Investigation of the Optimal Freehand Three-Dimensional Ultrasound Configuration to Image Scoliosis: An In-vitro Study

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Abstract— **Scoliosis is a three-dimensional (3D) spinal deformity. 3D ultrasound has been used to image scoliotic spines. This in-vitro study was to investigate the optimal 3D ultrasound parameters by comparing the reconstructed images and the phantom.**

A medical ultrasound system, a convex and a linear ultrasound probes, both with built-in positioning sensors, were used to scan cadaveric vertebra T7 immersed in a water tank. The operating frequencies were set at 2.5 MHz, 3.3MHz, 4.0 MHz, 6.6 MHz, and 10.0 MHz. The voxel-based method was deployed for the 3D reconstruction. The minimum distances (0.1, 0.2, and 0.3 mm) between two adjacent B-scan images and the reconstruction resolutions (0.2, 0.6, and 1.0 mm) were the inputs for the reconstruction algorithm. A total of 45 configurations were investigated. Four distance parameters were measured three times on both the images and the cadaveric vertebra by one rater in one week apart to minimize memory bias. The mean absolute difference was the distance measurement difference between the images and phantom. The paired Student's t-test was used to determine the probability between the two populations. The determination of the optimal configuration was based on both accuracy and intuitive image quality.

The results showed that the convex probe with the configuration (0.2-mm minimum distance, 0.6-mm reconstruction resolution, and 4.0 MHz) provided the best reconstructed image.

Keywords— **scoliosis, freehand ultrasound, mean absolute difference, voxel-based method.**

I. INTRODUCTION

Scoliosis is a complicated spinal deformity associated with vertebral rotation and lateral deviation with a Cobb angle of 10^o or more [1, 2]. Among different types of scoliosis, adolescent idiopathic scoliosis (AIS) is the most common type, which accounts for 80% of the cases and affects 1.5 – 3% of the population [3]. The treatment of idiopathic scoliosis depends on the severity of scoliosis and the probability of progression. Currently, the Cobb method is the gold standard recommended by the Scoliosis Research Society to assess the severity of scoliosis on posteroanterior (PA) radiographs. However, this method may underestimate the 3D severity because it only reflects the spinal curvature on the coronal plane.

As technology becomes more advanced, 3D images should be used to extract the 3D spinal deformity information. Both computed tomography (CT) and magnetic resonance imaging (MRI) can image and display 3D bone structures clearly; however, the CT modality exposes patients to more radiation than traditional X-ray imaging and requires patients in supine position, which alters the spinal curvature [4-6]. In addition, using MRI to image spine is costly and time consuming; thus, its use for imaging scoliosis is limited.

Three-dimensional images of spine can also be obtained from multi-planar standing radiography but ionizing radiation is still a concern. The EOS (EOS Imaging, France) is a medical imaging system that can perform the simultaneous acquisition of the PA and lateral radiographs in a standing position. This system generates better images and reduces radiation dosage when compared with standard radiography and CT [7, 8]. Even though the EOS exposes patients to much less radiation, the issue of radiation safety still attracts the attention of the community. In general, during the treatment or observation periods, AIS patients may take radiographs every four to twelve months; the cumulative amount of ionizing radiation may still increase the risk of developing cancer [8-12], especially for females when their incidence of scoliosis is about 80% of all cases [13].

In 2007, Purnama et al. [14] introduced a framework for human spine imaging using a freehand 3D ultrasound system with a 5 MHz curved array probe and an optical tracking system. The isotropic voxel size of 0.21 mm was used for the reconstruction. The axial vertebral rotation and the vertebral tilt of each vertebra are calculated based on the centers of mass of the transverse processes which are determined manually and semi-automatically for a comparison of accuracy. Ultrasound data from a healthy volunteer was used to build the 3D spinal model, which was then validated by 5 data sets from scoliotic patients [15]. The validation was not fully proved. Cheung et al. [16] also designed a system with a freehand 3D ultrasound system, a

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wide linear probe (L53L/10-5), and an electromagnetic spatial sensing device for scoliosis applications. An in-vitro study was performed and the accuracy of the Cobb angle value was reported to be within 2 – 5^{o} between X-ray and ultrasound measurements.

