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Original Contribution

VALIDITY STUDY OF VERTEBRAL ROTATION MEASUREMENT USING 3-D ULTRASOUND IN ADOLESCENT IDIOPATHIC SCOLIOSIS

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Abstract—This study aimed to assess the validity of 3-D ultrasound measurements on the vertebral rotation of adolescent idiopathic scoliosis (AIS) under clinical settings. Thirty curves (mean Cobb angle: 21.7° ± 15.9°) from 16 patients with AIS were recruited. 3-D ultrasound and magnetic resonance imaging scans were performed at the supine position. Each of the two raters measured the apical vertebral rotation using the center of laminae (COL) method in the 3-D ultrasound images and the Aaro-Dahlborn method in the magnetic resonance images. The intra- and inter-reliability of the COL method was demonstrated by the intra-class correlation coefficient (ICC) (both [2, K] >0.9, $p < 0.05$). The COL method showed no significant difference ($p < 0.05$) compared with the Aaro-Dahlborn method. Furthermore, the agreement between these two methods was demonstrated by the Bland-Altman method, and high correlation was found ($r > 0.9, p < 0.05$). These results validated the proposed 3-D ultrasound method in the measurements of vertebral rotation in the patients with AIS. (E-mail: m.s.wong@polyu.edu.hk) **© 2016 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Adolescent idiopathic scoliosis, 3-D ultrasound, Vertebral rotation, Validity, reliability, Measurement.**

INTRODUCTION

Adolescent idiopathic scoliosis (AIS) presents with a lateral and rotational deformity of the spine (Hresko 2013; Weinstein et al. 2008). The vertebral rotation is an important parameter of the deformity in AIS, which can be used to assess the severity of scoliotic spine, monitor the risk of curve progression and evaluate treatment outcomes (Lam et al. 2008). It is also associated with lateral curvature and ribcage asymmetry, leading to reduced respiratory capacity and cosmetically disfiguring the rib hump (Adam et al. 2008; Cui et al. 2012; Di Silvestre et al. 2013). Thus, an accurate and reliable assessment of vertebral rotation is of paramount importance in the diagnosis and treatment decision of scoliosis.

Several methods have been proposed to assess the vertebral rotation using radiographic images, based on the position of the projected landmarks in relation to the vertebral body (Lam et al. 2008; Vrtovec et al. 2009). However, the measurements taken from radiographic images only represent a projected rotation, which is not directly measured in the transverse plane. Furthermore, the frequent exposure to radiation has been of primary concern for scoliotic patients (Knott et al. 2014). Compared with radiographic assessment, computed tomography (CT) and magnetic resonance imaging (MRI) both can enable visualization of the transverse plane of the vertebra for the measurement of the vertebral rotation (Kotwicki 2008; Lam et al. 2008). The CT/MRI scans and measurements can provide the 3-D information of the spinal structure, thus they are clinically applicable for both pre-operative and post-operative assessments of vertebral rotation (Hong et al. 2011; Lee et al. 2013). However, CT exposes the patients to more radiation than the standard

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radiographs, and MRI examinations are often time-consuming and expensive. Therefore, it is not feasible to use CT/MRI in mass screening and frequent monitoring for scoliosis, such as the measurements of lateral curvature and vertebral rotation.

Currently, ultrasound has gained considerable attention in the assessment of scoliosis (Cheung et al. 2015a, 2015b; Li et al. 2012; Wang et al. 2015; Zheng et al. 2015). Ultrasound imaging is a non-radiation and cost-effective method that is accessible in the majority of medical institutes. The posterior structure of vertebrae could be displayed by ultrasound imaging in the transverse plane. Similar to CT/MRI images, ultrasound images can visualize and measure the vertebral rotation in the transverse plane of scoliotic spine (Burwell et al. 2002; Suzuki et al. 1989). The possibility of using ultrasound to assess vertebral rotation was first studied by Suzuki et al. (1989), who identified the spinous processes and laminae in the transverse plane of ultrasound images of each vertebra and assessed the vertebral rotation directly based on the inclination of the transducer.

The development of the 3-D ultrasound system can enable the 3-D reconstruction of vertebral images and facilitate the measurement of scoliotic spine in various anatomic planes that could not be accomplished previously (Cheung et al. 2013, 2015a, 2015b Nguyen et al. 2014; Purnama et al., 2010; Wang et al. 2015). Spinous, laminae and transverse processes can be visualized and used as landmarks to measure the lateral curvature and vertebral rotation in the coronal and transverse planes of the ultrasound images (Cheung et al. 2015a, 2015b; Li et al. 2012; Ungi et al. 2014; Wang et al. 2015). Recently, the center of laminae (COL) method has been proposed to measure the vertebral rotation in the transverse plane of 3-D ultrasound images (Chen et al. 2015; Vo et al. 2015). The reliability and validity of this proposed method have been demonstrated. However, the evidence is limited to phantom studies. Thus, the objective of this study was to explore the possibility of using the proposed 3-D ultrasound method (*i.e.*, COL) to measure the vertebral rotation in the patients with AIS in the clinical setting and to evaluate its reliability and validity with the concurrent MRI method.

