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Original Contribution

Monitoring of Curve Progression in Patients with Adolescent Idiopathic Scoliosis Using 3-D Ultrasound

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A R T I C L E I N F O

Keywords:
3-D ultrasound
Scoliosis
Scoliosis progression
Spine curvature
Adolescent idiopathic scoliosis

Objective: The aim of the work described here was to determine whether 3-D ultrasound can provide results comparable to those of conventional X-ray examination in assessing curve progression in patients with adolescent idiopathic scoliosis (AIS).
Methods: One hundred thirty-six participants with AIS (42 males and 94 females; age range: 10−18 y, mean age: 14.1 ± 1.9 y) with scoliosis of different severity (Cobb angle range: 10°− 85°, mean: of 24.3 ± 14.4°) were included. Each participant underwent biplanar low-dose X-ray EOS and 3-D ultrasound system scanning with the same posture on the same date. Participants underwent the second assessment at routine clinical follow-up. Manual measurements of scoliotic curvature on ultrasound coronal projection images and posterior−anterior radiographs were expressed as the ultrasound curve angle (UCA) and radiographic Cobb angle (RCA), respectively. RCA and UCA increments ≥5° represented a scoliosis progression detected by X-ray assessment and 3-D ultrasound assessment, respectively.
Results: The sensitivity and specificity of UCA measurement in detecting scoliosis progression were 0.93 and 0.90, respectively. The negative likelihood ratio of the diagnostic test for scoliosis progression by the 3-D ultrasound imaging system was 0.08.
Conclusion: The 3-D ultrasound imaging method is a valid technique for detecting coronal curve progression as compared with conventional radiography in follow-up of AIS. Substituting conventional radiography with 3-D ultrasound is effective in reducing the radiation dose to which AIS patients are exposed during their follow-up examinations.

Introduction

Scoliosis is a 3-D spine deformity characterized by lateral, rotational curvatures, often accompanied by abnormal sagittal profile and asymmetries of thoracic cage [1,2]. The Cobb angle, measured on X-ray images obtained in a standing position, is considered the gold standard for assessment of severity of the spine curvature in the coronal plane. Scoliosis is defined as a Cobb angle ≥10° [2]. Adolescent idiopathic scoliosis (AIS) refers to scoliosis that develops from ages 10 to 16 without any underlying congenital, neuromuscular or syndromic pathology [3]. The prevalence of AIS among the general population is 0.47%−5.2% globally and 3%−4% in Hong Kong [4,5]. In recent years, the prevalence of AIS has been on the rise, reaching as high as 10% in northern countries [6]. Once the spinal deformity develops, it may or may not progress, with reported progressive rates of up to approximately 12° per year during the growth spurt [7]. Risk factors of progression include age, skeletal maturity and scoliosis apex location, and girls suffer from a higher risk of progression [8]. Progressive scoliosis not only affects the appearance and imbalance in adolescents but may also lead to compression of thoracic organs [7,9].

Among a group of untreated AIS patients reported, 29.1% manifested curve progression, while 17% of them had curve progression that required medical intervention [10]. To identify those progressed cases that require proper medical treatment, frequent monitoring of spine curvature progression is needed for AIS patients. Regular checkups every 6 mo are recommended for growing scoliosis patients until skeletal

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maturity [11]. The radiograph-based Cobb method is considered the gold standard for assessing the severity of AIS and is the most commonly used technology for monitoring curve progression [12]. Quantitative assessment of curve severity in scoliosis is important for diagnosis, treatment management, prognostication and monitoring disease progression [13]. An increase of at least 5° in coronal Cobb angle on posterior−anterior radiographs between two visits indicates scoliosis progression, despite inter- and intra-observer variability on measuring the curves in radiographs [14,15]. The accumulation of radiation dose from repeated exposures to radiographic assessment has been reported to increase the risk of cancers in AIS patients undergoing regular full spine radiography [16,17]. Despite the recommended checkup interval of at least 6 mo, curve progression can be fast, and many patients undergo more than 10 full-spine radiography sessions during the vulnerable period of adolescence [18,19]. A study in Denmark reported that those with AIS underwent an average of 16 radiographs during adolescence, and their prevalence of cancer was 4.8 times higher than that of their age-matched peers 25 y later [17]. Because of the radiation hazards, frequent radiographic assessment is not recommended, making close monitoring of disease progression and treatment outcomes challenging. A non-ionizing imaging modality could facilitate close monitoring of scoliosis progression and treatment outcomes without the harmful effects of radiation.

Several radiation-free technologies are available for detecting scoliosis progression, but are not commonly used clinically because of various limitations. Surface and electromagnetic topography systems, for example, can provide only surface information and cannot visualize the internal anatomical information of spine [20,21]. Studies have indicated that these systems are not precise enough and are unable to access vertebral rotation and visualize bone architectures [22]. Recently, artificial intelligence methods using deep learning have been reported to enhance the accuracy, but their clinical applications for progression monitoring still need to be carefully validated [23], given the fact that surface topography of the back yields only overall information on a scoliotic spine with 3-D deformity. Standing magnetic resonance imaging (MRI) is a radiation-free modality that can provide high-resolution internal anatomical information on the spine. However, its clinical use is limited by the specific and large installation space required, as well as the extremely high operating cost and long operating time associated with MRI scans [24].

Ultrasound has been increasingly used in the musculoskeletal system, including the spine and the nerve [25,26]. Three-dimensional ultrasound imaging is a radiation-free and highly portable modality available for spine imaging on sites, and is relatively more affordable and accessible for scoliosis patients [24]. The feasibility of using freehand 3-D ultrasound imaging to evaluate 3-D anatomic profiles of spines has been reported [27−30], as has its validity for assessment of scoliosis severity [29,31]. The feasibility, validity and reliability of a novel 3-D ultrasound system for coronal spine curvature assessment have been reported in literature [31−38]. Ultrasound curve angle (UCA), through localizing transverse processes on the spine, has also been determined to correlate closely with radiographic Cobb angle (RCA) [39]. A recent study found that the radiation dose used for children can be reduced by 50% for referral of treatment based on a threshold of a 20° Cobb angle if the 3-D ultrasound assessment is used [40]. If progression monitoring for AIS can also be conducted with 3-D ultrasound assessment, it is expected that the X-ray dose can be further reduced for those with AIS.

