

Three dimensional nuchal translucency assessment using magnetic resonance reconstruction imaging

Lai Khin Wee^{1,2*}, Hum Yan Chai³ and Eko Supriyanto²

¹Biomedical Engineering Department, Faculty of Computer Science and Automation, Institute of Biomedical Engineering and Informatics, Technische Universität Ilmenau, 98684, Ilmenau, Thuringia, Germany

²Department of Clinical Science and Engineering, ³Department of Biomedical Instrumentation and Signal Processing, Faculty of Health Science and Biomedical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

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This study presents an open-source 3D reconstruction and visualization technique using Visualization Toolkit (VTK) on magnetic resonance image (MRI) for Nuchal Translucency (NT) assessment. Real time 3D reconstruction model can be achieved through a series of computation processes, which include DICOM (Digital Imaging and Communication in Medicine) sources manipulation, grey interpolations, ray casting, color and opacity transfer function, and volume rendering. Experimental simulations show that 3D measurements of NT provide higher accuracy and consistency of thickness measurement.

Keywords: Three dimensional (3D), Magnetic resonance image (MRI), Nuchal translucency (NT), Trisomy 21

Introduction

In early 1990s, prenatal screening for high risk chromosomal defects (Down's syndrome, triploidy, and Turner syndrome) was introduced by the combination of maternal age and thickness of Nuchal Translucency (NT) in fetus within 11.0 to 13.6 weeks of gestation^{1,2}. Formation of NT behind neck of fetus is due to a blockage of fluid in developing fetal lymphatic system and high peripheral resistance of placenta. Fetus with large NT thickness (> 3 mm) is reported³⁻⁵ to be associated with an increased risk for aneuploidy, congenital heart defect and other fetal anomalies. Early detection of abnormal findings in pregnancy is pivotal in establishing premature evaluation of chromosomes and possible structural defects on a targeted basis^{6,7}. In current obstetrics and gynecology practices, 3D medical images are more valuable and powerful fetal diagnostic tool⁸. Visualization of conventional 2D medical data is rather trivial while visualization of 3D volumetric data is not⁹; volumetric models, on the other hand, represent interior of the object and are acquired using computed tomography (CT) or magnetic resonance (MR) imaging, obtained as the result of a simulation or procedural definition. Volume-rendered

3D images of fetal anatomy are easily recognizable whereas conventional 2D images were made up of a series of 2D thin slices and only one slice can be seen at one time. Real-time 3D models allow visualization of all three orthogonal planes, which provide correct mid-sagittal view of fetus for accurate NT measurements¹⁰. Volumetric models are exceptionally general in biomedicine and engineering since one can visualize external and internal structure of objects.

This study presents implementing generic computing for 3D volumetric reconstruction using open-source visualization toolkits (VTKs) in order to assess the feasibility of performing a complete anatomical survey, including NT measurement using stored DICOM (Digital Imaging and Communication in Medicine) data acquired by MR imaging and irrespective of fetal position.

Experimental Section

VTK is a core resource for achieving rapid development of medical imaging tools with excellent structure and operation mechanism in a cost-effective way. It is strictly designed according to object-oriented concept and takes into account the simplicity of compiled programming and interpreter programming. To encounter compatibility and ease of maintenance and upgrades, VTK utilizes standard programming language

