Abstract

Introduction
Since the 1970s, multiple topographic systems have been developed and applied in clinical evaluation as well as in research for children with spinal deformities, especially for children with idiopathic scoliosis. Through this historical review of topographic systems and based on our experience using the Quantec Spinal Imaging System and the recently developed Milwaukee Topographic System, we present the pros and cons for each major system and how they advanced the topographic assessment.

Discussion
The primary goal of topographic systems is to eliminate the need for X-rays and children’s exposure to radiation and to provide three-dimensional measurements of the backs contours, which two-dimensional X-rays cannot provide. Most studies demonstrate that topographic systems are moderately accurate for providing three-dimensional information of back deformities for children with idiopathic scoliosis; however, some systems are difficult for the clinicians to operate and need to be technically improved. Additionally, there is a lack of a standard clinical protocol for quantifying the degree of the spinal deformity using topographic systems.

Conclusion
When selectively used, a topographic system can be considered as an alternative to X-rays in the evaluation of the children with mild idiopathic scoliosis.

Introduction
We have reviewed a group of topographic systems that were published in the journals in chronological order:
- Moiré Topography, 1970
- Integrated Topography System (ISIS 1), 1986
- Raster Stereophotography, 1988
- InSpeck, 1994
- Quantec Shape Imaging System (QSS), 1995
- Formetric 3D, 1996
- ISIS 2, 2003
- Milwaukee Topographic System (MTS), 2009

1. Moiré Topography
Moiré topography was one of the first methods used for the early detection of scoliosis without radiation. It was first used in 1970 by Takasaki with an initial depth accuracy of 0.2%, size and depth of field of 1.8 × 1.8 × 0.9 m³ and a camera shutter speed of less than 1/8th of a second. It is composed of light sources, a camera, screen and a desktop computer. This is taken from the concept of Moiré patterning, commonly used in physics and manufacturing.

2. Integrated Shape Imaging System 1
The ISIS 1 was created in 1986 by Oxford Metrics (Oxford, UK). It is composed of a scanner, special computer console, plotter and a stationary television camera that produces a plane of light down the patients’ back, which is then measured by the computer to acquire a three-dimensional (3D) back surface shape and the black markers placed on the patients’ back. The accuracy of the central volume of a 350 × 100 mm shape is X = 1.1 ± 0.2 mm, Y = 1.5 ± 0.2 mm, Z = 1.7 ± 0.2 mm; for 450 × 140 × 500 mm shape is X = 1.2, Y = 3.0 mm and Z = 3.5 mm; and accuracy for identifying markers is X = 2 mm, Y = 4 mm and Z = 3 mm. It takes 1.5 s to scan and a few minutes for the computer to process. It generates 1000–2000 3D data points. It was initially described as an optical scanner designed primarily for assessing the shape of the human back.

3. Raster Stereophotography
Raster stereophotography was developed by Ian Stokes from the University of Vermont in 1988 as a sort of enhanced form of Moiré topography. The system is composed of an optical raster-stereography unit, stripe projector and video imaging system firmly attached to the projector with motorised height adjustment, a computer and screen for the patients to stand in front of. A square grid is optically projected onto the patient’s back and then photographed from an angle 30° above the patient. These images of the projected grid intersection are digitised to obtain the 3D coordinates. Around 150–200 points are obtained on each back.

4. InSpeck
InSpeck was founded in Canada in 1994. It has two main body-scanning systems: MegaCapturor II and MegaCapturor DFM. Both of these systems use white halogen light technology, phase-shifted Moiré...
projections, an interferometer-measuring method and an optical-triangulation technique to reconstruct 3D models. They both require multiple acquisitions or having multiple digitisers to produce a 3D image. The MegaCapturor DF is unique compared to the MegaCapturor II in that it has a dual-field camera that can capture two different volumes of measurements at the same time; for example it can capture 1–5 people with its large field camera. The specifications of the MegaCapturor II for its small field camera are: 435 × 350 mm field of view, 450 degrees of freedom, 0.3 mm X resolution, 0.3 mm Y resolution, 0.4 mm Z resolution, 1280 × 1024 pixel texture, 1.3 million points and 0.7 s acquisition time. The specifications of the MegaCapturor II for its large field camera are 1190 × 350 mm field of view, 1000 degrees of freedom, 0.9 mm X resolution, 0.9 mm Y resolution, 1.0 mm Z resolution, 1280 × 1024 pixel texture, 1.3 million points and 0.7 s acquisition time.