The aim of this study was to evaluate the validity of using 3-D ultrasound systems to detect coronal curve progression, with conventional radiography as the gold standard. It is hypothesized that use of the 3-D ultrasound system will have high sensitivity and specificity with a low negative likelihood ratio in detecting coronal curve progression in scoliosis when compared with conventional radiography. This would suggest that the 3-D ultrasound system could be a reliable and non-ionizing alternative for monitoring spine curvature changes in scoliosis patients. This allows clinicians and AIS patients to closely monitor spine curvature changes in a non-ionizing and affordable manner.

Methods

Study population

In this retrospective cohort study, 136 participants who had been diagnosed with AIS by conventional radiography and had undergone biplanar low-dose radiography and 3-D ultrasound at a minimum of two outpatient clinic visits were recruited from a local major scoliosis referral center. Exclusion criteria are as follows: (i) presence of metallic implants, as these may affect the function of spatial sensing elements of the 3-D ultrasound system; (ii) body mass index (BMI) higher than 30.0 kg/m^2; and (iii) presence of corrective braces in the patient.

All participants came for follow-up, and visited either two (n = 116) or three (n = 20) times. Participants underwent both X-ray assessment and ultrasound assessment during each visit. During each visit, the main (largest) curvature observed in the baseline radiograph was selected for analysis, and only that specific angle was monitored in the subsequent longitudinal follow-up. A change of ≥5° in the RCA and UCA is the indicator of curve progression detected by X-ray and 3-D ultrasound systems, respectively [15]. On 292 visits by 136 participants, 292 curvatures were extracted and analyzed.

Ethical approval

Human subject ethical approval was granted by the local institutional review board (Joint Chinese University of Hong Kong−New Territories East Cluster Clinical Research Ethics Committee) and the Department of Health. All methods were performed in accordance with relevant guidelines and regulations. The experiments were conducted in a generally acceptable ethical and humane fashion. Written informed consent was obtained from all participants (and guardians) involved for publication of this article and the accompanying images. A copy of the written consent is available for review by the Editors-in-Chief of this journal.

Image acquisition

A 3-D ultrasound system (Scolioscan, Model SCN801, Telefield Medical Imaging Ltd, Hong Kong) (Fig. 1) was used for ultrasound scanning. The technical details of the systems can be found in Zheng et al. [35].

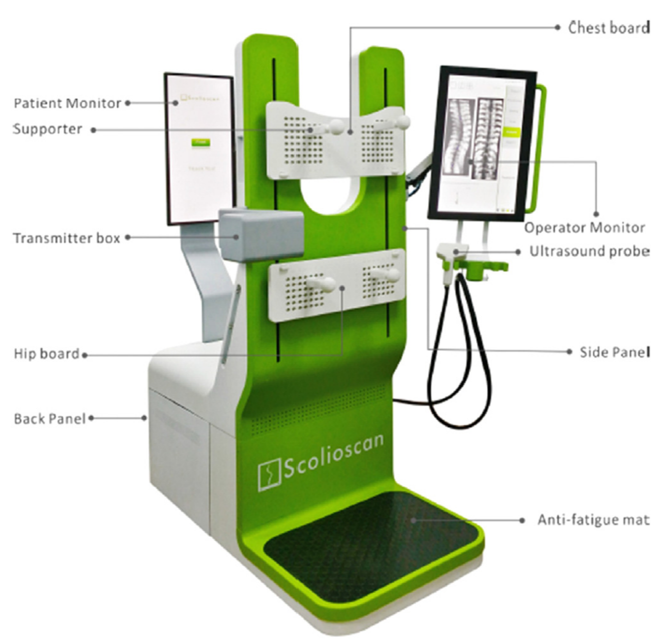

Figure 1. Three-dimensional ultrasound scoliosis assessment system Scolioscan with the components labeled.

The participant was instructed to undress and don a gown with an opening on the back; ultrasound gel was applied on the back. All metallic wear, electronics goods, magnets and any possibly ferromagnetic materials on participants were removed as these materials could interfere with the electromagnetic tracking sensor used in the 3-D ultrasound system. The participant was then instructed to step on the scanning platform in a natural standing position, with the supporters (Fig. 2). Scanning was then performed by moving the ultrasound probe slowly along the back from the region below vertebra level L5 to vertebra level T1 with an average scanning time of 15−20 s. At the same visit, participants were also scheduled to undergo biplanar low-dose X-ray EOS scanning in a standing posture similar to that used for the ultrasound scanning.

Angle measurements and study design

By use of the ultrasound projection images obtained with the 3-D ultrasound system, spine curvature was measured manually by a trained rater according to the UCA measurement protocol documented in previous literature [39]. Initially, the shadows of the transverse processes and lamina−articular processes were identified on the coronal ultrasound images. Before UCA measurement, the rater was required to locate appropriate points for line placement on the ultrasound images. Selection of the vertebra structure for line drawing depended on the location of the uppermost and lowermost tilted regions of the curve. In cases in which the most tilted region was observed at or above the T12 vertebra, the line was drawn through the center of the bilateral transverse process shadows. Conversely, if the most tilted region appeared below the T12 level, the line was drawn through the center of the widest bilateral part of the lump, formed primarily by the shadows of the bilateral superior articular processes. Subsequently, UCA values were computed using the lines corresponding to the most tilted regions. The measurements were performed with the RadiAnt DICOM Viewer (Medixant, Poznan, Poland). Both the operators and the rater were blinded to prior diagnostic results. The posterior−anterior radiographs obtained by the EOS system were assessed for spine curvature by an experienced rater with more than 5 y of expertise in spinal research, referred to as RCA. RCA measurements were performed using the traditional Cobb method to determine the angle formed between the most tilted upper endplate and the most tilted lower endplate on coronal X-ray images. The measurements were performed with a RadiAnt DICOM Viewer (Medixant). UCA and RCA measurements obtained during the two to three visits were compared and investigated (Figs. 3 and 4).

