed radiography (CR) system for 50 patients followed for spinal deformities.

Objective. Based on their physical properties, slot-scanners show the potential to produce image quality comparable to CR systems using less radiation. This article validates this assertion by comparing a new slot-scanner to a CR system through a wide-ranging evaluation of dose and image quality for scoliosis examinations.

Summary of Background Data. For each patient included in this study, lateral and posteroanterior images were acquired with both systems. For each system, entrance dose was measured for different anatomic locations.

Methods. Dose and image quality being directly related, comparable images were obtained using the same radiograph tube voltage on both systems while tube currents were selected to match signal-to-noise ratios on a phantom. Different techniques were defined with respect to patient's thickness about the iliac crests. Given dose amplitudes expected for scoliosis examinations, optically stimulated luminescence dosimeters were chosen as optimal sensors. Two radiologists and 2 orthopedists evaluated the images in a randomized order using a questionnaire targeting anatomic landmarks. Visibility of the structures was rated on a 4 level scale. Image quality assessment was analyzed using a Wilcoxon signed-rank tests.

Results. Average skin dose was reduced from 6 to 9 times in the thoracoabdominal region when using the slot-scanner instead of CR. Moreover, image quality was significantly better with EOS for all structures in the frontal view ($P < 0.006$) and lateral view ($P < 0.04$), except for lumbar spinous processes, better seen on the CR ($P < 0.003$).

Conclusion. We established that the EOS system offers overall enhanced image quality while reducing drastically the entrance dose for the patient.

Key words: spine radiographs, scoliosis, radiation dose, image quality. **Spine 2010;35:989–994**

Follow-up of spinal deformities, such as scoliosis, typically involves many radiographs of the patient throughout childhood and adolescence. In the last 20 years, these multiple radiograph exposures have become a source of concern with several studies showing that harmful effects can be linked to ionizing radiation, especially for younger patients.[1–3] Highly irradiant methods, like computed tomography (CT)-scans and image-guided interventions, are the primary targets of these publications. However, some other findings conclude that radio-induced harmful outcomes, like breast cancer, can also be linked to standard radiographs follow-up examinations used for evaluation of scoliosis progression.[4–6] These results triggered a widespread campaign in the medical imaging community to reduce dose, especially in centers providing pediatric care.

On the other hand, dose reduction should not be conducted at the expense of valuable diagnostic information. Since dose-free imaging methods, like magnetic resonance imaging and ultrasound, fall short in producing high resolution images of bony structures, the practical solution resides in minimizing the dose while preserving or even enhancing image quality. This is what the EOS system (Biospace, Paris, France) claims to do. This new slot-scanning radiograph imager allows the acquisition of radiograph images while the patient is in weight-bearing position. Physical properties of slot-scanners suggest high-quality images with less irradiation than standard imagers. Collimation of both the beams and detectors minimizes the scattered radiation, potentially enhancing effective detective quantum efficiency, and increasing the detected signal-to-noise ratio (SNR). This improvement should translate into the desired combination of high image quality and reduced dose.[7,8]

This article intends to further investigate this assertion by means of a thorough clinical study on patients fol-

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The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication.

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Supported by This study obtained CHU Sainte-Justine's ethic committee approval. Informed consent was obtained from the patients, if over 18 years old. For minors, informed consent was obtained from the parent or guardian. The slot-scanning system evaluated in this paper was obtained through a grant from the Canadian Foundation for Innovation. The evaluation was supported through research funds by Biospace Med, the company producing the new slot-scanning device that is the subject of this manuscript. At the end of the study, Gilles Beaudoin and Sylvain Deschênes, the physicists working on this project, have come to a consulting agreement with Biospace Med.