MATERIALS AND METHODS

Clinical patients

The patient inclusion criteria of this validity study were the following (i) female adolescents; (ii) diagnosis of AIS; (iii) Cobb angle of 10°–80°; (iv) no prior surgical treatment; and (v) out-of-brace MRI examination of the whole spine. Ethics approval was obtained from the local health research ethics board. All examination procedures were explained to the patients, and written informed consent was obtained.

Sixteen female patients with AIS (aged 15.4 ± 2.6 y) were recruited from a scoliosis clinic. Of the patients, three had a single thoracic curve, one a single lumbar curve, 10 a double curve and two a triple curve, producing a total of 30 curves for analysis in this study. The distribution of apical vertebra of these curves was 19 thoracic, three thoracolumbar and eight lumbar levels. The Cobb angles of these curves measured from MRI coronal images ranged from 10.2° to 68.2° and the average value was 21.7° ± 15.9°.

Equipment

To evaluate the validity of the 3-D ultrasound method, 3-D ultrasound and MRI scans of the full spine were arranged on the same d (within 3 h) and performed in the same supine position so as to match the observations.

The 3-D ultrasound scans were performed with a 3-D SonixTABLET ultrasound unit (Analogic Corporation, Peabody, MA, USA), coupled with a C5-2/60 convex transducer, SonixGPS and 3-D guidance device (driveBAY; Ascension Ltd., Milton, Florida, USA) (Fig. 1a). A purpose-design couch with a central rectangular slot (size: 12 cm [width] × 60 cm [length]) was used to facilitate ultrasound scanning at the supine position (Fig. 1a). The MRI scans were conducted using a

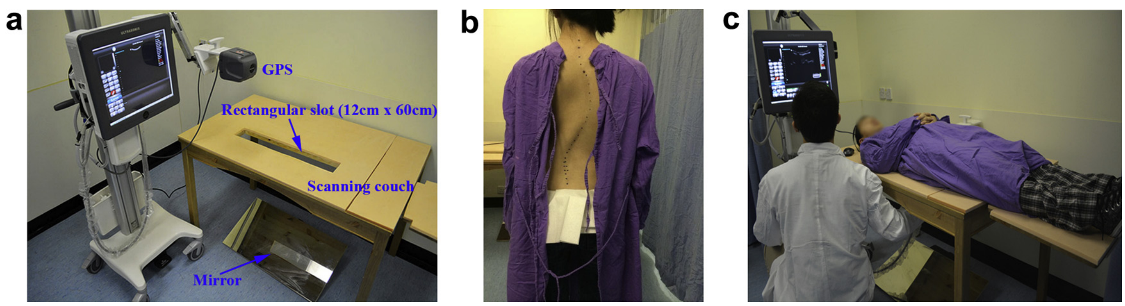

Fig. 1. 3-D ultrasound system and ultrasound scan; (a) 3-D SonixTABLET ultrasound unit with a SonixGPS System; (b) a patient with AIS; (c) ultrasound scanning was performed in the supine position. AIS = adolescent idiopathic scoliosis.

3.0T MR scanner and a spine array coil (Achieva, Philips Medical Systems, Best, The Netherlands).

Data acquisition

Before scanning, a level meter was used to ensure the anterior superior iliac spines (ASISs) of patients were at a horizontal level, which was used as a reference for measuring vertebral rotation for both the 3-D ultrasound and MRI measurements. In addition, to prevent shifting of the trunk, the position of the patients' ASISs were also adjusted to be parallel with the edge of either the ultrasound or the MRI scanning couches. In the coronal plane of MRI images, the connected line of both sides of ASISs was found in horizontal level. Likewise, the upper endplate of the S1 in the coronal plane of 3-D ultrasound images was also observed in a horizontal line (Wang et al. 2015). These precautions ensured the ASISs of the patients at level position at both the ultrasound and MRI scanning and measurements.

In the ultrasound method, the spinous processes from C7 to S1 were palpated as the start and endpoints. Then, the general trend of the coronal curvature was marked on the patient's back by a water soluble marker (Fig. 1b). Ultrasound gel was applied to ensure a good skin contact between the transducer and the patient's back. Ultrasound scanning was performed continuously along the coronal curvature from C7 to S1, with the patients lying on the scanning couch (Fig. 1c). Under the scanning couch, a mirror was used to reflect the marked trend of the coronal curvature, which assisted to place the probe correctly while moving it along the spine. Each patient underwent six scans (two raters, each with three scans), each of which took less than a min to perform.

The ultrasound data were then exported into a purpose-design software that reconstructed the 3-D ultrasound images of the vertebrae and performed semi-automatic measurements. The reconstructed 3-D ultrasound images of vertebrae were shown in the three orthogonal planes (coronal, sagittal and transverse) (Fig. 2).