Statistical analysis

For the determination of spine curvature progression determination, for each participant, any RCA change not less than the 5° increment was regarded as indicating a progressive case (X-ray progressive results) by X-ray, and any UCA change not less than the 5° increment was regarded as indicating a progressive case (3-D ultrasound progressive results) by the 3-D ultrasound system. Cases with all RCA changes less than the 5° increment were regarded as non-progressive cases (X-ray non-progressive results) by X-ray, while cases with all UCA changes less than the 5° increment were regarded as non-progressive cases (3-D ultrasound non-progressive results) by 3-D ultrasound system. Progressive results for both UCA and RCA were regarded as true positive (TP) results. Non-progressive results for both UCA and RCA were regarded as true negative (TN) results. Progressive results for RCA with non-progressive results for UCA were regarded as false-negative (FN) results. Non-progressive results for RCA with progressive results for UCA were regarded as false-positive (FP) results. The sensitivity of using the 3-D ultrasound system to detect scoliotic curve progression was determined as the ratio of TP cases to radiographic progressive cases (*i.e.,* TP/[TP + FN]). The specificity of using 3-D ultrasound system to detect scoliotic curve progression was determined as the ratio of TN cases to radiographic non-progressive cases (*i.e.,* TN/[TN + FP]).

In addition, the likelihood ratio for detection of negative results with the 3-D ultrasound system in UCA measurement was (1 − sensitivity)/

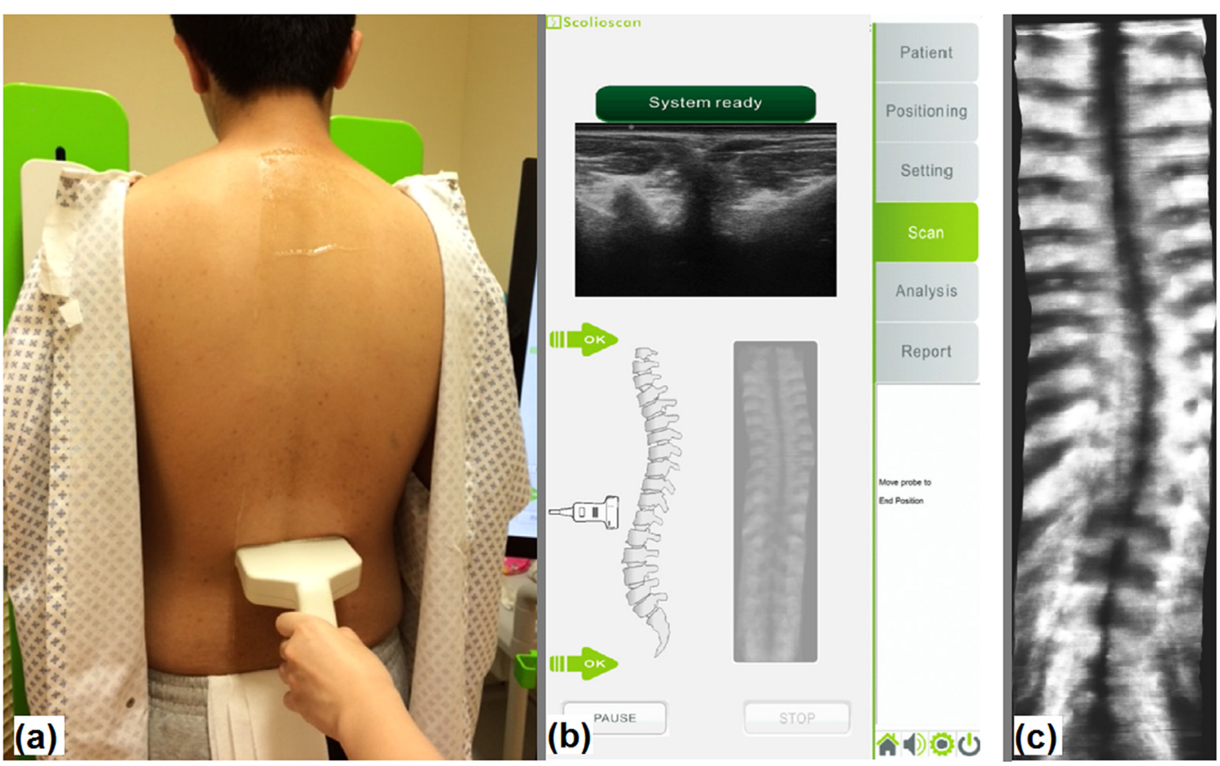

Figure 2. Assessment with the 3-D ultrasound system. (a) Participant being scanned with the ultrasound probe. (b) Software interface shown during scanning. (c) Typical ultrasound projection images of a participant with scoliosis in the coronal plane, obtained with the 3-D ultrasound system.

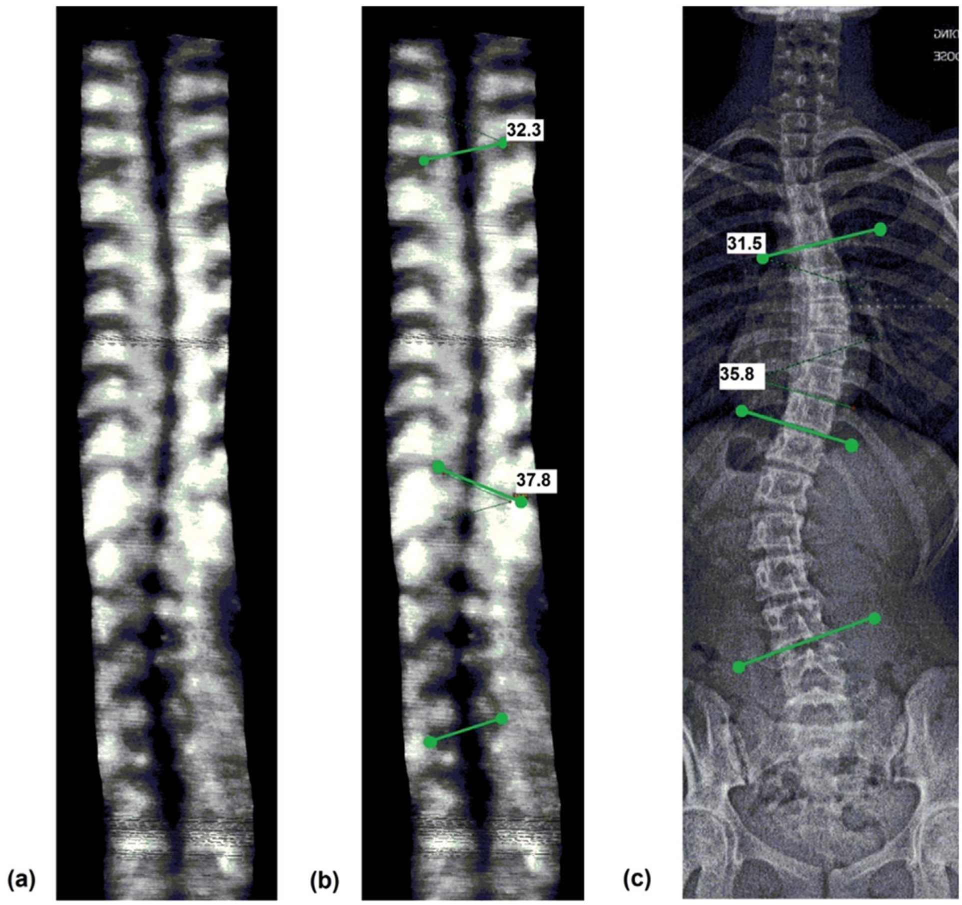

Figure 3. Typical scoliosis case. (a) Coronal plane ultrasound image. (b) UCA measured on the ultrasound image. (c) RCA measured on the EOS image for the same participant. RCA, radiographic Cobb angle; UCA, ultrasound curve angle.