5. Quantec Shape Imaging System

The QSIS was created by Quantec Image Processing in the UK in 1995.6 It bases its technology on raster stereography/photography and is composed of a digital camera, computer software to measure the 3D trunk images and to record and quantify scoliosis deformity, a quartz halogen light and booth. It is capable of recording trunk balance, spinal angles, sagittal angles, rib humps and surface asymmetry. It measures a Q-angle instead of a Cobb angle, which is correlated to the Cobb angle and used to measure scoliosis.

6. Formetric 3D

The Formetric System was created in Germany in 1996 by DIERS International GmbH. It combines raster stereography and biomechanical modelling to obtain body surface measurements. It uses white light raster line technology to scan an object and capture the raster lines. It produces frontal and sagittal projections of the symmetry line on the back and an estimate of the vertebral body line to produce a kyphotic angle, lordotic angle and scoliotic angle. It is in its fourth generation as of 2008. Its accuracy for topographical representation is 2 mm, high precision of profile is ≤0.1 mm, spinal midline root mean square (r.m.s.) deviation is 1.54 mm, lateral and anteroposterior r.m.s. deviation is <3 mm, and repeatability r.m.s. deviation is 1.7 mm and 2.8°.7 Drerup et al.8 analysed 478 images and compared X-rays with Formetric scans taken on the same day. They found an r.m.s. deviation of 4 mm, vertebral rotation r.m.s. of 3° and no systematic difference of vertebral and surface rotation, and concluded that these values are sufficient for clinical application.

7. Integrated Shape Imaging System 2

The ISIS 2 was developed starting in 2003, with preliminary studies done starting in 2006. It is an improvement of the ISIS 1 system in terms of speed, accuracy, reliability and ease of use. It is composed of a camera/projector stand, reference plane for the patient to stand in and a Mac computer. The generated pixel size is ~0.5 mm and fringe frequency is ~0.16 fringes/min or ~6.5mm/fringe.9 The camera shutter speed is 100 ms and the time needed to analyse the obtained photographs is only 40 s.10

8. Milwaukee Topographic System (MTS)

The MTS was created by Rankine et al. in 2009 at the Children’s Hospital of Wisconsin, Medical College of Wisconsin.11 This newly developed raster stereography system is composed of a new software system, handheld light source and hardware, which can be easily transported among clinical rooms. It takes MTS 30 s to finish a scan if operated by an experienced practitioner. It is a novel and fast 3D measurement tool, presenting quantitative information and providing some parameters that X-ray is unable to measure. Another advantage of MTS is that the usage of electro-magnetic sensors on the back helps eliminates the noise caused by the movement of the patient during the acquisition time. A Windows XP®-based software enables the practitioners to easily process the data and save it directly in the patient’s database.

The aim of this review is to discuss the experience with the use of surface topographic systems in children with idiopathic scoliosis.

Discussion

The authors have referenced some of their own studies in this review. These referenced studies have been conducted in accordance with the Declaration of Helsinki (1964) and the protocols of these studies have been approved by the relevant ethics committees related to the institution in which they were performed. All human subjects, in these referenced studies, gave informed consent to participate in these studies.

In 1977, Adair et al.12 conducted a pilot study with Moiré topography to measure and track the progression of scoliosis in children. They found that Moiré topography produced only eight false-negatives compared with 72 from the forward bending test and that positive scoliosis is indicated by asymmetric fringe patterns. Daruwalla et al.13 determined the accuracy of Moiré topography in detecting the site and size of a spine curve. They found that Moiré topography accurately diagnosed the location of the curve in 54% of the patient population, most accurately in the thoracic region, and 100% accurately for kyphosis. They concluded that there were too many false-negatives, the forward bending test was cheaper and more accurate and that Moiré topography could potentially be useful to assist in the detection of minor curves and monitor the progression of curves, but not as a standalone method. Ruggereon et al.14 examined 42 patients with Moiré topography, 22 with scoliosis,
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Cobb angle, computer Cobb angle and maximum back-surface rotation, while their stereophotographic measurements were a surface Cobb angle and maximum vertebral axial rotation. They found that their computer Cobb measurement was most precise and back-surface measurements were least precise. There was a positive correlation between changes in vertebral axial rotation and changes in Cobb angle and they also noted that Cobb angles remain constant during longitudinal growth, while stereography measurements are able to track this growth. More recently, Schulte et al.\textsuperscript{20} investigated the reliability and accuracy of raster stereography compared to X-rays in a longitudinal study in idiopathic scoliosis (Figure 2). They analysed 16 patients with an average follow-up of 8 years (range of 3–10 years). They found that during follow-up Cobb angle increased by an average of 13° and that progression of lateral vertebral deviation was greater in radiographs than the Cobb angle and lower in raster-stereographs.