Apical vertebral rotation measurement

The measurement of vertebral rotation was chosen at the apical level of the curve, which is normally used to predict the progression and evaluate the treatment outcomes (Cui et al. 2012; Di Silvestre et al. 2013; Kotwicki 2008). Before measurements, the level of apical vertebra was selected with reference to the MRI images. The COL method was applied to measure the apical vertebral rotation (AVR) in the 3-D ultrasound images (Chen et al. 2015; Vo et al. 2015). The two raters identified the COLs manually in the transverse plane of apical vertebral level. The AVR was automatically

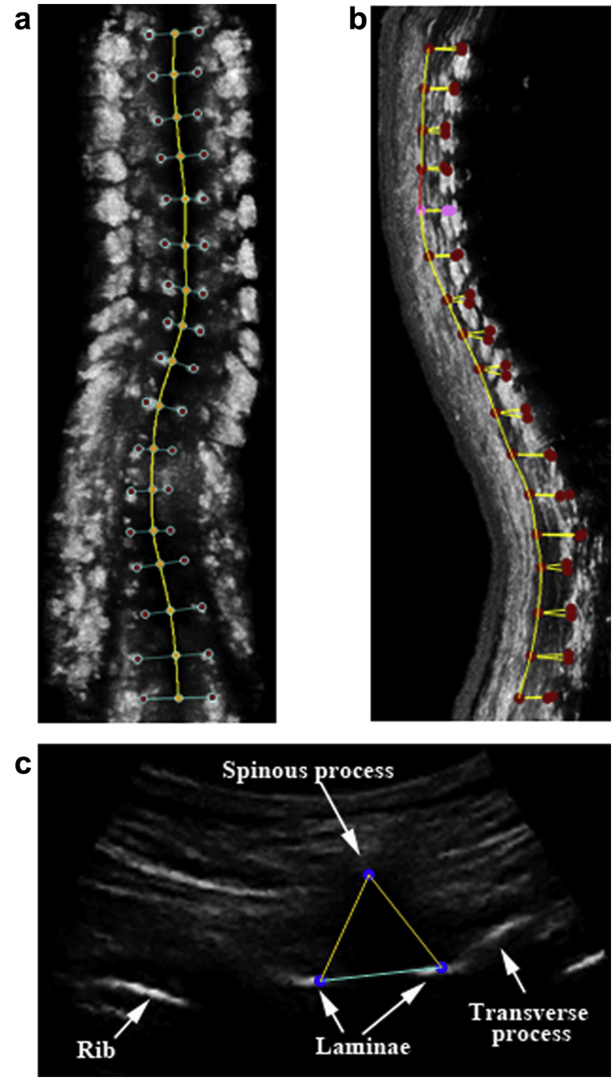

Fig. 2. The reconstructed 3-D ultrasound images of a scoliotic spine in the 3 orthogonal planes: (a) coronal plane; (b) sagittal plane; (c) transverse plane.

measured by the angle between the line joining the centers of laminae and the reference horizontal line (scanning couch) by the purpose-design software (Fig. 3a).

The MRI images would be processed using the DICOM Viewer Version R3.0 SP3 (Philips Medical Systems). The Aaro-Dahlborn method was used to measure the AVR in the transverse plane (Aaro and Dahlborn 1981; Vrtovec et al. 2009, 2010a, 2010b). The AVR was calculated by the angle between the line connecting the point at the posterior junction of the two laminae of vertebral arch with the mid-point of vertebral body and the reference line (Fig. 3b).

Raters 1 and 2 had approximately 5 y and 2 y experience using ultrasound to measure the scoliotic spine, respectively. Before the study, each rater was required

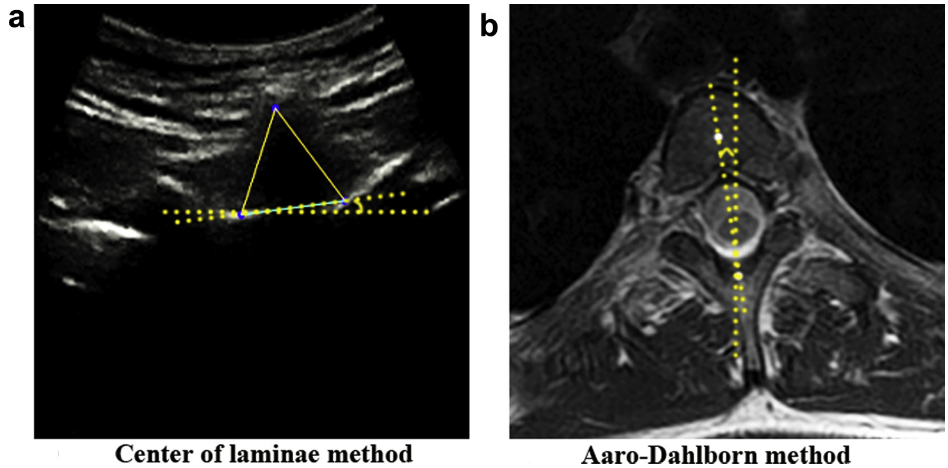

Fig. 3. Apical vertebral rotation measurements: (a) center of laminae method in 3-D ultrasound image; (b) Aaro-Dahlborn method in MRI. MRI = magnetic resonance imaging.

to practice ultrasound scanning at the supine position and measurements for more than 10 patients. During this study, the 3-D ultrasound and MRI images were randomly assigned without specific order for measurements. The two raters were blinded to patients' clinical information, and they measured AVR independently in three trials, each with a 1 wk interval. The time required was about 3 min for either 3-D ultrasound or MRI measurements.