specificity. A negative likelihood ratio >1 indicates a negative test result is more likely to occur in people with the disease than in people without the disease. A negative likelihood ratio less than 1 indicates a negative test is less likely in people with the disease than in people without the disease [41].

Results

Basic information on the 136 participants (42 males and 94 females, age range: 10−18 y, mean age ± SD: 14.1 ± 1.9 y) with AIS involved in this study is summarized in Table 1. All participants

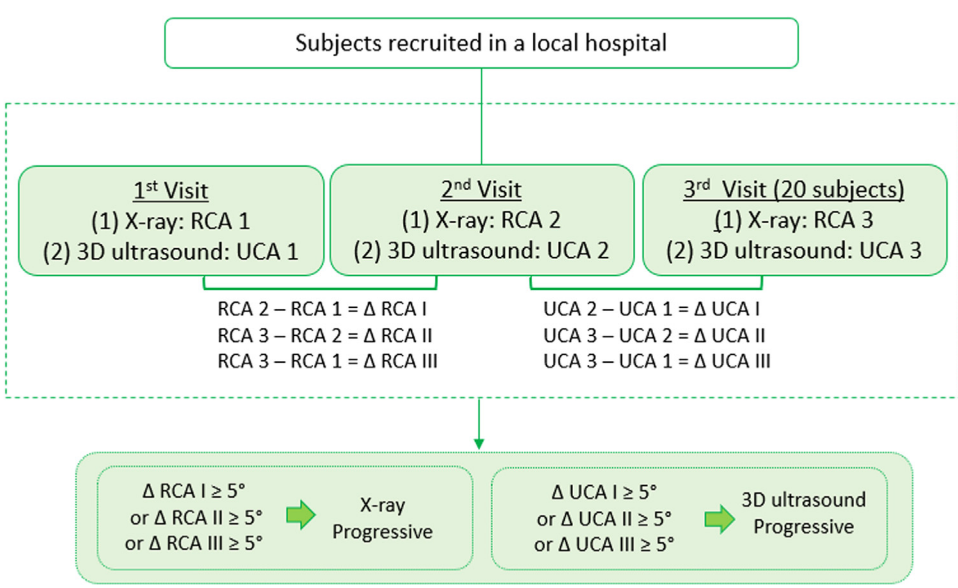

Figure 4. Schematic of the study design. UCA, ultrasound curve angle; RCA, radiographic Cobb angle.

Table 1
Distribution of the 136 participants with adolescent idiopathic scoliosis

Gender	
Males	42
Females	94
Age (y)	14.1 ± 1.9 (10−18)[a]
Body mass index (kg/m^2)	18.3 ± 2.2 (13.7−24.8)[a]
Curve severity (°)	24.3 ± 14.4 (10−85)[a]
Duration between visits (mo)	15.53 ± 8.8 (4−32)[a]

[a] Mean ± standard deviation (range).

came for follow-up visits, either once (n = 116) or twice (n = 20). The duration between two visits ranged from 4−32 mo, with a mean of 15.5 mo.

For those diagnosed progressive cases, the mean intervisit duration was 18.0 ± 9.1 mo (range: 4−31 mo) while the mean intervisit duration for the non-progressive cases was 15.0 ± 8.6 mo (range: 4−32 mo). It was observed that the progressive status was independent of intervisit duration.

In terms of RCA and UCA measurements, 21 and 27 cases were detected as progressive, respectively (Fig. 5), whereas 115 and 109 cases were detected as non-progressive, respectively (Fig. 6). Among 21 progressive cases determined by RCA measurement, 19 had pro-

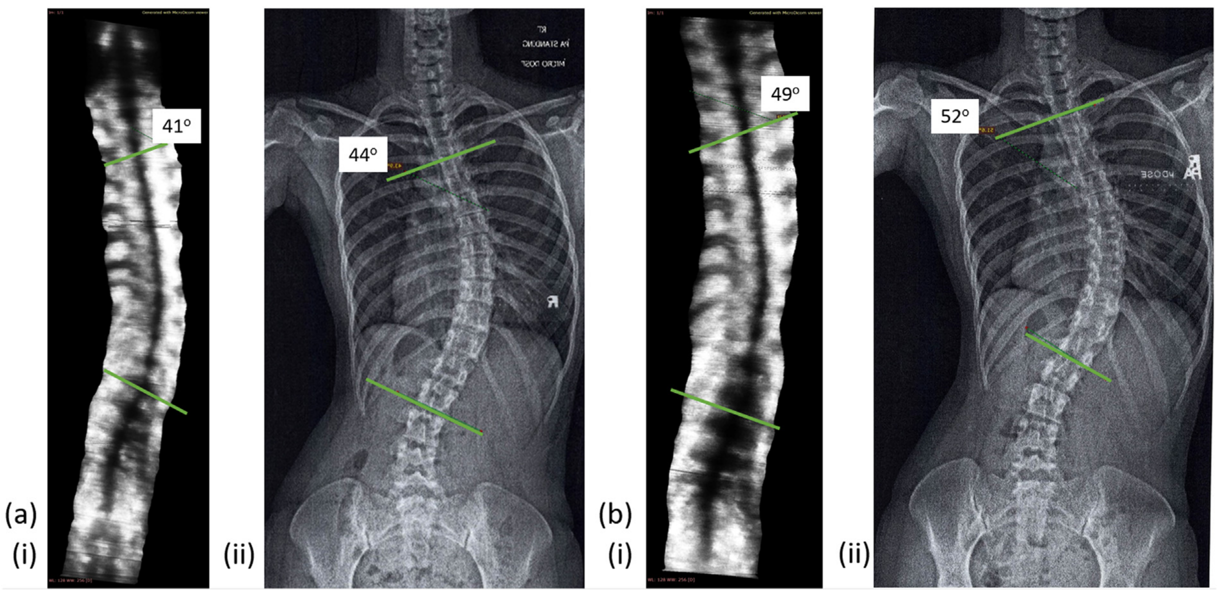

Figure 5. Typical progressive case at (a) first visit with (i) UCA measurements and (ii) RCA measurement. (b) Follow-up visit after 24 mo with (i) UCA measurements and (ii) RCA measurement. RCA, radiographic Cobb angle; UCA, ultrasound curve angle.

