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Imaging Spinal Curvatures of AIS Patients using 3D US Free-hand Fast Reconstruction Method

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***Abstract*—The Voxel-Based Nearest Neighbor method (VNN) is one of the most commonly used reconstruction algorithms for a freehand ultrasound (US) acquisition system, however, it is time-consuming due to large scale of vector arithmetic. The objectives of this study are to develop 3D US reconstruction algorithms which can reduce the reconstruction time to the required range of real-time demonstration and processing and to improve the US image quality for higher brightness and contrast. The execution time, numerical difference comparison, brightness and contrast analysis were used to demonstrate the new methods. The result showed that the new FDP US imaging method could provide 3D spine images with faster reconstruction procedure and better image quality.**

Keywords*—Ultrasound spine imaging, 3D ultrasound image reconstruction, Fast Dot-Projection, Multiple Plane Interpolation, Scoliosis

I. Introduction

Adolescent idiopathic scoliosis (AIS) is a complex 3D deformity of the spine with a lateral curvature more than 10º. The prevalence rate of AIS is about 5% in China [1]. Cobb angle measured on radiographs is widely used as the gold standard for assessment of scoliosis[2], however, excessive exposure to ionizing radiation could cause health issues to adolescents. Currently, 3D ultrasound (US) imaging technique is becoming a promising method for scoliosis studies because it is radiation-free and flexible to use. Some researchers have demonstrated its validity[3]. 3D US spine imaging technique is developed to detect spinal curvature and shows comparable measurement results with Cobb angle method[4], [5].

In 3D US imaging system, four different kinds of approaches have been discussed: mechanical scanners, freehand technique with position sensing, freehand technique without position sensing and 2D arrays[6]. For the most commonly used freehand methods, a position sensor is inserted into the conventional 2D scanner to label the orientation and rotation of each acquired frame.

Numerous 3D US image reconstruction algorithms have been reported in the literatures based on different implementation. They can be categorized to Voxel-Based Method(VBM), Pixel-Based Method(PBM) and Function-Based Method[7]. The Voxel-Based Nearest Neighbor method (VNN) is the most frequently applied reconstruction algorithm. However, the conventional projection method (CPM) of VNN is time-consuming due to large scale of vector arithmetic, thus restrained from the applications of real-time observation and diagnosis. On the other hand, the VNN method employs very few data during the reconstruction, therefore frequently causes fuzzy illustration and missing structures on US images.

In this research, the Fast Dot-Projection (FDP) method was developed to reduce the processing time of calculating projection distances from each frame to the reconstructed volume, and a new reconstruction algorithm Multiple Plane Interpolation (MPI) was proposed to improve imaging quantity. The execution time using FDP and VNN methods on 20 data sets was recorded and compared. The average intensity and variance of the reconstructed spine images using MPI and VNN methods were calculated respectively to compare the image quality.

II. Methods

A. Acquisition system

As shown in Fig. 1, the acquisition system consists of SonixTABLET unit, a 128-element C5-2/60 GPS transducer, and the SonixGPS transmitter (Analogic Ultrasound – BK Medical, Peabody, Massachusetts, USA). The center frequency used during scan was 2.5 MHz and the penetration depth was set at 6cm. A series of 1000-1500 2D US transverse frames and the corresponding spatial information were obtained from equipped system for each subject [8]. The frame rate was 32Hz, and each frame was stored as a 640*480 8-bit image with 256 discrete intensity values. The resolution was 0.148*mm* in both horizontal and vertical directions.

The rotation and orientation of the probe were recorded as spatial information matrix during the scan, including Cartesian coordinates(x, y, z), calibration array and transformation array. After spatial transformation, the coordinates of four vertices of these 2D frames were obtained to rebuild a new 3D volume[9]. The voxel size in this volume was set to 0.5*mm* in width (x direction) and 0.5*mm* height (y direction), and 1*mm* in depth (z direction). The value of each voxel was designated by the

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reconstruction algorithms.

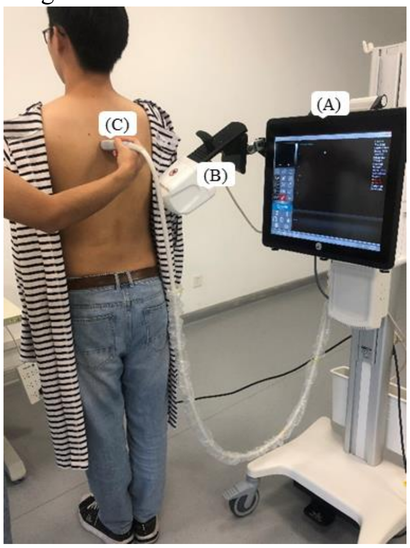


Fig. 1. System equipment (A) SonixTABLET (B) SonixGPS transmitter, and (C) C5-2/60 GPS transducer.