Statistical analysis

Statistical analyses were performed using the IBM SPSS Statistics Version 21 (IBM, Armonk, New York, USA). A p value < 0.05 was considered to be statistically significant. Statistical graphs were made with GraphPad Prism Version 6.01 software (GraphPad, La Jolla, California, USA). To assess the reliability of 3-D ultrasound assessment, the intra-class correlation coefficient (ICC) (2, k) with 95% confidence intervals was used according to the Currier criteria (Currier 1984). Paired Student's t-test was applied to compare the mean values between the 3-D ultrasound and MRI measurements; the Bland-Altman method was used to examine the agreement between these two methods; the relevant correlation was evaluated by Pearson's correlation method.

RESULTS

Reliability of vertebral rotation measurement using 3-D ultrasound

Tables 1 and 2 show the intra- and inter-rater reliabilities of AVR measurements using the 3-D ultrasound and MRI methods. The intra-rater ICC (2, k) values of the COL method in 3-D ultrasound were 0.989 (0.979–0.994) and 0.981 (0.966–0.990) for rater 1 and rater 2, respectively. The inter-rater ICC (2, k) value was 0.978 (0.954–0.989). Similar to the Aaro-Dahlborn method in MRI, the intra- and inter-rater ICC (2, k) values of the COL method in 3-D ultrasound were above 0.9, which demonstrated high intra- and inter-rater reliabilities.

Validity of vertebral rotation measurement using 3-D ultrasound

To determine the validity of 3-D ultrasound measurement, the means comparison, the Bland-Altman method and the Pearson correlation analysis were applied between the 3-D ultrasound and MRI measurements in the patients with AIS. Table 3 shows the relevant statistical parameters of these three statistical methods.

Comparison between 3-D ultrasound and MRI measurements

For the entire curve cohort (n = 30), the mean value of AVR measured by the COL method in 3-D ultrasound was 7.7° ± 5.7°, while the average value by the Aaro-Dahlborn method in MRI was 7.5° ± 5.2°. Figure 4 shows three scatter plots of AVR measurements using 3-D ultrasound versus MRI methods in the categorized samples. The mean absolute difference between these two methods were 0.3° ± 0.3°, 0.5° ± 0.3° and 1.0° ± 1.1° for the samples with AVR of 0.0° ∼ 5.0°, 5.0° ∼ 10.0° and >10.0°,

Table 1. Intra-rater reliability of apical vertebral rotation measurements using 3-D ultrasound compared with MRI

Methods	Raters	Curves, n	ICC [2, k] (95% CI)
Ultrasound (COL)	R1	30	0.989 (0.979–0.994)
	R2	30	0.981 (0.966–0.990)
MRI (Aaro-Dahlborn)	R1	30	0.989 (0.980–0.994)
	R2	30	0.987 (0.976–0.993)

CI = confidence interval; COL = center of laminae; ICC = intra-class correlation coefficient; MRI = magnetic resonance imaging.

Table 2. Inter-rater reliability of apical vertebral rotation measurements using 3-D ultrasound compared with MRI

Methods	Raters	Curves, n	ICC [2, k] (95% CI)
Ultrasound (COL)	R1 versus R2	30	0.978 (0.954–0.989)
MRI (Aaro-Dahlborn)	R1 versus R2	30	0.987 (0.972–0.994)

CI = confidence interval; COL = center of laminae; ICC = intra-class correlation coefficient; MRI = magnetic resonance imaging.

respectively. The paired Student's *t*-test results showed that there was no significant difference between these two methods (Table 3).

Bland-Altman method

The agreement between the 3-D ultrasound and MRI measurements was investigated using the Bland-Altman method. The Bland-Altman plot showed the average of the two measurements against the difference between the two measurements. Additional horizontal lines represented the mean difference (bias) and the limits of agreement, that is, the 95% confidence intervals of the measurements (mean ± 1.96 × standard deviation) (Bland and Altman 1986, 1995). As shown in Figure 5a, the Bland-Altman plots exhibited good agreement between the 3-D ultrasound and MRI measurements for the overall curve cohort (n = 30). The absolute bias between these two methods was 0.2°, and the 95% limits of agreement were −1.4° ~ 1.8° (Table 3).

On analyzing the impact of different Cobb angles on the agreement between the 3-D ultrasound and MRI measurements, the samples with a Cobb angle of 10.0° ~ 20.0° showed lower discrepancy with respect to mean difference than the samples with a Cobb angle >20.0° (Fig. 5b and 5c). The absolute bias between these two measurements was 0.1° for the samples with a Cobb angle 10.0° ~ 20.0°, compared to 0.6° for a Cobb angle >20.0°. Similarly, the 95% limits of agreement were −0.9° ~ 0.9° and −1.7° ~ 2.9° for the samples with a Cobb angle 10.0° ~ 20.0° and >20.0°, respectively (Table 3).

On analyzing the impact of different AVR degrees, the samples with AVR 0.0° ~ 5.0° showed lower discrepancy than the others with AVR 5.0° ~ 10.0° and >10.0° (Fig. 5d–f). The corresponding values of the absolute bias (0.1°) and the 95% limits of agreement (−0.9° ~ 0.7°) were the least for the samples with AVR of 0.0° ~ 5.0° (Table 3).