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lowed up for scoliosis. Dose assessment of the EOS system is conducted through a combined image quality and entrance skin dose comparison with the CR system formerly dedicated to scoliosis radiograph examinations at our site. Weighing both aspects concurrently is essential since dose can be arbitrarily decreased, but at the cost of lower image quality. Our results will also be compared with dose measurements that were obtained for scoliosis examinations from other pediatric centers.[9–12]

Materials and Methods

Scoliosis Radiologic Follow-up Examination

This study respects the standard radiological examination designed for spinal deformity follow-up developed through a collaboration of the orthopedic and medical imaging departments. The clinical setup combines the acquisition of posteroanterior (PA) and sagittal views of the spine. A setup was designed to avoid any major alteration to the natural posture. Patient must be in weight-bearing position, arms folded at 45° in order to avoid superposition with the spine in the radiograph image. Images were taken, so at least the last cervical vertebra and the pelvis were visible.

Radiographic Systems

The EOS system, shown in Figure 1, is a new slot-scanning radiologic device that allows the acquisition of 2 x-ray images simultaneously. It is composed of 2 x-ray sources, shaped as fan beams through collimation slits. The sources are coupled to linear detectors built using the micromesh gaseous structure technology.[13] Distance between sources and detectors is 1.3 m, with the patient standing at approximately 1 m of both sources.

The 2 source-detector pairs are positioned orthogonally, so the patient's face and profile images are generated line-by-line while the whole system is vertically translated. The system also offers the possibility to activate only one source for single view image acquisition.

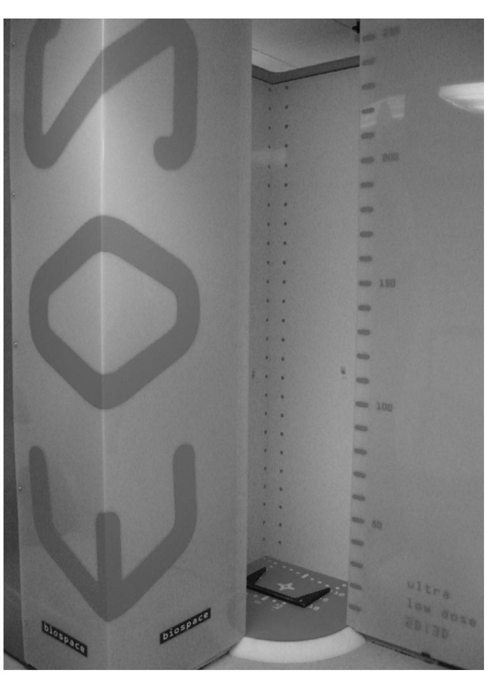

Figure 1. EOS slot-scanning radiologic device.

The user determines the start and finish heights of the vertical scan. This way, irradiation to body parts outside the region of interest is minimized. The result is a pair of digital images, with height depending on the vertical course's length while each line contains 1764 pixels. Image resolution at the detector is isotropic at 254 μm, but a numerical rescaling reconstructs the images in the patient's plane. Default settings assume the patient is standing at the intersection of the beams. In this case, effective resolution is brought down to 193 μm by 185 μm for the frontal view and to 179 μm by 185 μm in the lateral view. Horizontal resolutions differ due to a slight variation in distance between patient and detector for the 2 incidences. Image's dynamic is particularly wide, spreading over 30,000 gray levels. For a spine examination, scan time lasts from 8 to 15 seconds, depending on the patient's height. Patients are asked to hold their breath during the scan. Since images are taken simultaneously, there is no movement of the patient between each radiograph. This characteristic benefits techniques such as 3-dimensional reconstruction of bony structures from 2 radiographic views since their accuracy depends strongly on the spatial correspondence of the structures from one view to the other.[14,15]

Comparison was conducted with a Fuji Computed Radiography FCR 7501S system. It consists of a standard radiograph source and 3 embedded photostimulable phosphor imaging plates. Each image is generated by exposing one of these plates. The plate is then read and images are digitized and stored. A new plate is brought forward and the system is ready for a new acquisition. Distance between source and imaging plates is 1.83 m, with the patient standing approximately 30 cm from the plate.