B. Fast Dot-Projection (FDP)

Fig. 2 (a) shows a 3D reconstructed volume with a volume plane and a frame plane. Volume plane is a plane within the reconstructed regular volume and the frame in the regular volume is called frame plane. Fig. 2 (b) displays more details of the geometric relationship between the volume plane and the frame plane.

The 3D point-to-plane distance, d can be calculated as follows:

$$d = \overrightarrow{AB} \cdot \vec{n} \tag{1}$$

Where, $\overrightarrow{AB}$ denotes a vector from point A to B, A is a point outside the plane, B is any point in the plane. $\vec{n}$ is the normal vector of the plane.

Therefore, as illustrated in Fig. 2(b), the perpendicular distance from a voxel point in the volume plane to a frame plane was expressed as[10]:

$$d = \overrightarrow{V_iP} \cdot \vec{n} \tag{2}$$

where $V_0, V_1, \ldots, V_i$ was a voxel point in the volume plane, and P was any point in the frame plane. $\vec{n}$ was the normal vector of the frame plane. The distance from voxel V_0 to the frame plane was denoted as d_0, the coordinates of V_0 and P were denoted as (x_0, y_0, z_0) and (x_p, y_p, z_p). Then, the distance d_0 was calculated by

$$d_0 = \overrightarrow{V_0P} \cdot \vec{n} = a(x_0 - x_\mathrm{p}) + b(y_0 - y_\mathrm{p}) + c(z_0 - z_\mathrm{p}) \tag{3}$$

where

$$\vec{n} = (a, b, c) \tag{4}$$

$$\overrightarrow{V_0P} = (x_0 - x_\mathrm{p}, y_0 - y_\mathrm{p}, z_0 - z_\mathrm{p}) \tag{5}$$

Defining any voxel in the volume plane as V_i and the distance from V_i to the frame plane as d_i. The coordinate of V_i in volume was (x_i, y_i, z_i). Then, the distance d_i was calculated by

$$d_i = \overrightarrow{V_iP} \cdot \vec{n} = a(x_i - x_\mathrm{p}) + b(y_i - y_\mathrm{p}) + c(z_i - z_\mathrm{p}) \tag{6}$$

Let

$$\begin{cases} \Delta x = x_\mathrm{i} - x_0 \\ \Delta y = y_\mathrm{i} - y_0 \\ \Delta z = z_\mathrm{i} - z_0 \end{cases} \tag{7}$$

The distance d_i was simplified

$$d_i = a\Delta x + b\Delta y + c\Delta z + d_0 \tag{8}$$

Therefore, only the projection distance of d_0 was required, and it can be used to calculate the projection distance of other voxels in the same volume plane using equation (8). The complex vector operation could be avoided and numerous repetitive operations could be reduced.

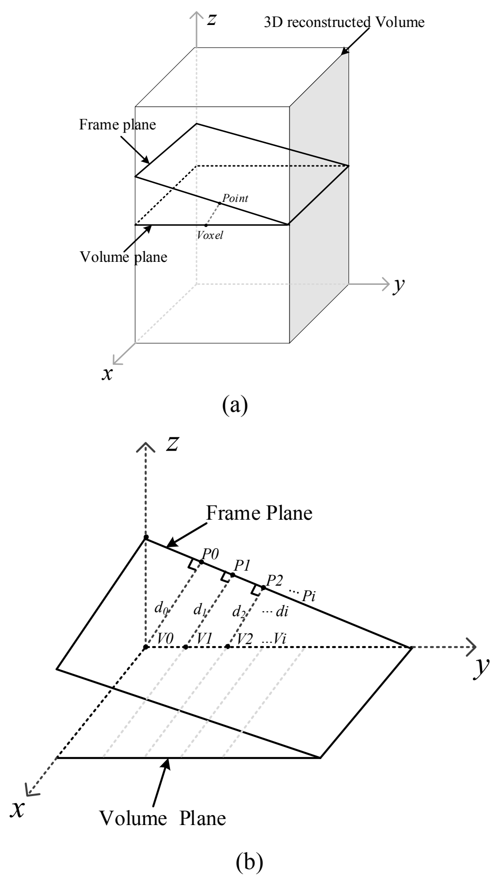


Fig. 2. FDP method in 3D reconstructed volume. (a) 3D reconstructed volume. A plane in the regular reconstructed volume and a frame plane around it were drawn. (b) The diagram of FDP. In this paper, FDP was used only in the same volume plane.