Notably, on analyzing the impact of variation in selected apical vertebra, the samples with no variation showed lower discrepancy than the samples with variation (equal to 1), but larger than the samples with variation (equal to 2) (Fig. 5g–i). Correspondingly, the least absolute bias and 95% limits of agreement were 0.1° and −0.6° ~ 0.8° for the samples with variation in selected apical vertebra (equal to 2) (Table 3).

Pearson correlation analysis

The Pearson correlation analysis showed a similar trend to that observed using the Bland-Altman method (Fig. 6). The correlation coefficient (r) in all the sample categories was greater than 0.8 ($p < 0.05$), indicating high correlation between the 3-D ultrasound and MRI assessments of vertebral rotation (Table 3).

Taken together, the validity of the 3-D ultrasound measurements of vertebral rotation in the transverse plane was confirmed with the MRI measurements of vertebral rotation at the supine position.

DISCUSSION

The major findings of this study were (i) the COL method in 3-D ultrasound showed high intra- and inter-rater reliabilities in the measurements of vertebral

Table 3. Validity of apical vertebral rotation measurements using 3-D ultrasound compared with MRI

Variables	Curves, n	*t*-test *Sig.* (2-tailed)	Bland-Altman method: Bias	Bland-Altman method: SD of bias	Bland-Altman method: 95% Limits of agreement	Pearson correlation coefficient (*r*)
Cobb angle degrees						
Cobb angle: 10.0° ~ 20.0°	19	0.85	0.1°	0.5°	−0.9° ~ 0.9°	0.983
Cobb angle >20.0°	11	0.12	0.6°	1.2°	−1.7° ~ 2.9°	0.980
AVR						
AVR: 0.0° ~ 5.0°	12	0.54	−0.1°	0.4°	−0.9° ~ 0.7°	0.884
AVR: 5.0° ~ 10.0°	10	0.63	0.1°	0.9°	−1.1° ~ 1.3°	0.914
AVR >10.0°	8	0.13	0.8°	1.3°	−1.7° ~ 3.2°	0.941
Variation in selected apical vertebra						
Variation = 0	12	0.64	0.1°	0.7°	−1.3° ~ 1.5°	0.993
Variation = 1	12	0.28	0.4°	1.1°	−1.8° ~ 2.5°	0.992
Variation = 2	6	0.50	0.1°	0.4°	−0.6° ~ 0.8°	0.998
Total	30	0.18	0.2°	0.8°	−1.4° ~ 1.8°	0.991

AVR = apical vertebral rotation; MRI = magnetic resonance imaging; SD = standard deviation.

