Quantitative evaluation of spinal coronal curvature for scoliosis using a fast 3-D ultrasound projection imaging method

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Abstract—**In this study, a novel fast 3-D ultrasound projection imaging (FUPI) method to provide quantitative evaluation of spinal coronal curvature for scoliosis patients was proposed. Unlike conventional 3-D volume rendering approaches, this method directly projected the raw images to form the coronal images. The non-planar rendering method, following the natural curve of the spine, was utilized to contain the complete spine information into the projection images. Based on 30 patients with scoliosis (ages of 16.3±2.9 years), the comparison study between the new method and the conventional 3-D rendering method was performed. The processing time and the projection images were both compared. The average processing times for the two imaging methods were 15.07±0.03s and 149.50±33.44s, respectively. There were high correlations between the measurement results using the images obtained by the two 3-D imaging methods (y = 0.9733x, r=0.970 for thoracic region, y = 1.0224x, r=0.968 for lumbar region). The above results demonstrated the new method could greatly reduce the processing time while preserving the comparative image quality. It can be expected that the developed FUPI method may help to provide fast 3-D ultrasound diagnosis of scoliosis in clinics.**

Keywords— **scoliosis, spine, coronal image, 3-D ultrasound, projection imaging.**

I. INTRODUCTION

Scoliosis is a complex three-dimensional spine deformity associated with vertebral axial rotation and the lateral deviation. Adolescent idiopathic scoliosis (AIS) is the most common form of scoliosis, with the prevalence of 2% to 4% in the United States [1] and 3.08% in Hong Kong [2]. It was reported that AIS could cause a series of health problems including the thoracic insufficiency syndrome, back pain, spine degeneration, and psychosocial issues such as increased depression and lower self-image [3-5]. For the teenagers with AIS, the situation is even worse because the risk of curve progression is very high for the immature skeleton. However, the prognostics of AIS is still far from satisfactory, though many factors have been studied such as Risser sign, Cobb angle, standing heights, sitting heights, and curve pattern. Regular observation is important to monitor the curve progression, and it is a necessary step for the follow-up diagnosis, surgery planning, and the treatment outcome assessment.

In clinics, standing X-ray radiography is the most common diagnosis method for scoliosis curvature assessment [6]. However, it was reported that the frequent exposure to X-ray could raise the risk of cancer, especially breast cancer, because the breast was exposed to X-ray during scoliosis diagnostic radiography and the radiation dose cumulated to the breast with the frequent examinations [7]. In addition to the breast cancer, it was reported that the patients of AIS with radiation exposure had a 7.5% increased risk of developing lung cancer [8]. And it was reported that the risk was obviously increased with the cumulative radiation dose. Another drawback of X-ray radiography examination is that the intra-rater and inter-rater variation of curve deformation measurement using Cobb angle can be up to 3-5° and 6-9° respectively [9, 10]. In clinics, an increase of 5° or more is used as the indicating curve progression. So the measurement variation can cause problems to the clinical diagnosis based on the angle measurement results, especially for the long-term monitoring. Except for the standing X-ray radiograph, the surface topographic methods are also used to estimate spine curvature using stereo cameras or finger palpation. Measurement systems of surface topography are radiation free and cost effective. However, these methods are fraught with limitations of inability to provide accurate measurements and to visualize the bony structure.

Compared with the above assessment methods, ultrasound has advantages of being radiation-free, low-cost, real-time, and it allows visualizing the accurate bony architecture. Therefore, the approach of using ultrasound for scoliosis has attracted more and more attentions over the past decade. The feasibility of ultrasound measurement in scoliosis was investigated in as early as 1989 [11]. In recent years, freehand 3-D ultrasound, combining conventional 2D ultrasound with position sensor, has been advanced to overcome the limitations of 2D viewing and measuring of 3-D anatomy, and a number of such systems have been reported for scoliosis assessment. One approach for scoliosis measurement is to measure the spinal curvature on the 2D ultrasound images with the help of the positional tracking. The images containing the transverse processes were either picked from a pile of recorded 2D raw B-mode images [12] or captured in real-time while locating the target from observations [13].

However, this approach is time-consuming because of the identification of the sonographic landmarks of the transverse process from dozens of acquired images. In addition, this method does not generate 3-D representation of the spine anatomy, lacking the ability of viewing the whole spine anatomy. Another approach to utilize the positional information of images is to form the whole spine image. One study was to use the maximum intensity projection method to get the coronal images and use land-marks of laminae to measure the spinal curvature [14]. In this method, the sagittal images were firstly generated and used as the guidance. This method was relative tedious and time-consuming for the manual marking. Another study to generate the coronal spine image was conducted by Cheung et al [15]. In this study, a 3-D volume was reconstructed according to the acquired data set. And then the coronal images were generated from the volume data. Compared with the above method, this volume projection imaging method can provide coronal image without the manual intervene. However, the 3-D volume recon-struction is still time-consuming because of the large raw image data (2000 scans, 640*480 pixels, about 600 MB).