C. Multiple Plane Interpolation (MPI)

Voxel-Based Method MPI (VBM-MPI) was applied to assign intensity value to each voxel during 3D reconstruction by projecting the voxel into the surrounding planes to acquire the maximum intensity. The projection range was determined by the z coordinate values of each frame plane: using coordinate transformation, the coordinates of four vertices in each frame plane have been obtained. The maximum and minimum z values of these four vertices were located. If the z value of the selected voxel was in this projection range, then this frame was considered to be the plane surrounding the voxel.

The projection distances from the voxel to the surrounding planes were obtained using FDP method, and then the surrounding planes with the smallest projection distance were implemented for 4-neighbor maximum interpolation. The value of voxel was assigned by the maximum value of the calculated results.

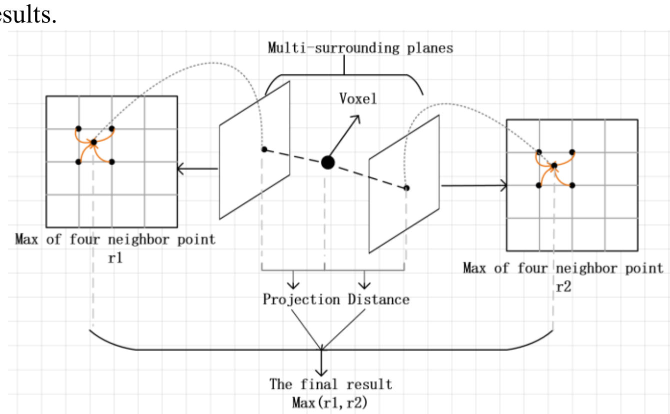


Fig. 3. MPI method. Multi-surrounding planes were used.

III. Data Analysis

A. Data Acquisition

Twenty data sets were acquired on scoliosis patients using SonixTABLET system. Among these patients, there were 4 males, 16 females. The Cobb angles of these patients was in the range of 11° to 42°, average angle was about $23^{\circ}\pm6.5^{\circ}$.

B. Average intensity and variance

The brightness and contrast of the reconstructed spine images using MPI and VNN methods were calculated respectively to compare the image quality.

The average intensity was used as the measure of image brightness and calculated as

$$m = \sum_{i=0}^{L-1} r_i p(r_i) \tag{9}$$

where r_i was the intensity levels in the range [0, L-1], $p(r_i)$ was the probability of the occurrence of intensity level r_i, L was the maximum intensity level and 256 in this experiment.

Intensity variance of the spine image was calculated as below to illustrate the image contrast

$$u = \sqrt{\sum_{i=0}^{L-1}(r_i - m)^2 p(r_i)} \tag{10}$$

A higher value of m and u indicated the higher brightness and better contrast for an image, respectively.

C. Numerical difference comparison

The numerical difference between CPM-VNN and FDP-VNN methods was expressed as

$$e = \frac{1}{N}\sum_{i=1}^{N} |c_i - f_i| \tag{11}$$

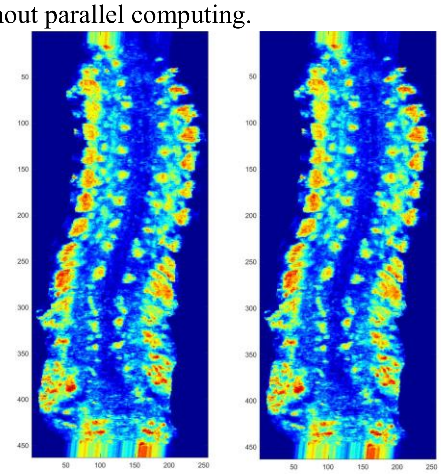
Where c_i and f_i was the volume voxel intensities reconstructed by CPM-VNN and FDP-VNN method respectively, and N was the number of voxels in the reconstructed volume.