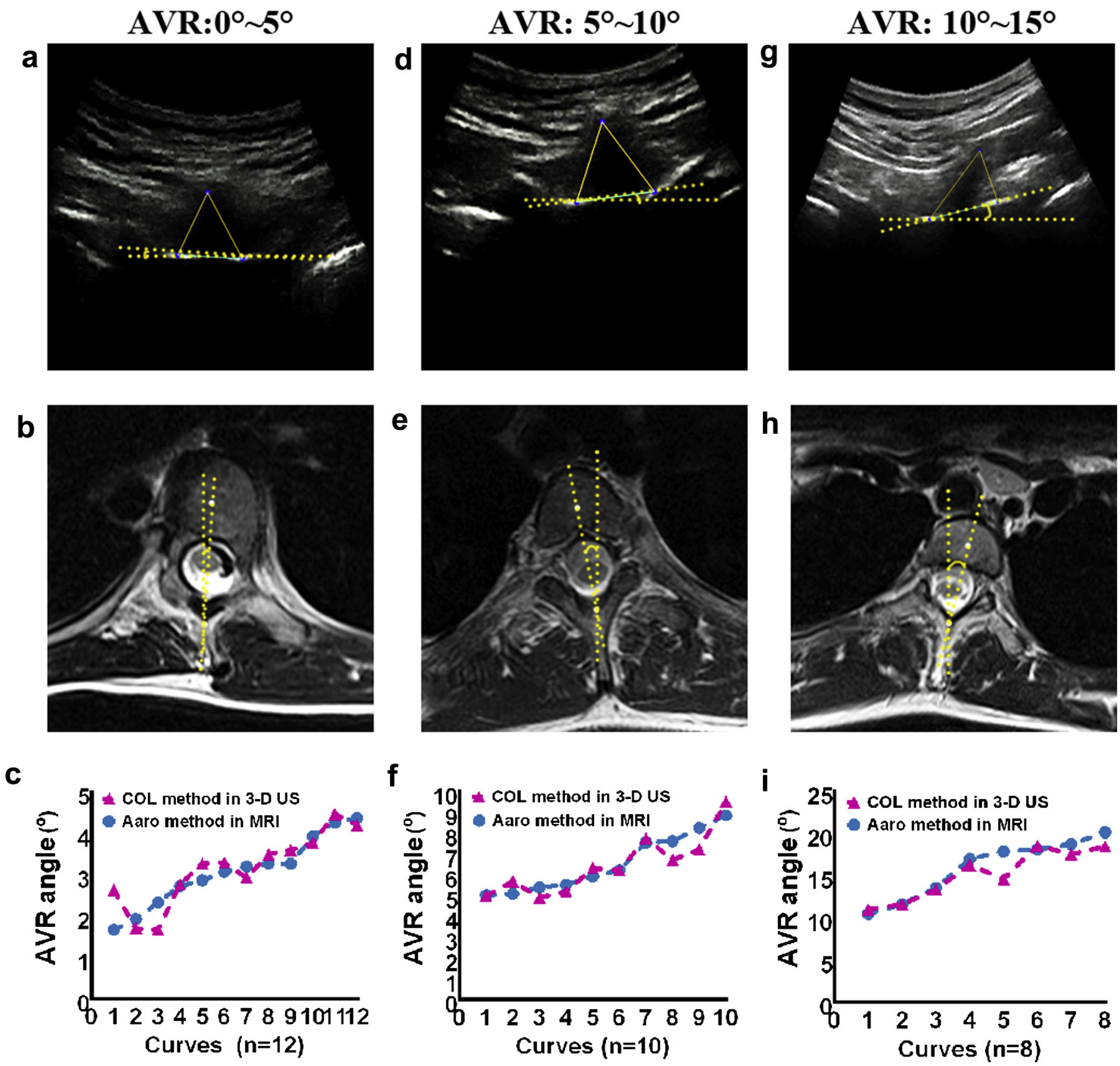

Fig. 4. Comparison of measurements of apical vertebral rotation using 3-D ultrasound versus MRI methods in the sample categories; (a)–(c) AVR: 0.0° ~ 5.0°; (d)–(f) AVR: 5.0° ~ 10.0°; (g)–(i) AVR: >10.0°. 3-D US = 3-D ultrasound; AVR = apical vertebral rotation; COL = center of laminae; MRI = magnetic resonance imaging.

rotation; (ii) compared with the Aaro-Dahlborn method in MRI, the COL method in 3-D ultrasound showed no significant difference when measuring the AVR in the transverse plane; (iii) the agreement between 3-D ultrasound and MRI measurements was demonstrated by the Bland-Altman method; and (iv) high correlation was found between 3-D ultrasound and MRI measurements of vertebral rotation.

Compared with the studies of 3-D ultrasound in the coronal plane, few studies have used 3-D ultrasound to measure vertebral rotation in the transverse plane (Chen et al. 2013; Li et al. 2012; Ungi et al. 2014; Young et al. 2015; Zheng et al. 2015). Recently, the reliability and validity of 3-D ultrasound measurements of vertebral rotation has been validated in phantom studies. The COL method was proposed to measure the rotation of three vertebrae: T7, L1 and L3 (dry bones). The intra- and inter-rater ICC values of this method ranged from 0.987 to 0.997 (Chen et al. 2015; Vo et al. 2015). In the present clinical study, the results were consistent with the previous phantom study. Moreover, the 3-D ultrasound measurement showed similar reliability to the MRI assessments. These results indicated that the 3-D ultrasound could provide reliable measurements of vertebral rotation for the patients with AIS.

An important parameter in determining the validity of the new method of measurement is the agreement with a standard method. A recent systematic review concluded that the Bland-Altman method, correlation coefficient and means comparison were the most common