Frontal and lateral views are acquired separately, one after the other. During the examination, the patient is positioned on a rotating platform to minimize variation of the posture between acquisitions. This setup was developed in part to reach adequate accuracy when performing 3-dimensional reconstruction from stereoscopic techniques. Images spatial resolution is 400 $\times$ 400 μm. Intensity information is stored on a standard 4096 gray levels dynamic range.

Radiographic Parameters

Clinical radiologic parameters for the CR system have been chosen by the medical imaging team in order to generate diagnostic images with the lowest possible irradiation dose. So as to conduct a fair comparison of the systems, we fixed the technical parameter of the slot-scanner to match the CR image quality. This was achieved by keeping the same tube voltage for both systems while varying the tube currents. This way, the x-ray penetration in tissues is kept constant while the dose is adjusted.

On the CR, dose is increased with respect to patient's thickness at the iliac crests. For the same patient, we computed the dose required to generate image quality on the slot-scanner that would be similar to the one observed on the CR. This is achieved by acquiring images of a step phantom, made of lucite and aluminum stairs for several tube currents on EOS and CR. These images depict signal intensities with respect to x-ray attenuation through different lucite and aluminum thicknesses. A second acquisition sequence was carried out with a block of lucite added behind the phantom to reach thicknesses comparable to clinical examinations for the scoliosis study of larger patients.

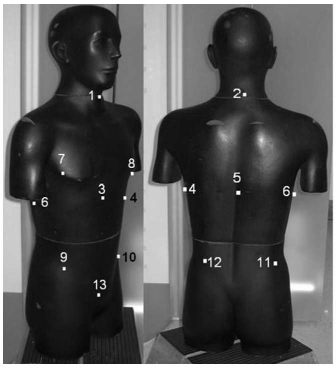

Figure 2. Dosimeters' positions for the study, shown on a RANDO anthropomorphic phantom.

Image quality is characterized using the SNR computed for regions of various attenuations in the phantom image. Matching images with comparable SNR in both methods leads to the definition of equivalent techniques on the EOS system.

Dose Evaluation

We chose Optically Stimulated Luminescence Dosimeters (OSLD) (Landauer, Glenwood, IL) to evaluate the entrance skin dose. These sensors, composed of aluminum oxide crystals (Al_2O_3:C), are invisible on the radiographs. After being exposed to ionizing radiation, dose can be measured by stimulating the crystal with green light. As a result, the crystal emits blue light proportionally to the amount of radiation exposure.

These dosimeters are sensitive to doses as low as 10 μGy and up to 100 Gy. This range largely covers the exposure values expected in this study. Besides, OSLD are very easy to read and manipulate, unlike thermoluminescent dosimeters. For instance, thermoluminescent dosimeter dose readings imply lengthy and burdensome annealing processes while the same reading can be obtained in 10 seconds by simply turning a knob on the OSLD reader.

Thirteen locations, easily spotted on patients of different shapes, were chosen to assess the main radiosensitive regions of the body. Figure 2 shows their positions on a RANDO phantom (Phantom Laboratory, Salem, NY). Two radiological technicians were thoroughly trained to correctly install the dosimeters.

Clinical Study and Image Quality Evaluation

A total of 50 patients (39 female, 11 males) needing spine radiographs, were recruited for this study. The patients (age, 14.8 $\pm$ 3.6 years) underwent examinations on both CR and EOS, 15 minutes apart. For each patient, a dosimeter set was installed and the first radiograph examination conducted. The complete set of dosimeters was then changed and stored for later analysis. The same steps were followed for the second examination. Images were anonymized and saved for later reading while dose values were read and stored in a database. An example of images obtained from this study is shown in Figure 3. One patient's radiographs had to be rejected due to a technical problem during image acquisition.