*Author for correspondence
E-mail: khin-wee.lai@tu-ilmenau.de

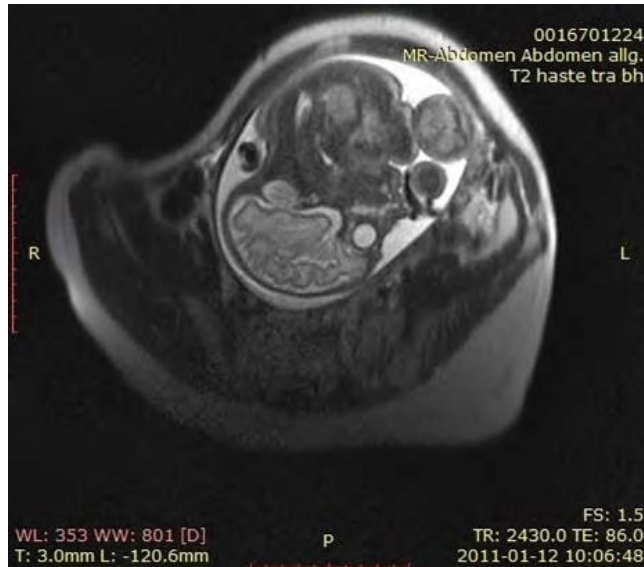


Fig. 1—Magnetic resonance (MR) images of fetus

environment (C++, TCL, Java or Python code) to encapsulate common visualization algorithms. It can be operated in Windows, UNIX, Linux or other operating systems independently. Developed 3D reconstructions and computerized rendering program were implemented on the basis of open-sources object-oriented VTK. Integrated IDE environment is Microsoft Visual Studio 8.0 in Window 7 using C++ language programming, where initial project file can be built using CMake 2.8.0 while configuring external libraries including OpenCV 2.2, VTK 5.4, FLTK 1.1, OpenIGTLink 1.0 and ITK 3.2. External libraries acts as parallel resources for VTK support classes. In present study, developed algorithm can achieve a variety of interactive visualization and measurement simulation by modifying part of VTK class, adjusting appropriate means of implementation and executing the code embedded in personalized coding. Since implementation of VTK class library possesses high flexibility and efficiency in real time interactive simulation, it was decided to employ C++ programming language for the proposed 3D MR images NT marker investigation.

MR Images Data Acquisitions

In proposed study, multi-frames of DICOM MR imaging data were collected for 3D volume reconstructions. Collected DICOM files were stored in 12 bits, and digital unsigned characteristic with grey-scale values (0 - 4096 pixels); total numbers of frames stored were 100 slices with Z spacing value (spacing between

slices) at 3 mm; resolution of image acquisition is 512 x 512 pixels with slices thickness 3 mm; MR imaging was performed using 1.5-T superconducting system (MAGNETOM Symphony; Siemens), with circular polarized (CP) coils.

Scanned subject in present study is a pregnant woman with 20 weeks gestation age. Volunteered consent of patient was obtained at Hospital in Jena, Germany. Target study marker is known as NT. Motivation of NT marker assessment is to classify the risk of fetus with Trisomy 21 during early pregnancy. A common way of NT marker thickness assessment during prenatal screening is to utilize 2D B-mode ultrasonic images. Ultrasonic assessment is prone to human error, and subject to inter and intra-observer variability¹¹⁻¹³, as deviation measurement can be larger, because operator changes the position of sagittal view during prenatal screening. Selecting correct sagittal plane is crucial, which is very subjective and highly personal experiences and technical skills dependent. A part of collected 2D slices of MR images is shown (Fig. 1) in present study, where patient's private information were anonymous.

Proposed 3D Reconstruction Algorithms

Implemented VTK classes in developed 3D reconstruction algorithms are pipeline mechanism. Volumetric reconstruction directly transforms 2D images on screen into 3D space samples, and restores original 3D data filed. Therefore, in this study, VTK and ray casting algorithms were applied together to construct a crossed scalable platform for 3D fetal volumetric formation (Fig. 2). Sources data are composed of multiple slices 2D MR images, which have to be converted into 3D voxel form. Subsequently, several filter classes in VTK will process the source data and its pixel will be mapped by *Mapper*. *Actor* play key role to represent drawing entity and the final volumetric will be displayed by *Renderer*. Defects of 3D volume reconstruction using VTK lie in the large amount of volume data and a long processing time.

In proposed algorithm (Fig. 3), volume rendering pipeline starts with data reader, *vtkVolume16Reader* class to receive case data, and call its subset function, *SetDimensions* and *SetSpacing* to define the dimension of data and determine pixel spacing (pixels interval must be in strict accordance with pixel interval of the original data set, otherwise it will create visual disparity results). Output of *vtkVolume16Reader* will access *vtkVolumeRayCastMapper*, which in turn forming 3D