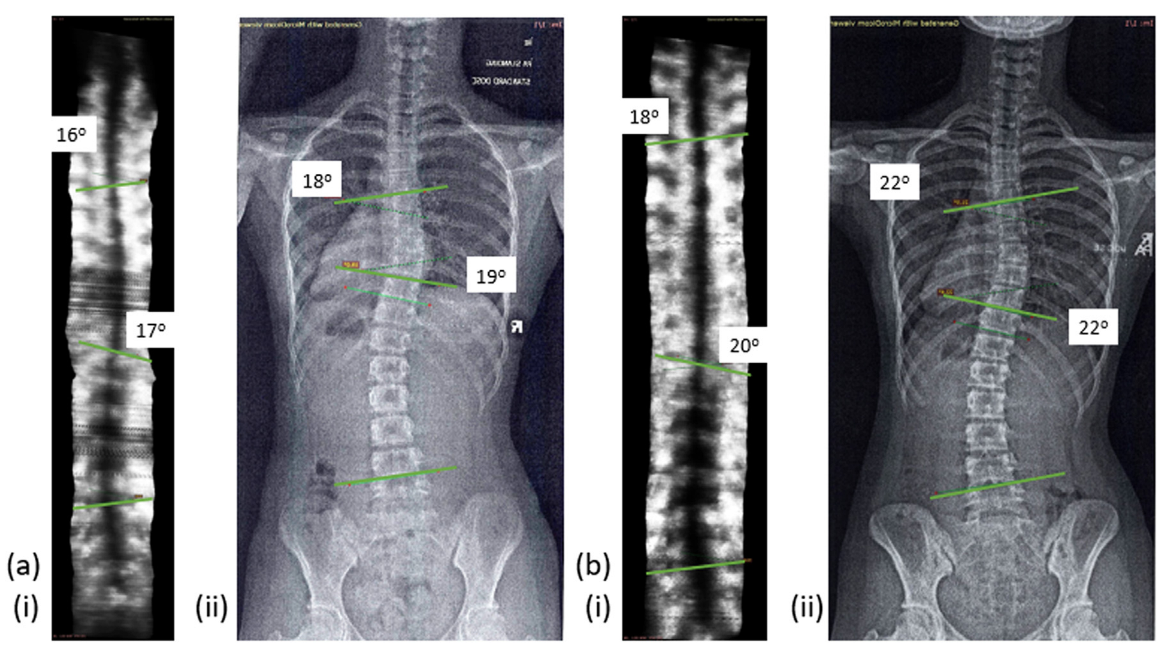

Figure 6. Typical non-progressive case at (a) first visit with (i) UCA measurements and (ii) RCA measurement and (b) follow-up visit after 24 mo with (i) UCA measurements and (ii) RCA measurements. RCA, radiographic Cobb angle; UCA, ultrasound curve angle.

gressive results for UCA and 2 had non-progressive results for UCA. The TP and FN values were 19 and 2, respectively. Among 115 non-progressive cases determined by RCA measurement, 107 had non-progressive results for UCA, and 8 had progressive results for UCA. The TN and FP values were 107 and 8, respectively. Using RCA measurements as the reference, the sensitivity and specificity of using the 3-D ultrasound system in monitoring spine curvature progression were 0.93 and 0.90, respectively. The negative likelihood ratio of the 3-D ultrasound system test for scoliosis progression was 0.08, which means that there was only an 8% probability of having progressive scoliosis detected as non-progressive if the 3-D ultrasound system measurement was used. Further analysis results indicated that age difference, gender difference and initial curve severity does not significantly affect the sensitivity and specificity of using 3-D ultrasound system to monitor spine curvature progression (Table 2).

Table 2
Sensitivity and specificity of using a 3-D ultrasound system to monitor spine curvature progression in various participant groups

	Sensitivity	Specificity
Combined batch	0.93	0.90
Gender		
Female (N = 94)	0.94	0.88
Male (N = 42)	0.92	1
Age		
<13 y (N = 47)	0.94	0.91
13−15 y (N = 44)	0.95	0.86
>15 y (N = 45)	0.9	1
Curve severity		
<25° (N = 89)	0.93	0.85
25°−40° (N = 28)	0.92	1
>40° (N = 19)	0.93	1