In this study, a fast 3-D ultrasound projection imaging method was proposed to provide the spinal coronal images. To demonstrate the system performance, its processing time and the generated coronal images were compared with that of an earlier reported volume rendering method.

II. Methods

A. System overview

A freehand 3-D ultrasound imaging system, named Scolioscan system (Model SCN801, Telefield Medical Imaging Ltd, Hong Kong), was developed with industrial and ergonomic designs of the hardware for the assessment of scoliosis. The system is shown in Fig. 1. A rigid frame, consisting of the chest board, hip board and four supporters, was used to help the subject to maintain a stable posture during the ultrasound scanning. Before scanning, the subject stood on the platform and the two boards moved up and down along the side panel to be repositioned according to the height of the subject. Two supporters on the chest board were relocated to align with clavicle anterior concavities, whereas two supporters on the hip board were relocated to align with bilateral anterior superior iliac spines, the length of supporter's shafts on both boards were adjusted until they came in contact with the patient. A liner 2D ultrasound probe (frequency: 4-10 MHz; width: 10 cm) was used to scan the subject. An electromagnetic position sensor was attached to the probe to obtain the spatial information of ultrasound images. The electromagnetic transmitter was put in the transmitter box. Two LCD monitors were utilized in this system. The operator monitor was used for setting scanning parameters, saving and retrieving data, performing reconstruction, displaying images, conducting measurement, and generating reports. The patient monitor was to provide information for patients, including a green eye spot with location set according to the height of patient to facilitate him/her to keep a stable posture for head and neck during scanning.

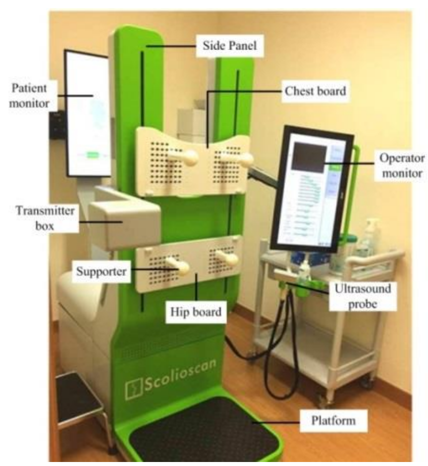
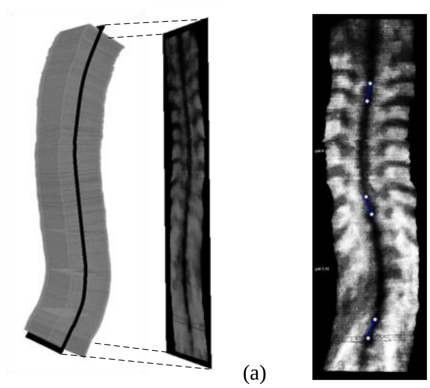


Fig. 1 The Scolioscan system and it components

B. Data acquisition and the fast 3-D ultrasound projection imaging method (FUPI)

Before scanning, the subject was asked to remove all metallic items. He/she wore a gown with back opened to the operator and stood in front of the boards. The operator adjusted the chest and hip boards, and the four supporters as required to keep the subject in a natural stable posture. Then the ultrasound gel was applied to the scanning area to ensure the good coupling between the probe and the skin. The operator put the probe on the subject and adjusted the ultrasound parameters according to the tissue condition. In this study, the scanning covered the spine area from the fifth lumbar vertebra (L5) to the first thoracic vertebra (T1). The operator put the probe on L5 and T1 to record the lower and upper boundaries of the scanning, respectively. Finally, the operator moved the probe to L5 to initiate the scanning. The probe was steered to cover the spine vertically. The ultrasound images together with their corresponding position data were recorded. When the probe passed through the upper boundary, the data collection would be stopped automatically. It took about 30 seconds to complete the whole scanning and about 2000 2D ultrasound images were recorded for the further processing.