IV. Results

A. Difference comparison and Computation cost

From Fig. 4, the reconstructed US spine images using FDP-VNN method showed no difference from CPM-VNN method. Fig. 5 shows the comparison result of numerical difference. The average value of difference e was about 0.0000101. The result of computation cost analysis is shown in Fig. 6. The reconstruction time was averagely reduced 111 seconds, about 80%, in comparison to CPM-VNN method.

All the reconstruction algorithms were written in Matlab 2018a without parallel computing.



(a) (b)

Fig. 4. Spine image of reconstructed volume. (a) FDP-VNN (b) CPM-VNN

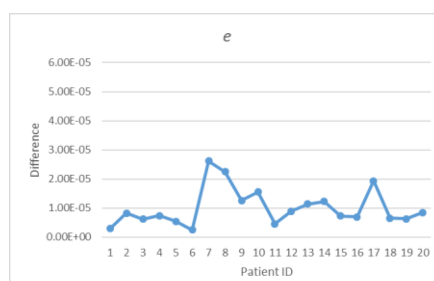


Fig. 5. Numerical difference comparison.

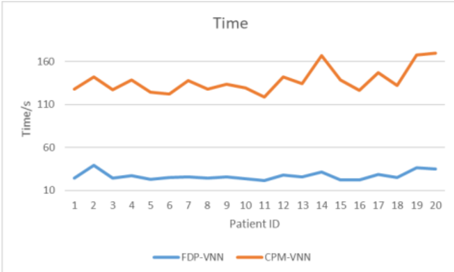


Fig. 6. Computation cost for FDP-VNN and CPM-VNN method.

B. Average intensity and variance

Fig. 7 and Fig. 8 shows average intensity m and variance u of the reconstruction spine images from different methods. When applying the MPI method, the brightness and contrast of all the reconstructed spine images were increased by 14% and 11% than VNN method, respectively.

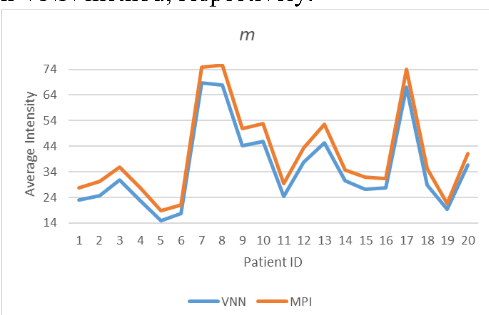


Fig. 7. Average density of VNN and MPI were recorded and compared.

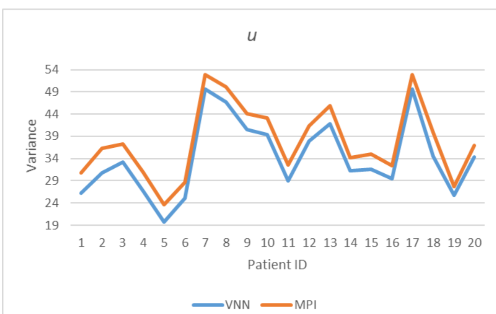


Fig. 8. Variance of VNN and MPI were recorded and compared.

V. Discussion

High-quality 2D images can only be obtained by fitting perpendicularly against the patient's sagittal curved back during manual scanning. Therefore, the general stacking method, which requires the probe strictly perpendicular to the coronal plane of patients, has difficulties to obtain detailed and accurate spine structure information. In this study, because the probe's Cartesian coordinates and attitude angles were recorded for coordinate transformation and reconstruction, a more flexible scanning pose could be used: the probe was able to rotate in any direction within a certain angle range to fit the patient's back according to the spinal curvature. By this way, the ultrasound probe could maintain good contact with patient's back, and the reconstructed images could retain more details of the spine structure.

FDP method can accelerate VNN projection calculation process without changing or deleting any source data. In addition, only the voxel in the same volume plane was considered when used FDP in this paper. Actually, due to the existence of Δz in equation (8), voxels in different volume planes can also be calculated using FDP. In that case, FDP will be more effective when the amount of data is larger.

The FDP method can also be applied to Pixel nearest-neighbor interpolation (PNN) [11]. Combined with the PNN method, the reconstruction time can be reduced to the range that satisfies real-time processing. Hence, the spine image will be able to be observed while scanning, which will significantly improve the efficiency of diagnosis.

VI. Conclusion

This paper proposed a new algorithm FDP to reduce reconstruction time. And the new MPI method is proposed to improve the quality of reconstructed spine images. The results demonstrated that the improved US imaging method with application of MPI and FDP could provide 3D spine images with faster reconstruction procedure and better image quality.

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