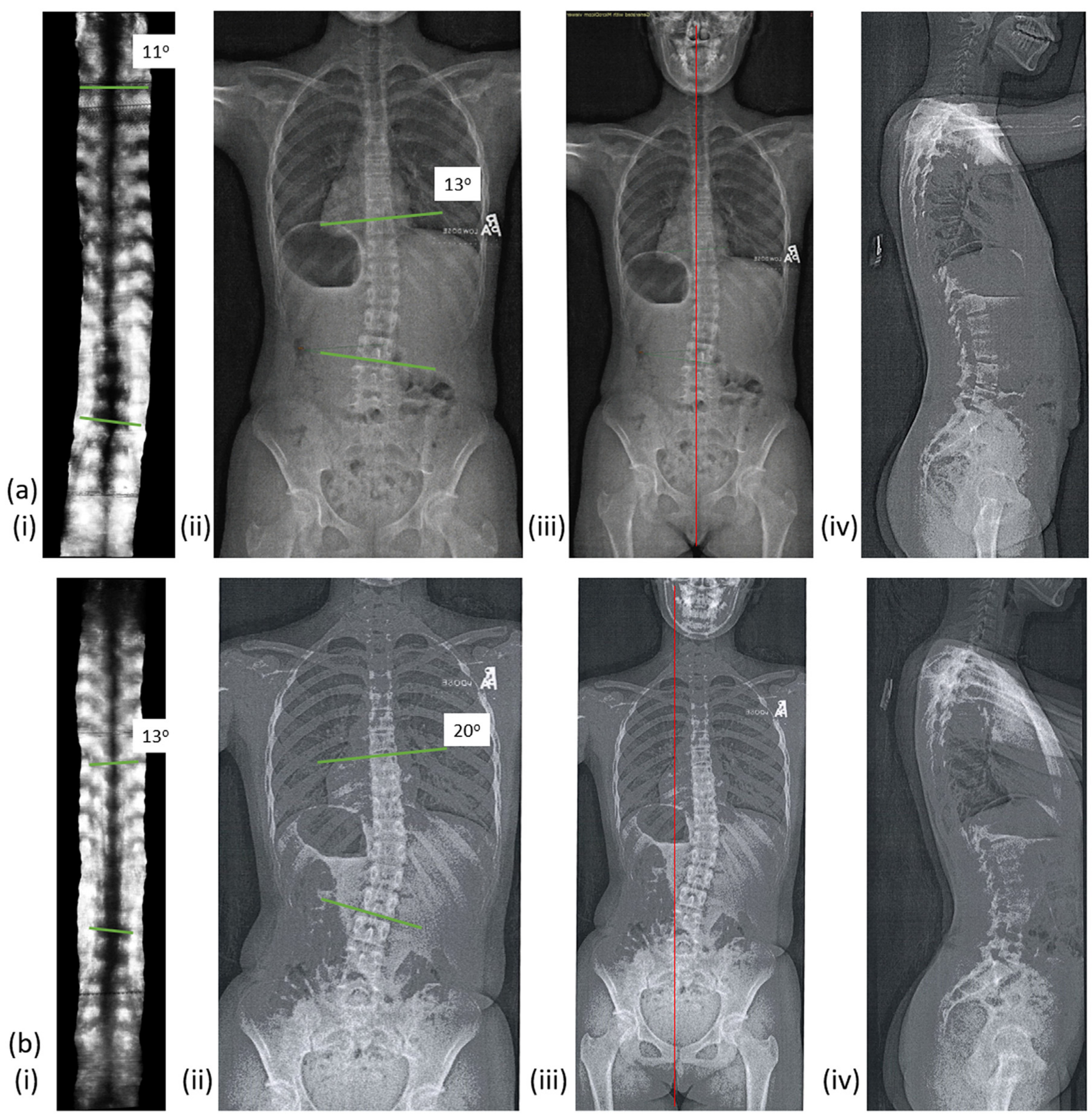

Figure 7. (a) False-negative case 1 at first visit with (i) UCA measurements on ultrasound coronal plane image, (ii) RCA measurement on coronal plane radiograph, (iii) full-scale coronal plane radiograph and (iv) full-scale sagittal plane radiograph. (b) Follow-up visit with (i) UCA measurements on ultrasound coronal plane image, (ii) RCA measurement on coronal plane radiograph, (iii) full-scale coronal plane radiograph and (iv) full-scale sagittal plane radiograph after 12 mo. RCA, radiographic Cobb angle; UCA, ultrasound curve angle.

Discussion

Overall, this study determined the feasibility of using 3-D ultrasound to monitor spine curvature progression with high sensitivity and specificity in detecting spine curvature progression. With respect to the manual scanning procedures of the 3-D ultrasound system used in this study for single coronal spine curvature assessment, previous articles have reported on its feasibility, validity and reliability with promising results [31−38]. Additionally, the reliability of ultrasound curve angle measurement, both intra-rater and inter-rater, was documented in a recent study [39]. Apart from detecting scoliosis in a single clinical visit, the 3D- ultrasound system is aimed at monitoring spine curvature progression longitudinally without any radiation hazard. The results of this study indicated that the sensitivity and specificity of using the 3-D ultrasound system to monitor spine curvature progression were 0.93 and 0.90, respectively, with a negative likelihood ratio of 0.08.

Some studies have reported on the feasibility of using non-radiation imaging technologies for longitudinal follow-ups of scoliosis. A cross-sectional study reported the application of surface topography for monitoring scoliosis curve progression in 100 participants. With some limitations, the reported sensitivity and specificity were 0.86 and 0.72, respectively [20]. Another study reported that the sensitivity and specificity of using the DIERS surface topography system to detect scoliosis curve progression were only 0.64 and 0.69, respectively [42]. Compared with several surface imaging technologies, ultrasound imaging technology can reveal internal anatomical information on the spine, making its assessment results more promising. Ultrasound technology can significantly reduce the unnecessary exposure of AIS patients to radiation. One study reported the application of the ultrasound system SonixTABLET (Analogic Ultrasound—BK Medical, Peabody, MA, USA) equipped with a position and orientation tracking transducer, in 200 participants. In that study, with a 3-D ultrasound technology, the reported sensitivity