In conventional 3-D ultrasound imaging method, two steps are usually utilized to visualize the spine anatomy. The first step is to reconstruct the tissue volume according to the 2D ultrasound raw data and positional information. Then the volume is visualized using the planar or non-planar reslicing method. An earlier reported method for scoliosis, named volume projection imaging (VPI) method, just adopted the above two-step imaging method to get the spinal coronal images [15]. However, in 3-D ultrasound imaging system for scoliosis, the purpose is to provide the coronal images to further assess the spine deformity. So the first step of volume reconstruction can be skipped to improve the speed of visualization. In this study, a fast 3-D ultrasound projection imaging method (FUPI) which bypassed the procedure of volume reconstruction was proposed to generate the volume projection images. This method was based on a narrow-band volume rendering method introduced by Gee et al [16]. In the proposed FUPI method, the rendered coronal image was obtained by directly projecting a layer with a certain thickness of the raw image data to the coronal plane. To follow the shape of the spine, a non-planar layer which was defined using the distance to the skin, was applied to be projected to the coronal plane, as shown in Fig. 2a. A coronal image coordinate system with a regular pixel array was defined according to the data set. Based on the spatial information and the calibration matrix, each pixel on the defined layer was transformed to the new coordinate system. The final value of the pixel on the new coronal plane was determined on the basis of all pixels falling into its region. The average blending method was used to determine the final intensity of the pixel by using all pixels in the region. After images were processed, the interpolation was implemented to fill the gaps in the projection image. In this study, considering the computation time and the interpolation performance, the common bilinear interpolation method was adopted. The average of the non-empty pixels in the nearest 2-by-2 neighborhood was set as the value of the empty pixel. Finally, the image was further enhanced with Histogram equalization that is one of the most useful image enhancement techniques.



(a) (b)

Fig. 2 Illustration of the non-planar rendering approach and curvature angle measurement method. (a) The non-planar rendering method; (b) The angle measurement method.

To evaluate the spine deformity, the angle measurement method using the shadow generated by the spinous was developed by Cheung et al [15]. The principle of this measurement method was to identify the inflection point of the spinous shadow line and the vertebrae containing the inflection point was treated as the most tilted one. As shown in Figure 2b, three short lines were manually drawn. They located in the middle of the shadow line and covered the corresponding vertebra. Then the angle between two lines were calculated and used as the spine curvature angle. There are two curvature angles in Figure 2b, the first angle between the upper two lines is the angle in thoracic regions and the second angle between the lower two lines is the angle in lumbar regions.

C. Comparison study between the fast 3-D ultrasound projection imaging (FUPI) method and the conventional volume rendering method

To investigate the performance of the FUPI method, a comparison study between the new method and the earlier VPI method was performed. The two imaging systems ran on the same computer with configuration of Intel Core i5 and 32.0GB of memories. 30 patients with scoliosis (7 male and 23 female; mean age, 16.3 ± 2.9 years; BMI, 18.5 ± 1.6 kg/m^2) were recruited in the Department of Orthopaedics and Traumatology of The Chinese University of Hong Kong. This study was approved by the human subject ethics committee of the institution and all patients (or their parents for those patients under 18 years old) gave the informed consent. The recruited patients were scanned by the sonography operator using the Scolioscan system and the raw data including the images and their positional information were saved. The raw data were processed by the two imaging methods respectively. The comparison study included the processing time comparison the curvature angle measurement results comparison. The processing times of the two imaging methods were recorded respectively. For each patient, two images were obtained using the two methods. And there were totally 60 images (30 patients * 2 processing methods) to be measured in this test. The same operator measured the angles on all projection images using the previously described method, as shown in Figure 2b.

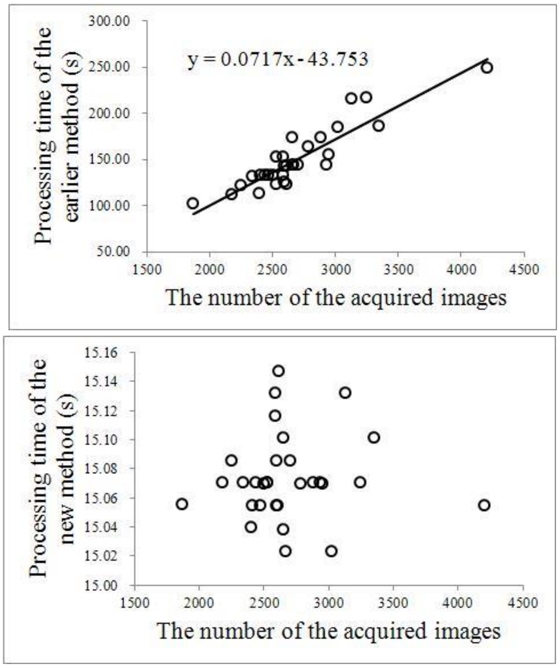
D. Data analysis

The processing times using the FUPI method and the VPI method on 30 patients was analyzed. The correlation relationship of the processing time and the data size was also presented. The angles on the measurement images were manually drawn and values were compared to observe the difference between the two imaging methods. The Pearson correlation coefficient r was used to assess the correlation of the two methods. All statistical evaluations were performed using the statistical software (SPSS for Windows, version 17.0; SPSS, Chicago, IL, USA).