Proficient dose comparison must be correlated with an evaluation of image quality. Quantitatively assessing image quality was conducted using a questionnaire based on the "European Guidelines for Quality Criteria for Diagnostic Radiographic Images in Pediatrics"[16] and adapted by medical experts to fit the clinical and research needs for scoliosis. Namely, the focus was placed on structures used to either define anatomical landmarks involved in the computation of clinical parameters, such as Cobb angles and vertebral rotations, or to generate a 3-di-

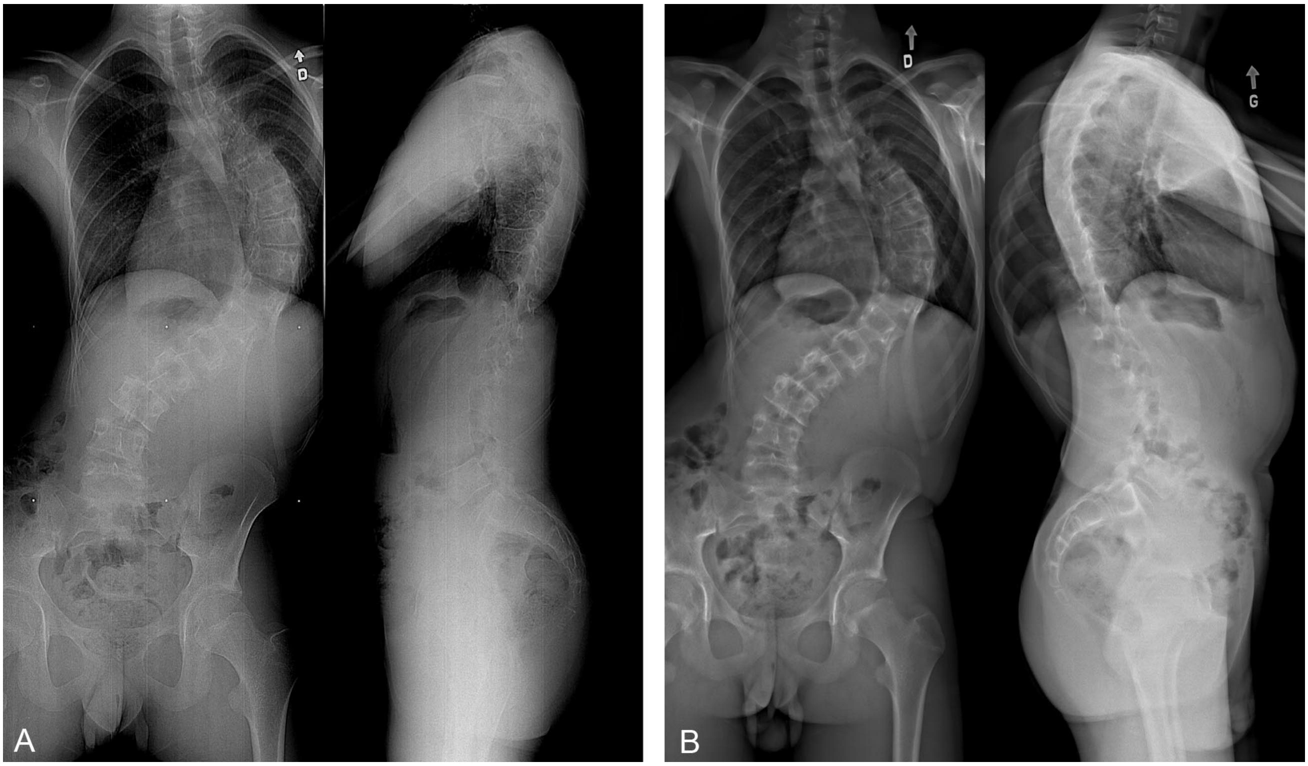

Figure 3. **A,** Posteroanterior and lateral view of a patient taken with the CR system and (**B**) radiographs of the same patient acquired by the slot-scanner.