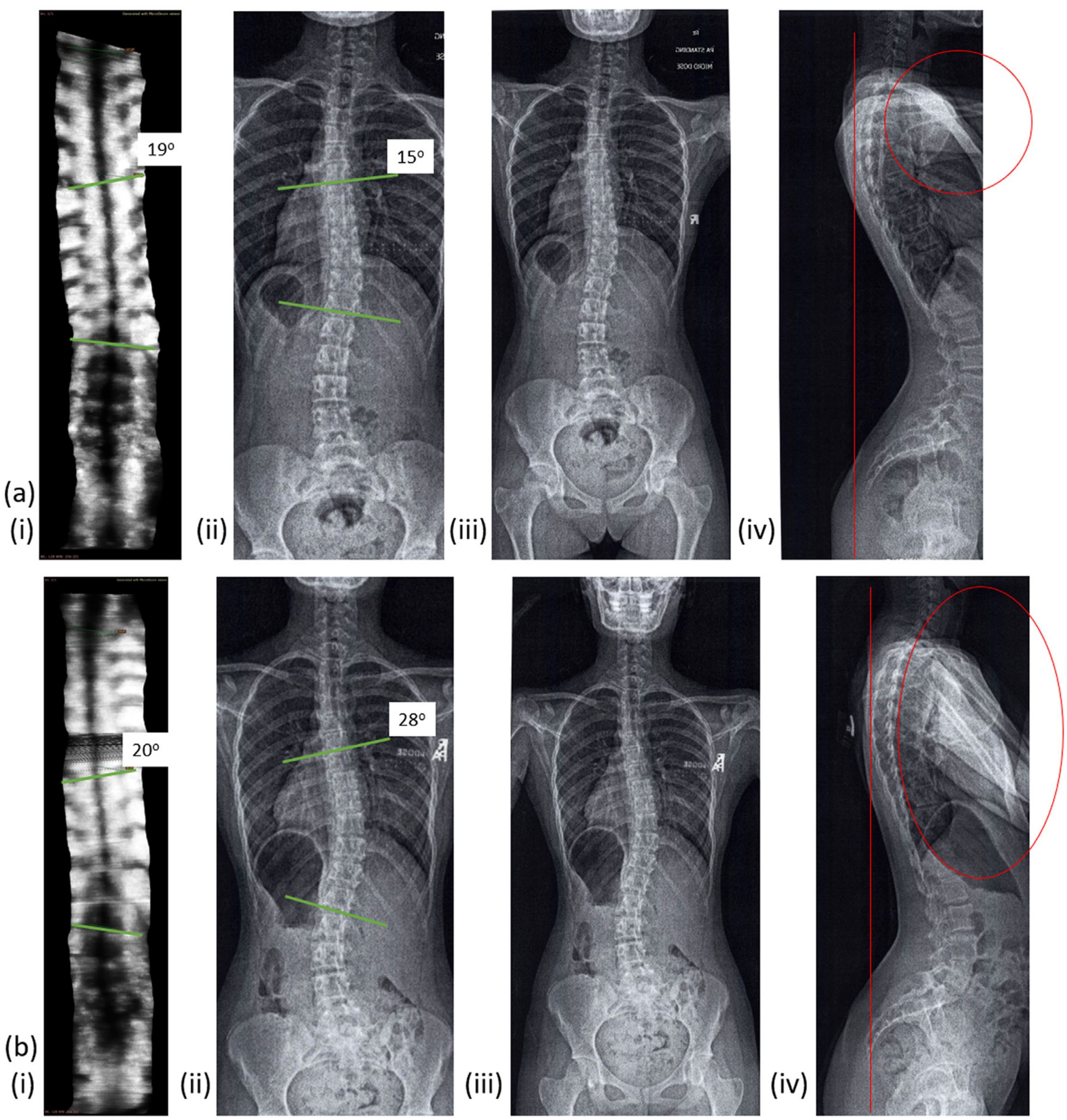

Figure 8. False-negative case 2 at (a) first visit with (i) UCA measurements on ultrasound coronal plane image, (ii) RCA measurement on coronal plane radiograph, (iii) full-scale coronal plane radiograph and (iv) full-scale sagittal plane radiograph. (b) Follow-up visit with (i) UCA measurements on ultrasound coronal plane image, (ii) RCA measurement on coronal plane radiograph, (iii) full-scale coronal plane radiograph and (iv) full-scale sagittal plane radiograph after 21 mo. RCA, radiographic Cobb angle; UCA, ultrasound curve angle.

and specificity for detecting scoliosis curve progression were 0.90 and 0.85, respectively, with a negative likelihood ratio of 0.08 [43]. The present study confirmed a similar finding to similar, but obtained more promising results with higher sensitivity of 0.93 and specificity of 0.90 and with a similar likelihood ratio, with the biplanar low-dose X-ray as a reference. The present study used a commercially available 3-D ultrasound system specifically designed for scoliosis assessment. Taking advantage of the volume projection imaging method [33], the 3-D ultrasound system used in this study involves fewer manual procedures in scoliosis angle assessment after scanning, which enhances the potential of its application in scoliosis progression monitoring. Moreover, this study ensures that each participant undergoes ultrasound assessments using the same system and postures at both baseline and follow-up visits, allowing for a direct comparison of the results. This study represents the first publication to use ultrasound exclusively for assessing progression in scoliosis. By focusing solely on ultrasound as a monitoring tool, the findings of this study provide valuable insights into the feasibility and potential of ultrasound as a standalone modality for tracking scoliosis progression, highlighting its innovative and ground breaking nature. The promising results of this study indicate that using 3-D ultrasound system for detecting scoliosis progression can greatly reduce the radiation to which AIS patients are exposed.

Among the cases with FN and FP results, those cases with FN results are of most concern clinically because these can underestimate the curve severity of patients, causing a delay in treatment and related consequences. There were two FN cases that exhibited progression in RCA but not UCA. The unclear transverse processes in the thoracolumbar region and the postural difference between radiographs taken are potential causes of the inconsistent results between 3-D ultrasound and biplanar low-dose radiography. Unclear transverse processes may lead to error in the manual drawing of the horizontal lines for UCA measurement, while a thick fat layer may cause a large attenuation of the ultrasound signal so as to limit the penetrating power to reach the bone surface.

For FN case 1, the RCA changed from 12.6° to 19.8° while the UCA changed from 11.0° to 13.0° (Fig. 7). In this case, postural deviation was observed between the radiographs taken. Lateral trunk shift between head and pelvis was observed in the follow-up visit but not the first visit. And spine curvature was relatively small so that a slight manual deviation in horizontal line drawing may affect the positive/negative result. Moreover, the transverse processes were not clear on the ultrasound projection images. A relatively thicker fat layer in the follow-up visit might contribute to the unclear transverse processes in the ultrasound image for this case as the thick fat layer may facilitate the ultrasound attenuation. For this and similar cases, an ultrasound probe with lower frequency and higher penetrating ability can be explored and investigated.

For FN case 2, the RCA changed from 14.9° to 27.7° while the UCA changed from 19.0° to 20.2° (Fig. 8). In this case, there was a comparatively larger curvature at the follow-up visit, and the potential cause of the inconsistency was the postural difference between visits on which the radiographs were obtained. As shown in the radiographs, the participant's hands were lifted up and kept at a 90° angle to her core body for the first visit, but freely placed in front of her core body for the follow-up visit. This reminds us that it is important to have a consistent posture during follow-up imaging assessment, whether X-ray or 3-D ultrasound imaging is used. The 3-D ultrasound system used in the present study has an integrated body positioning device, possibly facilitating a consistent posture during follow-up examinations.