3D ultrasound has been used to image scoliotic spines, mostly on phantom and volunteers. Researchers used different ultrasound configurations including the type of transducer, the operating frequency, and the reconstruction resolution (the voxel size) to acquire images, which makes the image quality vary. This in-vitro study was to investigate the optimal 3D ultrasound parameters by comparing the reconstructed images and the phantom.

II. MATERIALS AND METHODS

A. Materials

The medical ultrasound system Ultrasonix SonixTablet (Ultrasonix Ltd., Canada), a built-in magnetic global positioning system (GPS) (SonixGPS), and a 3D Guidance device (driveBAY, Ascension Ltd., USA) (Fig. 1) were used in this study. In addition, two types of GPS-assisted transducer, which were compatible with the ultrasound equipment, were used: a flat linear transducer and a convex transducer. The flat linear transducer can operate at the ultrasound frequency range between 5 to 14 MHz, the depth range between 2 and 9 cm, and the active scanning area of 38 mm x 9 mm. Meanwhile, these parameters for the convex transducer are 2 – 5 MHz, 5 - 30 cm, and 60 mm x 15 mm, respectively. The spatial sensor (GPS receiver) embedded inside the transducer interacts with the GPS transmitter via the 3D Guidance to provide 3D orientation information of each acquired B-scan ultrasound image relative to the location of the transmitter.

B. Methods

A cadaveric vertebra T7 was scanned when immersed in a water tank. The tank was made of 4.5-mm thick acrylic to simulate the body setting. The vertebra was set with its posterior arch facing the surface of the transducer and without any vertebral rotation. The GPS transmitter was set up within the working range of 5 – 20 cm relative to the GPS receiver recommended by the manufacturer. Within this range, the GPS accuracy is ± 1.0 mm.

The operating frequencies were set at 2.5 MHz, 3.3MHz, and 4.0 MHz for the convex probe and 6.6 MHz and 10.0 MHz for the linear probe, respectively. Each frequency was used in turn to scan T7 for data acquisition. The depth was set at 9 cm and the acquisition frame rate per second was automatically set to 27, 36, 36, 8, and 10 for five frequencies, respectively. The scanning time was approximate 23 seconds for the convex probe and 46 seconds for the linear one. After the scanning process, a series of B-scans was acquired, including two data sets: intensity data (*.b8*) and GPS data (*.gps*). These two data sets were saved in the ultrasound system and then imported into an in-house developed program, which deployed the voxel-based method for the 3D reconstruction of T7.

In order to eliminate the overlap among acquired B-scans, the minimum distance (MD) between two adjacent B-scans (0.1, 0.2, and 0.3 mm) was set. If the distance between two adjacent B-scans was less than the preset minimum distance, one of the two B-scans was eliminated. In addition, the resolution of the reconstructed volume (RR) (the isotropic voxel size) (0.2, 0.6, and 1.0 mm) was also determined. The MD and RR were the inputs for the reconstruction algorithm. A total of 45 configurations (3 MD x 3 RR x 5 frequencies) were investigated. Four distance parameters (Fig. 2) were measured three times on both the images and the cadaver by one rater in one week apart to minimize memory bias. These measurements were used to evaluate the accuracy of the 3D reconstruction. The mean absolute difference (MAD) was the distance measurement difference between the images and phantom. The paired Student’s t-test was used to determine the probability between the two populations (p-values). It was assumed that the two groups have unequal variance and two-tailed t-test was performed. The determination of the optimal configuration was based on a comparison among 45 configurations in terms of both accuracy and intuitive image quality.