Table 1. Anatomical Structure Evaluated by Experts

T1–T7 vertebrae
Vertebral body
Pedicles
Transverse process
Spinous process
T8–T12 vertebrae
Vertebral body
Pedicles
Transverse process
Spinous process
L1–L5 vertebrae
Vertebral body
Pedicles
Transverse process
Spinous process
Pelvis
Iliac crest
Femoral heads
Other structures
Craniocervical junction
Clavicles
Rib cage
Cervicothoracic junction
Lumbosacral junction

mensional surface model from stereoradiographic reconstruction methods. Table 1 lists the structures retained for the purpose of this study.

A blind evaluation of image quality was conducted on all images by 2 orthopedists and 2 radiologists. They randomly examined 196 images using the questionnaire mentioned above. The visibility of each structure was evaluated on a 4 level scale: (1) Structure not detectable; (2) Structure visible but features not perceptible; (3) Features discernible but not clearly defined; and (4) Features clearly defined.

At first, a simple assessment of the comparative paired scores was performed. Statistical analysis of the questionnaire results followed, using all paired visibility scoring to perform a Wilcoxon test. This test is a nonparametric alternative to the paired Student *t* test. An interobserver agreement evaluation is then obtained using an analysis of variance on the results from the 4 experts who filled the questionnaires. All statistical results were computed using the SPSS software.

Results

Based on their position relative to the beam, 7 of the 13 dosimeters' locations were selected to evaluate entrance skin dose. Each of the points was facing the beam for at least 1 of the 2 incidences. As seen in Table 2, average radiation dose measured with EOS was consistently lower at all points, reducing dose as much as 9.2 times compared to the CR system.

Entrance skin dose is decreased from 6 to 9 times with EOS for the thoracoabdominal region while 3 times less radiation hits the nape of the neck. The dose reduction at this point is inferior due to each system's geometry. CR produces conic projection, whereas an EOS scan produces a cylindrical projection. In the slot-scanner's configuration, the x-rays travel less distance to reach the neck compared to the source of the CR, which is centered near the thoracolumbar junction.

Table 2. Average Dose Measured With Dosimeters Directly Facing at Least 1 of the X-ray Sources

Number	Anatomic Entrance Point	EOS Dose	Fuji Dose	Ratio
2	Nape of the neck	0.20 mGy	0.59 mGy	2.9
5	Center of the back	0.18 mGy	1.04 mGy	5.9
6	Proximal lateral point	0.27 mGy	2.38 mGy	8.8
7	Outer side of the proximal breast	0.11 mGy	0.83 mGy	7.6
9	Proximal anterosuperior iliac spine	0.16 mGy	1.47 mGy	9.2
11	Proximal iliac crest	0.30 mGy	2.47 mGy	8.2
12	Distal iliac crest	0.11 mGy	0.73 mGy	6.5

Image quality results are shown in Table 3. As expected from our radiographic parameter optimization, a majority (51% and 62%) of the comparison criteria shows equal scores for both systems. However, in the case where a bias toward a system arises, results show that the EOS system is favored in a large proportion.

These observations are supported by a Wilcoxon statistical analysis of all visibility scoring. Results show that visibility on EOS images is significantly better ($P < 0.006$) for all structures in the PA view. EOS is also significantly better ($P < 0.037$) for all structures in sagittal view with one exception: the lumbar spinous process for which Fuji has better visibility ($P < 0.003$).

Interobserver agreement was assessed using an analysis of variance test. It showed that the experts agree on the visibility all structures in PA views, except for one reader at odds regarding the lumbar transverse process. In the sagittal view, the experts agree for all structures above the lumbar region. Results are less consistent for the lumbar region. This can be explained by the fact that the scanning technique delivers a uniform dose across the vertical span of the examination. Technical parameters were set to reach equivalent image quality, but since the amount of radiation varies with the geometry of the x-ray beam, a trade-off had to be made. In our case, the CR's tube is aligned with the lumbar region, where the patient's thickness is maximal. Conic projection leads to reduced irradiation for more distant anatomy like the cervical spine. This is fortunate since patient's thickness is lesser in this region. In contrast, slot-scanning gives equivalent dose throughout the translation of the source-detector couple. Therefore, we decided on setting the technical parameters to match image quality around the thoracic spine. This way, dose reduction is less and image quality is maximal around the cervical region while