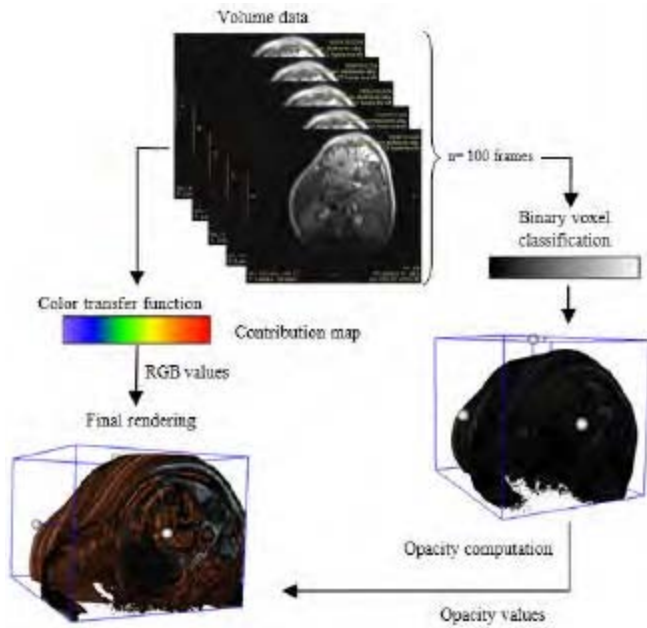


Fig. 2—Reconstruction of real-time 3D fetus volumetric model using multi-slices MR images

volumetric rendering. Color transfer function was implemented into *vtkVolumeProperty* to define mapping of voxels to an RGB color value. The function allows for specification of midpoint as a normalized distance between nodes, where midpoint refers to the region that function reaches the average of two bounding nodes. Since all

voxels are rendered opaque by default, therefore, one can introduce an Opacity transfer function to classify voxels and control their opacity with regard to their scalar value. Similar to Color transfer function, Opacity transfer function removes empty voxels (background image), and displays varying opacity for remaining voxels (organ or tissue of scanned subject). In present case, transfer functions are often attached to this attribute and used to define more specifically the appearance of volume properties, thus the function makes NT marker more apparently.

Employment of *vtkVolumeProperty* in representation of common properties associated with volume rendering. This class includes properties for determining the type of interpolation is to be opted when sampling a volume (color, scalar opacity, gradient opacity and shading parameters). If scalar opacity or gradient opacity is not set, the function is defined to be a constant value of 1.0; when a scalar and gradient opacity are both set simultaneously, opacity is defined to be the product of scalar opacity and gradient opacity transfer functions. Satisfactory mapping combined with *vtkVolumeProperty* is able to provide motivated 3D rendering scene.

3D Euclidean Distance Measurement

Proposed algorithm will convey mouse and keyboard input messages to *vtkPicker* through command updates.