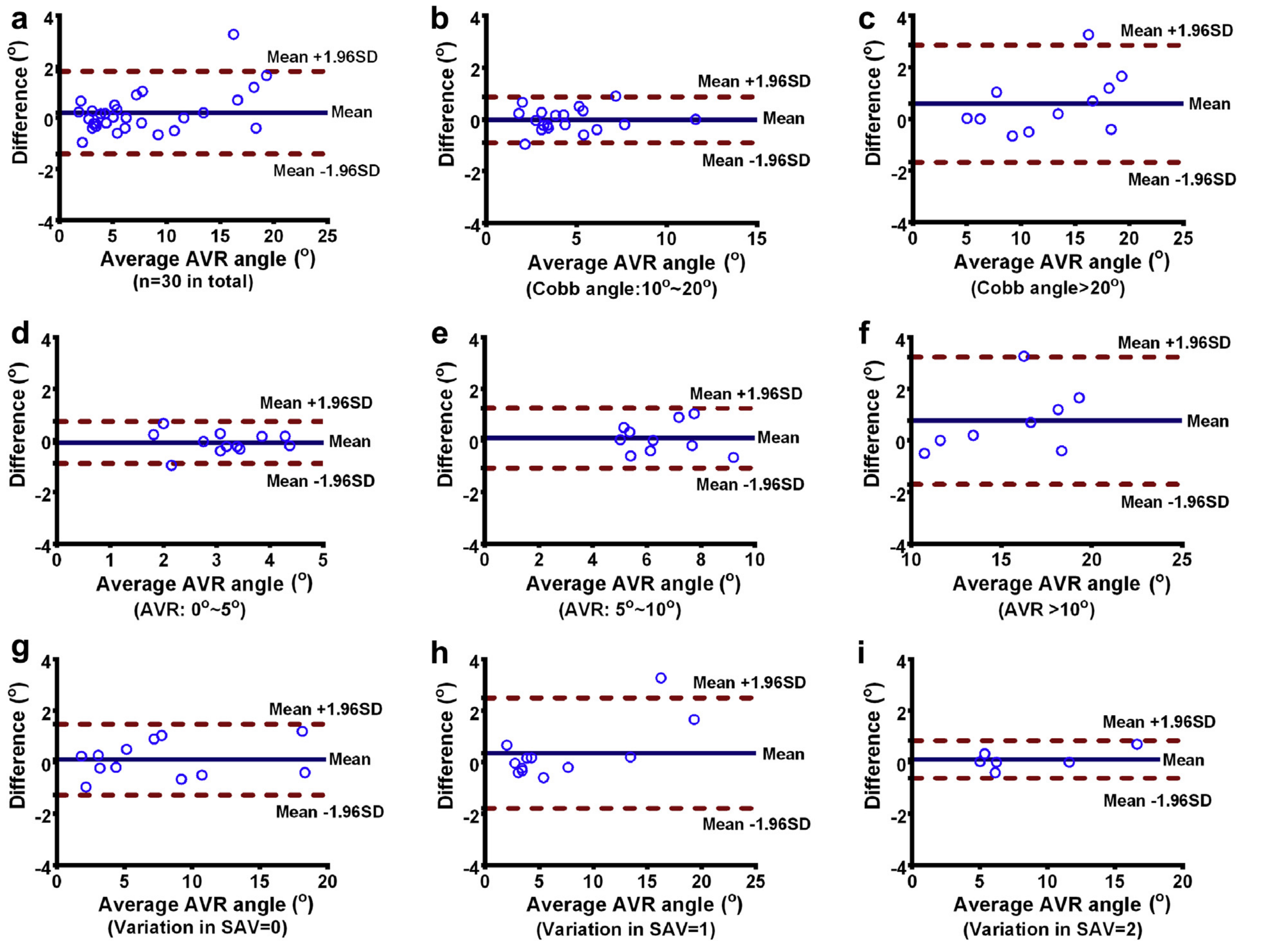

Fig. 5. Bland-Altman plot assessing the agreement of apical vertebral rotation measurements using 3-D ultrasound versus MRI methods in the sample categories: (a) the entire curve cohort; (b) Cobb angle: 10.0° ~ 20.0°; (c) Cobb angle >20.0°; (d) AVR: 0.0° ~ 5.0°; (e) AVR: 5.0° ~ 10.0°; (f) AVR >10.0°; (g) variation in SAV = 0; (h) variation in SAV = 1; (i) variation in SAV = 2. The x-axis represents the average AVR angle measured using 3-D ultrasound and MRI methods; the y-axis shows the difference between these two methods; the central line represents mean differences (bias); upper line shows mean+1.96 SD and lower line mean−1.96 SD. AVR = apical vertebral rotation; SAV = selected apical vertebra; SD = standard deviation.

statistical methods used to measure the agreement in relevant studies (Zaki et al. 2012). In the present study, the validity of 3-D ultrasound assessment of vertebral rotation has been demonstrated by these statistical methods. Additionally, the results of means comparison indicated that the difference between the 3-D ultrasound and MRI measurements seemed to be enlarged (0.3° ± 0.3°, 0.5° ± 0.3° and 1.0° ± 1.1°) with the AVR degrees increased (0.0° ~ 5.0°, 5.0° ~ 10.0° and >10.0°). This observation was also supported by the Bland-Altman method, which clearly showed that the 95% limits of agreement (−0.9° ~ 0.7°, −1.1° ~ 1.3° and −1.7° ~ 3.2°) were extended with the increase of AVR degrees (0.0° ~ 5.0°, 5.0° ~ 10.0° and >10.0°). These observations suggested that the measurement error of vertebral rotation using ultrasound may be related with the extent of the rotation of the vertebra. In addition, the agreement between the 3-D ultrasound and MRI assessments was higher in the samples with Cobb angle of 10.0° ~ 20.0° than the samples with Cobb angle >20.0°. The results indicated that the magnitude of the curve in the coronal plane may affect the accuracy of vertebral rotation measurements. It is noticeable that the variation in selected apical vertebra (equal to 2) did not decrease the agreement between these two methods compared with the samples with no variation and variation (equal to 1). This may be due to the lower sample size (n = 6) in the samples with variation in selected apical vertebra (equal to 2) relative to the other two samples (both n = 12). Contrary to the results obtained from the Bland-Altman method, the correlation coefficient (r) between these two methods for the samples with AVR of