Table 3. Image Quality Comparison Between Slot-Scanner and Computed Radiography System

	EOS = CR	EOS > CR	CR > EOS
Global image quality	50.5%	46.7%	2.8%
Structures visibility	61.9%	32.4%	5.7%

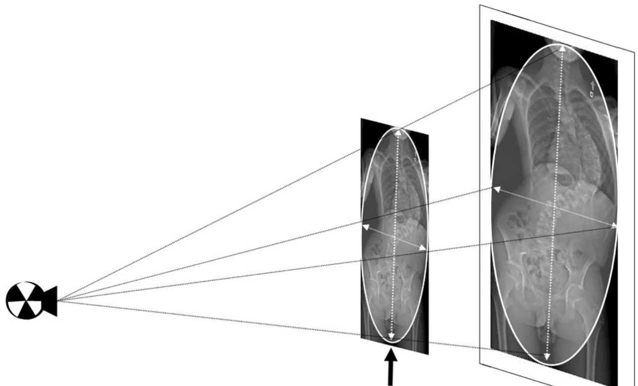

Figure 4. Image formation using a system with conic projection.

dose reduction is maximal in the lower lumbar part of the spine, at the cost of image quality.

Lastly, we compared the slot-scanner's entrance skin dose with other studies measuring the entrance air kerma for scoliosis examinations. These results were weighed against entrance dose found at point 5 for the PA view and point 6 for the lateral view. For patients of age groups similar to our study, the lowest entrance dose, obtained on a CR system using air-gap and no antiscatter grid, was still 18% higher than with the slot-scanner.[9] However, no image quality assessment was presented with this technique. Other studies, using both CR and digital radiography systems, show average entrance doses varying from 0.5 mGy to 3.1 mGy in PA view and 0.89 mGy and 3.9 mGy in lateral view.[10–12] This corresponds to 3 to 18 times more dose than what is given by the slot-scanner.

Discussion

The slot-scanning technology offers dose reduction benefits while considerably enhancing image quality. The main drawback resides in the fact that uniform dose is delivered across the entire area of the body. This translates in a similar irradiation along the scan even though patients' thickness varies. It also leads to compromises during the choice of the optimal parameters. We opted for a technique that would match image quality from both systems for a region around the thoracolumbar junction. That choice could explain the poorer results encountered for the lumbar region.

On the other hand, the fact that the slot-scanner's beams are always aligned with the detectors can also improve visual representations of anatomy. As shown in Figure 4, usual CR system will project information on the image plane through a conic perspective. This causes distortion from the center to the edges of the radiograph, leading to increasing errors in scale for structures far from the central region. Due to the fan-beam geometry, slot-scanning only encounters this distortion along the horizontal axis, as can be seen in Figure 5. However, this cylindrical projection's deformation of the image is corrected by the numerical rescaling performed by the system's visualization interface. This way, the image is reconstructed as if it was acquired in the patient's reference plane and limits the distortion to the patient's thickness instead of the whole distance between source and detector.

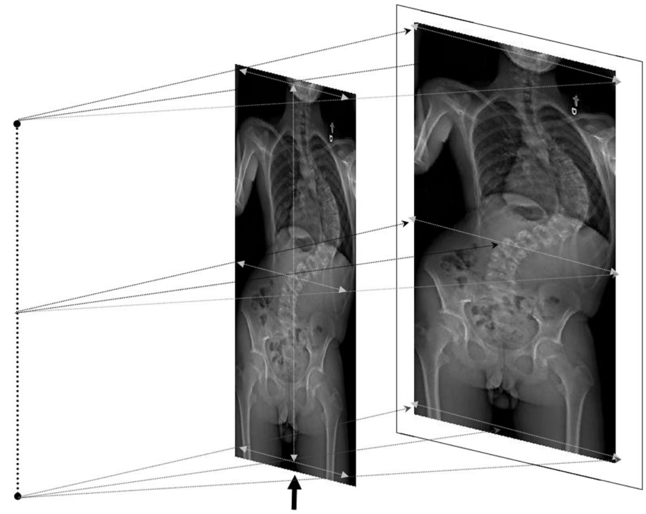

Figure 5. Image formation using a slot-scanner with cylindrical projection geometry.