There were a relatively large number of FP cases with up to 8 cases among 136 participants (Fig. 9). The traditional Cobb method uses the vertebra body for measurement while the UCA method uses the transverse processes for measurement, and the transverse processes are somehow further apart from the center of the vertebra bodies, especially on the lumbar region. Rotation and asymmetric deformation of the vertebra bodies may contribute to the overestimated results, mainly in severe cases. In addition to the severe cases with vertebra body deformation or rotation, there were some mild cases with FP results, perhaps because of the postural deviation between radiographs taken and unclear transverse processes shown on the ultrasound projection images. However, FP cases were not very concerning clinically in scoliosis progression assessment.

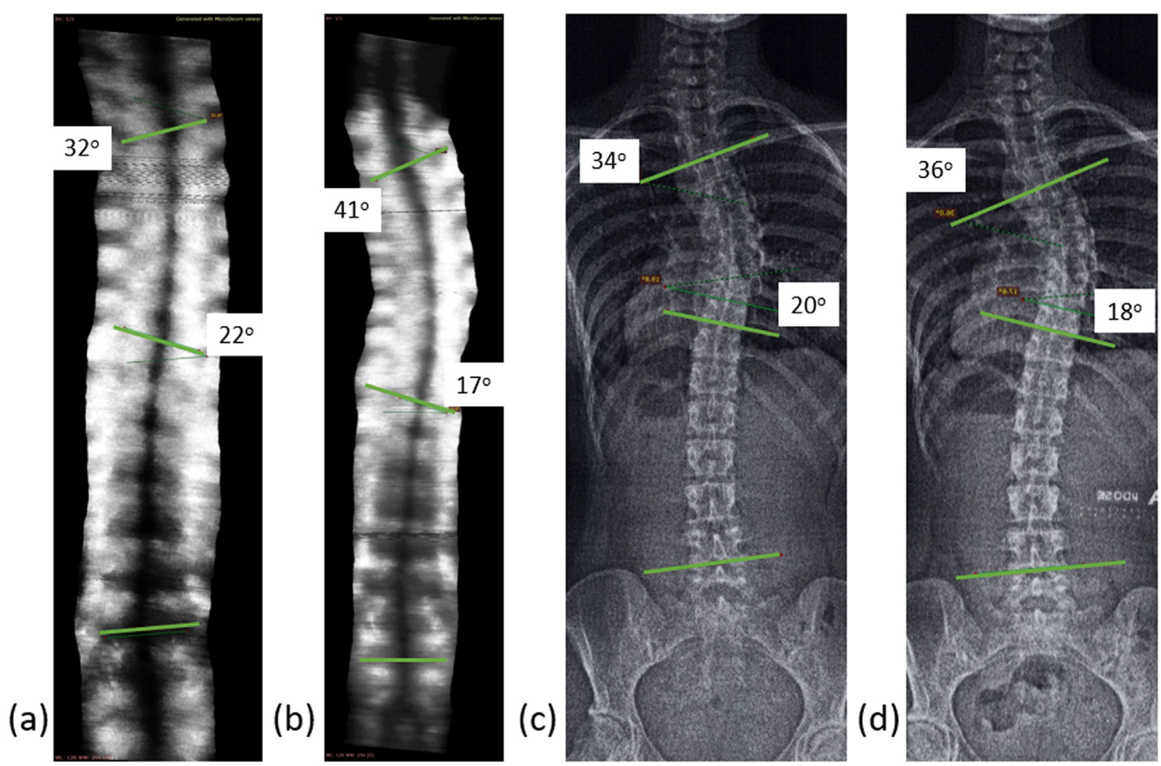

Figure 9. Typical false-positive case with ultrasound curve angle at (a) first visit and (b) follow-up visit after 29 months; and radiographic Cobb angle at (c) first visit and (d) follow-up visit after 29 mo.

There were limitations attributed to the unfavorable ultrasound image quality, which resulted in challenges in the UCA measurement. Some transverse processes of the lumbar vertebrae were not captured within the ultrasound transducer's scanning width. Additionally, the participants with thicker fat layers in the spine region, included in this study, had reduced image quality. To address these issues, future studies could explore the use of ultrasound transducers with curved surfaces and lower frequencies to improve penetration. Furthermore, rotation of the vertebra body led to relatively poor ultrasound images, as the features of bilateral vertebrae could not be shown on a single plane after volume projection [44]. As a potential solution, the adoption of changeable probes to suit different participants is recommended for the ultrasound assessment device.

In this study, the application of the 3-D ultrasound system involved manual procedures for selecting the best images among the nine various depth projection layers and for angle measurement. Automated procedures and deep learning techniques will be implemented to streamline these processes [45,46]. The quality of ultrasound images was also subject to scanning activities and participant condition. Therefore, providing more precise instructions to participants and offering adequate training to operators are crucial for further improving the results.

The sample size in this study was relatively small, and some participants had already reached skeletal maturity, making the progression information less clinically significant [47]. Therefore, future studies should aim to include a larger number of participants in the "higher chance of curve progression period" and to extend the follow-up period to cover the entire curve development until skeletal maturity.

In this study, only the ultrasound projection images obtained in the coronal plane using the 3-D ultrasound system were analyzed. To gain a more comprehensive understanding of spine curvature progression, future studies could analyze the 3-D profile of the spine using biplanar low-dose radiography in combination with the existing 3-D ultrasound system.

Conclusions

In this study, the feasibility of using 3-D ultrasound in monitoring spine curvature progression has been determined. The sensitivity and specificity of the 3-D ultrasound system, compared with the reference RCA, were 0.93 and 0.90, respectively, indicating its comparability to X-ray in monitoring scoliosis progression for the tested group of 136 participants. With a low negative likelihood ratio of 0.08, the 3-D ultrasound system effectively reduces unnecessary diagnostic radiation for monitoring scoliosis progression. This highlights its potential for minimizing patient exposure to radiation in scoliosis progression assessment and providing a safer approach to scoliosis treatment management. Further studies with larger sample sizes and longer follow-up periods, starting at an earlier stage of skeletal maturity, are recommended to evaluate the system's effectiveness and expand its application in clinical practice.

Data availability statement

The data for this study are available from the corresponding author on reasonable request.

Conflict of interest

Y.P.Z. reports his role as a consultant to Telefield Medical Imaging Limited for the development of Scolioscan, outside the submitted work, and is the inventor of a number of patents related to 3-D ultrasound imaging for scoliosis, which has been licensed to Telefield Medical Imaging Limited through Hong Kong Polytechnic University. He is also a director and shareholder of this company. R.M.C. is the clinical advisor of Telefield Medical Imaging Limited. All of the remaining authors have no conflicts of interest relevant to this article.

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