A study conducted by Cheriet et al.\textsuperscript{21} described using the InSpeck to create an internal and external 3D structure. They concluded that the effects of the data uncertain from the InSpeck are too great and that it is an unreliable method of tracking scoliosis progression. Most recently, Clin et al.\textsuperscript{22} conducted a study that included gravitational forces in a finite element model of the scoliotic spine assess with the InSpeck system. They concluded that they had created a realistic way to integrate gravity in a scoliotic trunk finite element model able to compute the stresses due to gravity, which will be useful for biomechanical modelling studies of scoliosis.

There were several more studies done by Thometz or Liu et al. in the late 1990s/early 2000s. Thometz et al.\textsuperscript{23} made use of the Quantec system as a means of measuring kyphosis and lordosis in the sagittal plane, Q-angle (an analogue to Cobb angle) with Cobb angle for the same subject: Q angles in the coronal plane measured by the QSIS (left); Cobb angles in the coronal plane recorded by radiography (right).
plane. They found that Quantec overestimates the value of kyphosis and underestimates the value of lordosis compared to X-rays, which could be explained by the two techniques measuring different parameters. Thometz et al.24 assessed the axial rotation in 149 patients, comparing the results between different measurement systems including the Moiré technique, Raster stereophotography, Perdriolle technique and Quantec system. They concluded that Quantec reduces the variability in measurements of axial surface rotation in the thoracic region. Liu et al.25 strived to produce a functional classification of spinal deformity in patients with mild idiopathic scoliosis with using X-rays. They found that it is possible to produce a quantitative assessment of mild spine deformity with 3D parameters and no radiography. Thometz et al.26 analysed 140 patients to determine the correlation between Cobb angle and Q-angle (Figures 3 and 4). They found that there was a correlation between these two angles with smaller curves with minimal rotation and that overall the Q-angle generated lower values than the Cobb angle. Sakka et al.27 had conducted a similar study correlating the Cobb angle with the Q-angle and found that the angles were correlated with an $r^2$ value of 0.801. They analysed 202 curves and found that Quantec overestimated 119 curves and underestimated 83 curves. This same group also produced a 3-year follow-up study5 concluding that after 3 years the patients had a mean Cobb angle of 21.2° and Q-angle of 22.9°, indicating their similarities. Another study conducted by Thometz et al.28 measured the Quantec system sensitivity to changes in the 3D trunk position. They concluded that there was a need to constrain trunk position to assure reliable measurements because postural sway in the transverse plane is critical to accurately estimate the coronal plane deformity.

Figure 5: Overall back contour measurement in relation to the spinal segment: calculation of deviation in the coronal and sagittal plane as well as surface rotation using Formetric 3D system (photo courtesy of Diers Company).

Figure 6: A dummy cast of one idiopathic scoliosis child with markers was scanned by the MTS system: three Q angles (8°, 21° and 15°) are analogous to Cobb angles in the coronal plane (left); Kyphosis (36°) and lordosis (25°) are analogous to Cobb angles in the sagittal plane (centre); axial surface rotation (ASR) in the transversal plane11.

Tessakov et al.29 examined 162 patients and concluded that the Formetric system provides an objective estimation of back shape, more precision orientation in the development of scoliosis and produces concrete data on anato-mo-biomechanical characteristics of the spine. They concluded that the Formetric system makes it possible to diagnose, track and predict the progression of scoliosis. Hackenberg et al. produced two manuscripts on the Formetric system (Figure 5). Their first30 was to determine the accuracy of the Formetric system analysis and spine reconstruction in idiopathic scoliosis treated by posterior correction and fusion. They concluded that the Formetric system is reliable in scoliosis up to 90° after posterior correction and that the system can...
be used post-operatively to reduce the number of X-rays needed. It also produces an objective quantification of post-operative improvement in cosmetic abnormality of back shape. Their second article was in cosmetic abnormality of back shape.