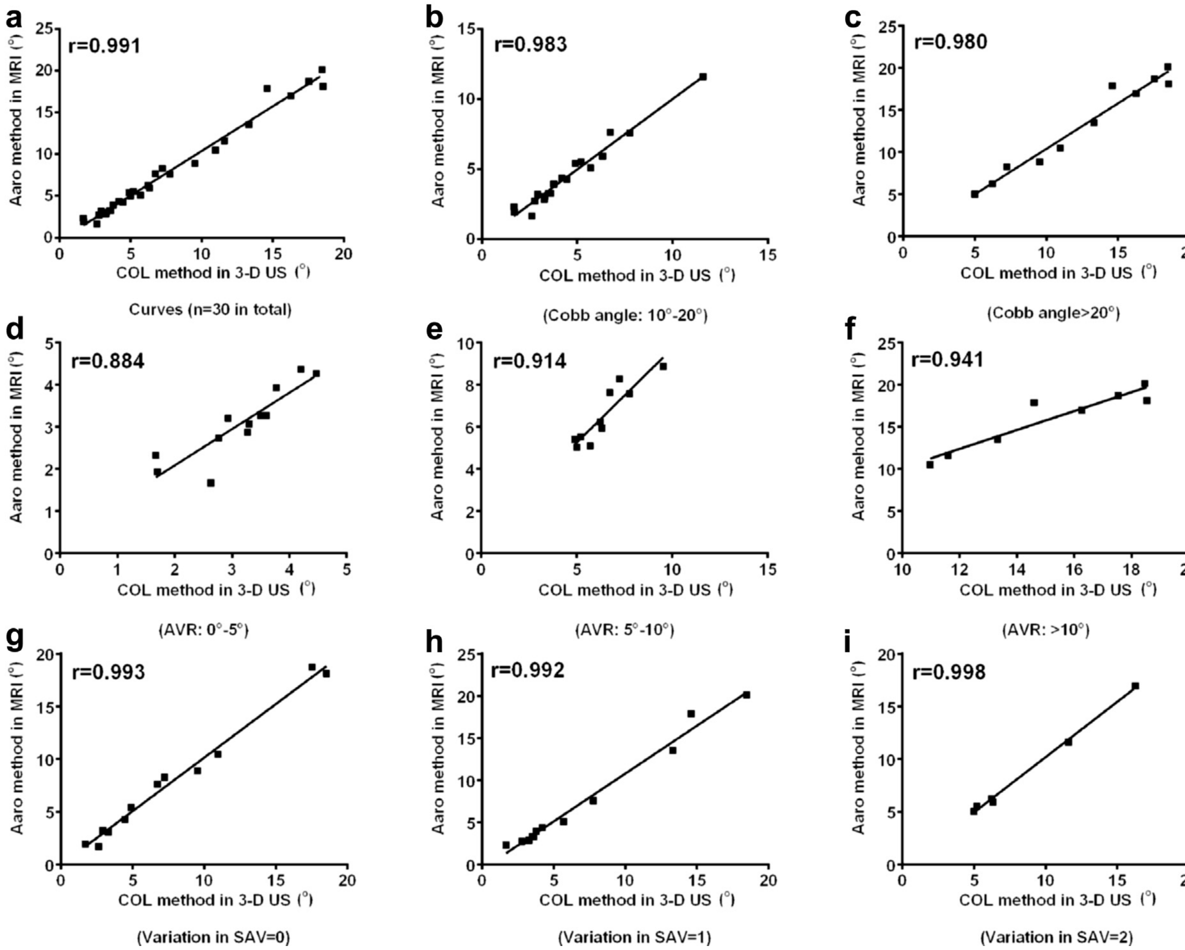

Fig. 6. Correlation of AVR measurements using 3-D ultrasound versus MRI methods in the sample categories; (a) the entire curve cohort; (b) Cobb angle: 10.0° ~ 20.0°; (c) Cobb angle >20.0°; (d) AVR: 0.0° ~ 5.0°; (e) AVR: 5.0° ~ 10.0°; (f) AVR >10.0°; (g) variation in SAV = 0; (h) variation in SAV = 1; (i) variation in SAV = 2. 3-D US = 3-D ultrasound; AVR = apical vertebral rotation; COL = center of laminae; MRI = magnetic resonance imaging; SAV = selected apical vertebra.

0.0° ~ 5.0° was lower than the samples with AVR of 5.0° ~ 10.0° and >10.0°. This might be due to the fact that the correlation coefficient does not perfectly represent the agreement between two variables (Bland and Altman 1986). Above all, this study provided the preliminary evidence to support the validity of vertebral rotation measurements using the 3-D ultrasound in comparison with the MRI measurements in the transverse plane. Continuous studies with large sample size to further validate the 3-D ultrasound measurements of vertebral rotation in the patients with AIS will be necessary.

On the other hand, there were several issues to be noted. The eligible curves in this study involved a range of curve severity (10.2°–68.2°) of the patients with AIS, but the proportion of severe curves was relatively small. Thus, further research is required to evaluate the validity of 3-D ultrasound measurements on the vertebral rotation of the severe curves. In addition, it is necessary to maintain a good contact between the transducer and the patient's back during 3-D ultrasound scanning. Thus, it is necessary to design appropriate devices to facilitate ultrasound scanning and reduce the manual labor cost. Additionally, the semi-automatic program used in reconstruction and measurement of 3-D ultrasound images should be upgraded to a fully automatic program to reduce human error.

CONCLUSIONS

In this study, the validity of 3-D ultrasound on vertebral rotation measurements has been demonstrated in patients with AIS under clinical settings. The COL method in 3-D ultrasound has been verified with the Aaro-Dahlborn method in MRI. A large sample size is required to further validate the proposed 3-D ultrasound method in the future studies.

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