With standard CR, radiographs are attenuated by the patient's body following trajectories more or less tilted with respect to the center line. Therefore, structures that are close to be aligned with the horizontal plane, like intervertebral discs and vertebral endplates, will partly overlap far from the source. The result is a lower contrast between these tissues. Slot-scanner's projection geometry therefore enhances contrast for structures lying in the horizontal plane. An example of this behavior can be seen in Figure 6, where higher delineation between the disc and vertebral endplates is observed in the upper thoracic spine imaged with the slot-scanner. Projection geometry also shows a faster occlusion of the cervical spine by the patient's head. Studies are presently underway to evaluate the effect of the EOS projection on clinical parameters.

Overall, the EOS system shows better image quality while substantially reducing patient's dose exposure. The dose reduction could further be improved by including an automatic exposure control similar to what is found in modern CT-scanners. This way, an optimal amount of dose could be delivered with respect to the patient's morphology. Evaluations of organ dose and effective dose are presently being finalized. A comparison between EOS and a digital radiography system for chest radiographs is also underway.

From a clinical perspective, one of the most interesting features of the slot-scanner is the possibility to simultaneously acquire 2 orthogonal images. This considerably facilitates the 3-dimensional surface reconstruction of vertebrae and pelvis using stereoscopic algorithms. New clinical parameters can then be computed, potentially offering information more appropriate than the 2D indexes normally used to assess the deformity. It is inter-

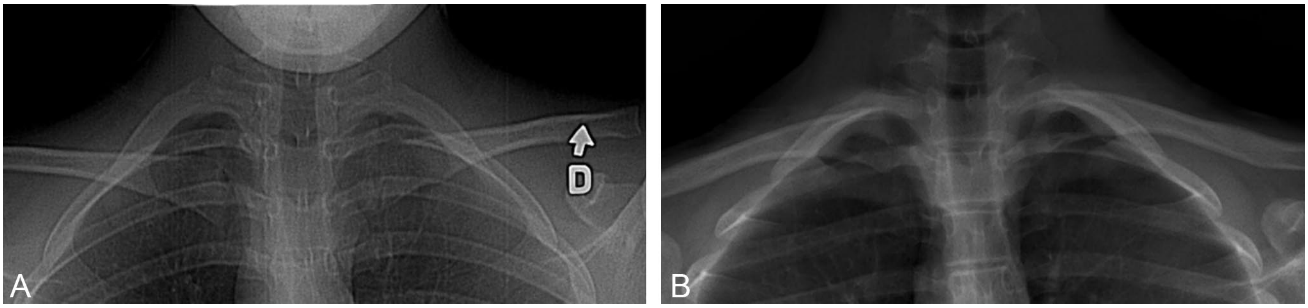

Figure 6. Delineation of the intervertebral spaces in (**A**) a CR system with conic projection and (**B**) a slot-scanner with cylindrical projection geometry.

esting to note that this 3-dimensional representation is obtained using hundreds of times less irradiation than what is required by a CT-scan image reconstruction.

■ Key Points

- This work presents a dosimetry study of radiograph examinations for spinal deformities follow-ups.
- The evaluation is based on a thorough comparison of doses and images obtained from a slot-scanner and a CR system.
- Dose evaluation shows that the slot-scanner delivers 6 to 9 times less entrance dose than the CR system.
- Four experts agree that image quality is significantly better for slot scanner.

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