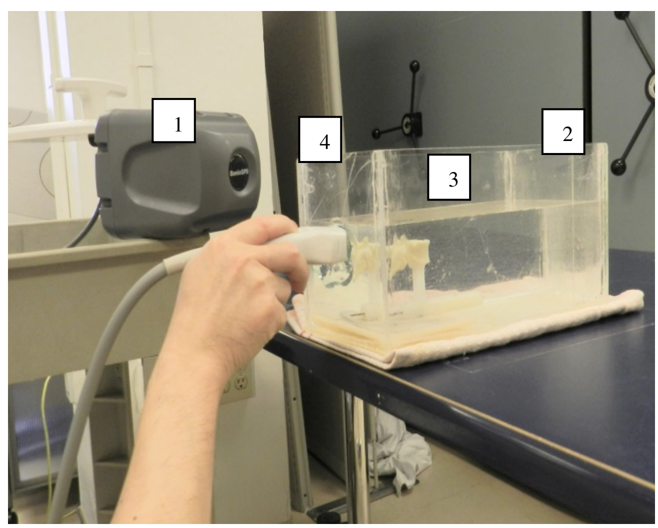

Fig. 1 The experimental setup: (1) GPS transmitter, (2) water tank, (3) cadaveric vertebra T7, and (4) GPS receiver embedded transducer.

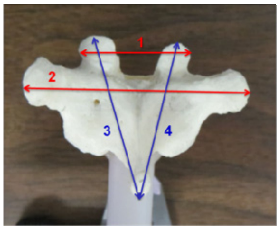

Fig. 2 The four distance parameters on the cadaveric vertebra T7: 1. superior articular process – superior articular process, 2. transverse process – transverse process, 3. Left superior articular process – spinous process, 4. right superior articular process – spinous process.

III. RESULTS

Table 1 tabulates the MAD and probability values of the 45 configurations. The best five reconstructed images based on both accuracy and intuitive image quality for each frequency are provided by the following 5 configurations (MD/RR mm, frequency MHz): (0.1/1.0, 2.5), (0.1/0.6, 3.3), (0.2/0.6, 4.0), (0.1/1.0, 6.6) and (0.1/0.6, 10.0) and shown in Fig. 3. The corresponding MAD (mm)/p-values of the measurements were 1.5±0.4/0.84, 0.9±0.6/0.89, 1.3±0.3/0.86, 1.5±0.3/0.90, and 1.7±0.5/0.97 respectively. In addition, the ranges of difference between the true values and the average measurements were 0.2 – 2.4 mm, 0 – 2.8 mm, 0.3 – 1.8 mm, 0.6 – 3.1 mm, and 0.4 – 2.6 mm for the four distances, respectively. Among the five aforementioned configurations, the best reconstructed image is given by the (0.2/0.6, 4.0) configuration.

IV. DISCUSSIONS

In this study, the probability p-values derived from the five best images are greater than 0.84, indicating a high correlation between measurements of the cadaver and those of the reconstructed images. The GPS accuracy was within ±1 mm and the MAD is not more than 1.7 mm. In order to increase the accuracy, the GPS system needs to be calibrated prior to data acquisition. Further measurements such as proxy Cobb angle and vertebral rotation will be performed on the 3D reconstructed model; therefore, the higher the accuracy, the better it is. Furthermore, the convex probe offered better images than the linear one. It was because the frame rate of the former was basically greater than that of the latter while keeping the same penetration depth and frame rate at "high" setting, resulting in a higher number of frames available for the 3D reconstruction process. Even though the scanning time of the linear probe doubled that of the convex one in order to compensate for its lower frame rates, the number of frames acquired by the linear probe was still lower. Technically, the reconstruction algorithm required an intensity value of the interpolated voxel, which was proportional to the intensities of the two nearest pixels of the two nearest frames from the voxel and inversely proportional to the distances between the voxel and the two neighboring frames. If the two frames were located far from the voxel due to the low number of acquired frames, the voxel's interpolated value was small and thus ignored, leaving a 'blank' (zero value) at the voxel's position. Increasing the scanning time is impossible because this is not reasonable in reality.