III. Results

A. Processing time comparison

The results showed that the processing times on 30 subjects were 149.50±33.44s (range: 102.07-248.59s) and 15.07±0.03s (range: 15.02-15.15s) for the VPI method and the FUPI method, respectively. The VPI method takes, on average, 10 times of processing time compared with the developed method. In addition, the standard deviation (SD) values is much larger (33.44s) for the time of the VPI method compared with the time of the FUPI method (0.03s), which means the processing time varies largely for different subjects. This is further demonstrated by Figure 3, which shows the relationship between the processing time and the acquired data size. As shown in Figure 3a, there is a clear linear relationship between the time and the processing images numbers for the VPI method. This tread indicates that the processing time increases along with the size of acquired raw data. While for the developed method, there is no relationship between the time and the acquired image number. In this study, for a data set with about 4000 2D images, the processing time of the VPI method was 248.59s, which was more than 16 times of the time (15.15s) used by the FUPI method. The large difference on the processing time indicates the great advantage of the proposed method on time saving, especially for the large image data.



(a)

(b)

Fig. 3 The relationship between the processing time and the number of the acquired image. (a) The relationship for the VPI method. (b) The relationship for the FUPI method.

B. Angle measurement results comparison

Fig. 4 shows three typical measurement images with the curvature angles from small to large. For each subject, two measurement images were generated using the VPI method and the FUPI method, respectively. The correlation plots between two measurements for 30 patients are shown in Fig. 5. Very good linear correlations were obtained for the measurements both in thoracic region (y = 0.9733x, r = 0.970) and in lumbar region (y = 1.0224x, r = 0.968). The results demonstrate that the two methods have the similar performance in the spine deformity illustration.

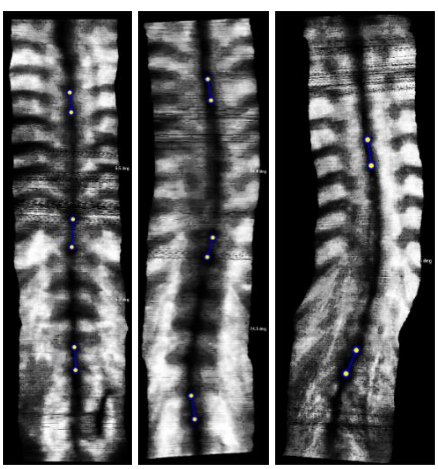


Fig. 4 The typical angle measurement results (Left to right: small angle to large angle)

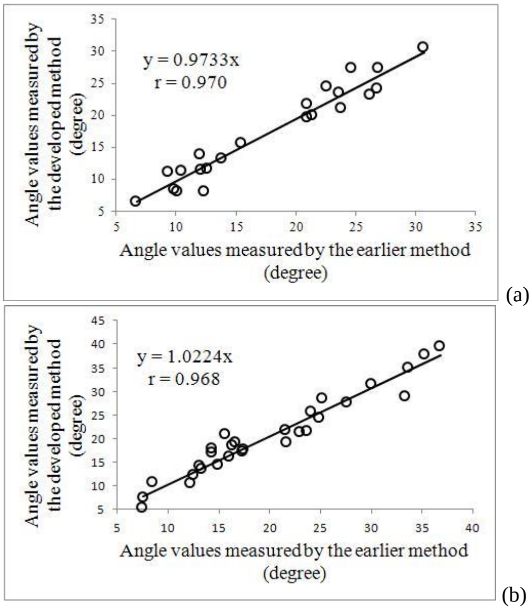


Fig. 5 The scatter plots of angle measurement results using the VPI method and the FUPI method. (a) The relationship for the thoracic regions. (b)The relationship for the lumbar regions.

IV. Discussion and conclusion

In this study, a fast 3-D ultrasound projection imaging method for scoliosis assessment has been developed. Instead of the volume generation in conventional 3-D rendering method, this system directly projected the raw images to the coronal plane to get the projection images. One of the most important advantages of the new projection method is that it can greatly save the processing time. Compared with the conventional 3-D rendering method, this method could save as much as 10 times of processing time on average. The time saving is very useful for the clinical application of the Scolioscan system. With the processing time of about 15s, this system allows the patients to get the spine measurement images at once when the scanning is finished. The short processing time also allows the operator to review the projected image right after the scanning. If there are problems in the projected image, for example the missed region during the scanning, the operator can perform the scanning again immediately.

In conclusion, this study presented a fast 3-D ultrasound projection imaging method for scoliosis. The in-vivo experiment revealed that this method could greatly reduce the processing time while preserving the comparative image quality. It can be expected that this new method may help to provide fast 3-D ultrasound diagnosis of scoliosis in clinics.

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Conflit of interest

The author Zheng YP owned a number of patents related to the Scolioscan system, which have been licensed to Telefield Medical Imaging Limited for commercialization. Zheng YP was currently a consultant for this company for the improvement of Scolioscan system.

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