Their second article was very similar, only differing in instead looking at patients who were anteriorly corrected with fusion. They found that the Formetric system was satisfactorily accurate in patients with Cobb angles between 50 and 88°, precision was good, and can be used for post-operative follow-up exams.

Zubovic et al. released the first manuscript confirming that ISIS 2 3D back shape measurements are valid for assessment and follow-up in patients with scoliosis. They concluded that ISIS 2 scans had excellent repeatability and found no statistically significant differences between ISIS 2 scans and X-rays in 111 patients. Also, Berryman et al. showed that this system had many advantages over the ISIS 1 and that lateral asymmetry is most likely the most important parameter for spine surgeons because of its correlation to Cobb angle and the ISIS 2 has good correlation with this parameter.

A dummy cast (plastic cast) of one patient with adolescent idiopathic scoliosis was used to test the reliability of the MTS. The dummy cast was positioned and rotated in 3D while scanned by two investigators using the MTS (Figure 6). A total of 12 parameters including Q-angle (an analogue to X-ray’s Cobb angle) were extracted. All measurements of intra-rater and inter-rater reliability were excellent (Intraclass Correlation Coefficients ranging from 0.89 to 0.99) with the exception of Pelvic Tilt (Intraclass Correlation Coefficient (ICC) is 0.61) and lordosis angle (inter-rater ICC is 0.82). No significant variability among investigators was observed for all tested metrics. No significant variability due to position was observed for the majority of back contour measurements; however, there were significant changes in the T1–S1 angle, T1–S1 deviation, T1–NC angle, T1–NC deviation and Back Height metric ($p < 0.05$). In another study, typically developing subjects were measured with the MTS. Two investigators separately scanned the same subjects multiple times, yielding a total of four scans per subject per investigator. There were highly reproducible ICC values between investigators for six parameters (ICC > 0.75), moderate ICC values for eight parameters (0.75 > ICC > 0.4) and poor ICC values for three parameters (ICC < 0.4), all with $p < 0.05$. Intra-investigator ICCs were moderate to excellent for almost all parameters.

### Conclusion

The common advantages of all surface topographic system are as follows:

- They do not use radiation.
- There are some correlations between radiographic Cobb angles and topographically measured angles.
- They provide an objective record of contours for longitudinal review and tracking.
- Most have automated digitisation.

However, each system also displays the disadvantages that we summarise in Table 1.

Each topographic system has its own pros and cons for measuring

<table>
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<th>Systems</th>
<th>Disadvantage</th>
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| Moiré Topography | 1. Takes a long time to digitise photographs  
2. High rate of false-negatives  
3. Poor accuracy |
| ISIS 1 | 1. Generates only 1000–2000 3D data points of the back surface |
| Raster Stereophotography | 1. Has only 150–200 3D data points of the back surface  
2. Poor accuracy and reliability  
3. Not sensitive to small changes in backs |
| InSpeck | 1. Relatively slow 3D image acquisition  
2. Data uncertainty too great to be a reliable method of scoliosis progression tracking |
| Quantec Shape Imaging System | 1. Requires markers on the patients back  
2. Multiple images need to be taken  
3. Should not be used without X-rays as references  
4. Not compatible with Windows |
| Formetric 3D | 1. Uses model-based calculations of vertebral rotation |
| ISIS 2 | 1. Requires markers to identify bony landmarks on the back  
2. Is not as accurate for patients who are extremely obese or have heavy musculature |
| Milwaukee Topographic System | 1. Requires markers to measure the back contour  
2. Low reproducibility of axial surface rotation in the lower lumbar region  
3. Less accurate for obese children |
the 3D back contours. The various systems have been developed and applied in the clinical and research areas most appropriate depending on cost, feasibility, accessibility and goal of measurement. Many clinics lack the use of these topographic systems; therefore, we need to make an effort to gain more widespread use of these systems in clinical settings. There is still a lack of consensus on forming a standard protocol for monitoring the progression of spinal curvature using topographic systems. Nevertheless, a topographic system can be considered as an alternative to the use of X-rays in the evaluation of the children with mild idiopathic scoliosis.

Abbreviations list
ISIS, Integrated Shape Imaging System; MTS, Milwaukee Topographic System; QSIS, Quantec Shape Imaging System; 3D, three-dimensional.

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References