There are still some limitations due to the inherent characteristics of ultrasound. This method cannot image the vertebral body due to the acquisition configuration and the lack of ultrasound energy penetrating through bone.

V. CONCLUSIONS

The configuration with MD/RR being 0.2/0.6 mm and 4.0 MHz displayed the best image based on the in-vitro experiment. This configuration should be verified by the in-vivo data. This is an objective for our future research.

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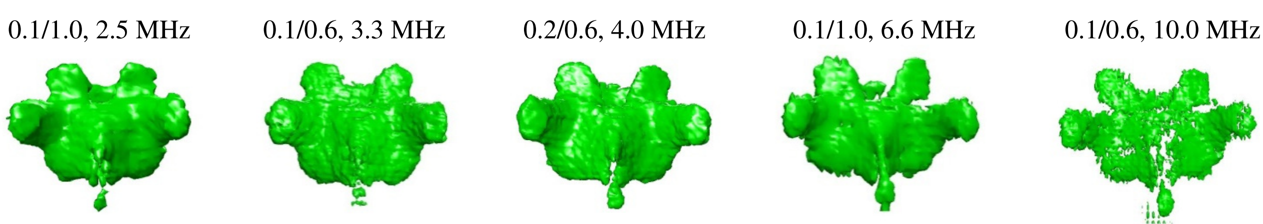

Fig. 3 The five best reconstructed images and the corresponding configurations (MD/RR mm, frequency).

Table 1 The MAD and p-values for the 45 configurations.

Frequency (MHz)		Resolutions (mm/mm) 0.1/0.2	0.1/0.6	0.1/1.0	0.2/0.2	0.2/0.6	0.2/1.0	0.3/0.2	0.3/0.6	0.3/1.0
2.5	MAD (mm)	2.0 ± 0.5	1.8 ± 0.4	1.5 ± 0.4	2.2 ± 0.5	1.8 ± 0.5	1.5 ± 0.4	2.1 ± 0.6	2.0 ± 0.5	1.5 ± 0.4
	p-value	0.78	0.82	0.84	0.78	0.81	0.83	0.77	0.79	0.84
3.3	MAD (mm)	1.2 ± 0.5	0.9 ± 0.6	1.2 ± 0.4	1.5 ± 0.5	1.2 ± 0.5	1.3 ± 0.5	1.3 ± 0.5	1.3 ± 0.4	1.1 ± 0.4
	p-value	0.86	0.89	0.91	0.82	0.87	0.85	0.85	0.85	0.90
4.0	MAD (mm)	2.1 ± 0.6	1.8 ± 0.5	1.9 ± 0.6	1.8 ± 0.6	1.3 ± 0.3	2.0 ± 0.6	1.7 ± 0.4	1.5 ± 0.4	1.9 ± 0.5
	p-value	0.76	0.80	0.79	0.79	0.86	0.78	0.83	0.84	0.79
6.6	MAD (mm)	2.1 ± 0.4	2.1 ± 0.6	1.5 ± 0.3	2.0 ± 0.5	1.9 ± 0.5	1.6 ± 0.3	2.3 ± 0.4	2.1 ± 0.4	2.1 ± 0.6
	p-value	0.85	0.94	0.90	0.94	0.90	0.89	0.83	0.89	0.83
10.0	MAD (mm)	1.8 ± 0.5	1.7 ± 0.5	2.1 ± 0.5	1.9 ± 0.4	1.9 ± 0.5	2.2 ± 0.5	1.9 ± 0.5	1.7 ± 0.5	1.7 ± 0.5
	p-value	0.91	0.97	0.95	0.89	0.92	0.94	0.89	0.97	0.96

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