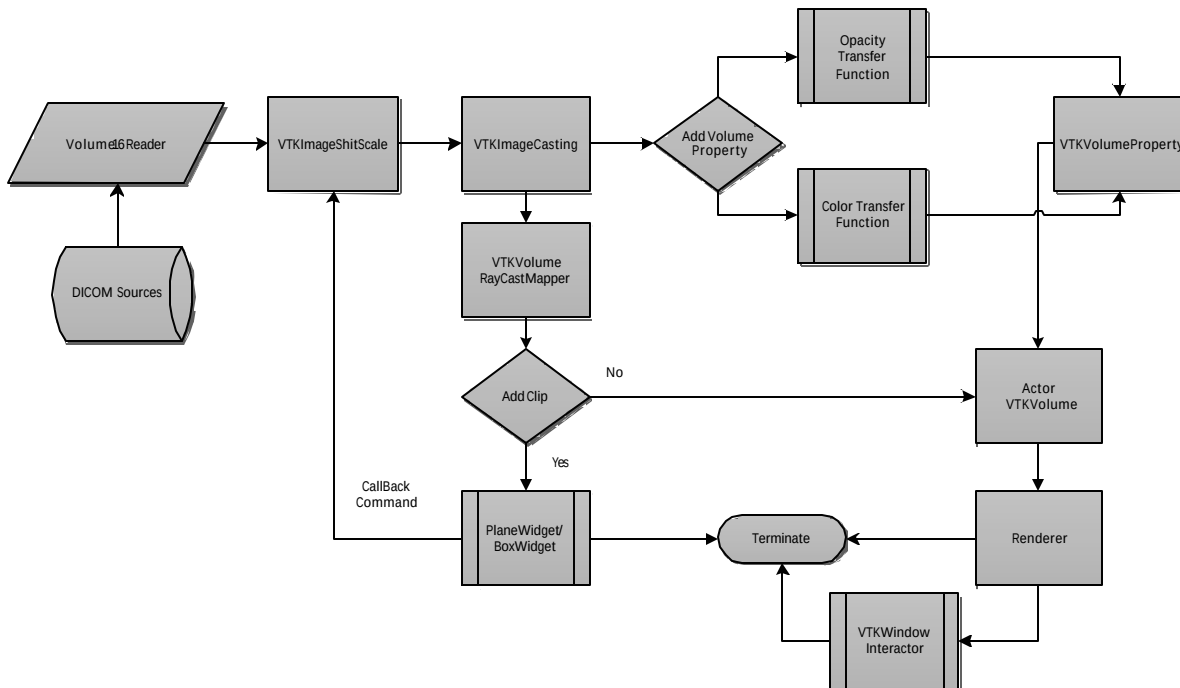


Fig. 3—Volume rendering pipeline in VTK

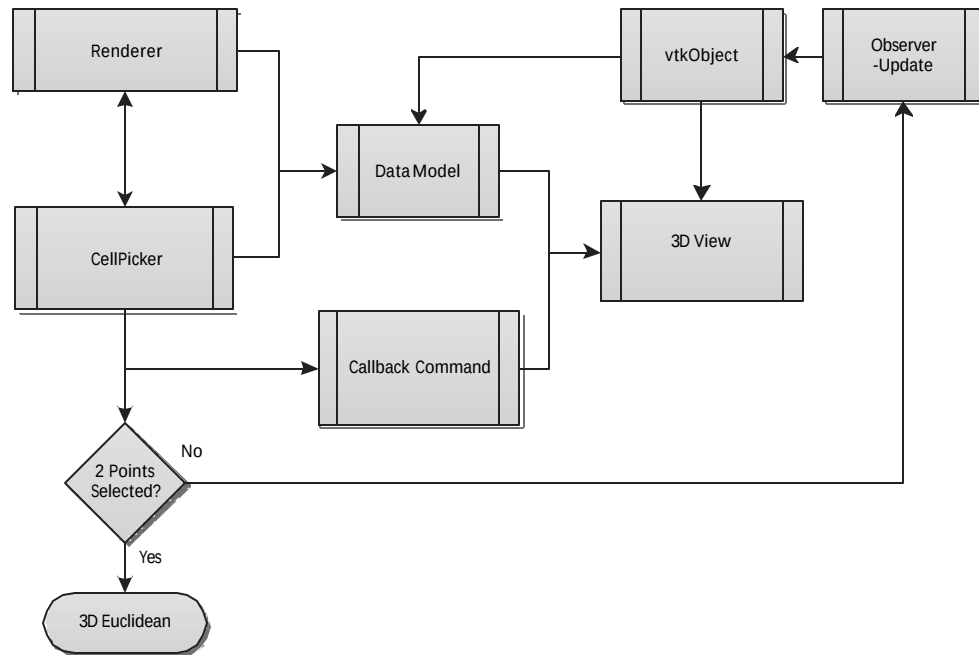


Fig. 4—Algorithm connection between *vtkPicker* and renderer data channel for 3D Euclidean computation

For 3D Euclidean distance computation (Fig. 4), two world coordinates are required. Point picker in computer screen is 2D coordinate, which has no direct relation with 3D objects, and therefore, conversion into world coordinate is necessary. Difference between 2D coordinate and world coordinate is that the latter contains depth information, reflecting depth of Z-coordinate spaces. In present study, selected 2D coordinate will be introduced as a straight line extended into Z spacing, which might penetrate 3D rendering objects. Straight line may intersect with more than one plane; therefore, several interactions are possible. Algorithm compares the distance of all intersecting points with initial point coordinates. Shortest distance calculated coordinates will be selected as 3D world coordinates. Assuming that selected two points are $P(x, y, z)$ and $Q(x, y, z)$, vector of PQ or QP can be computed as

$$\begin{aligned}
 E(p, q) &= \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + \dots + (p_n - q_n)^2} \\
 &= E(q, p) = \sqrt{\sum_{i=1}^n (q_i - p_i)^2} \quad \dots(1)
 \end{aligned}$$

E denotes Euclidean distance between point q and p with the vector line $\overrightarrow{qp}$. In present case,

$$E(p, q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_3 - q_3)^2} \quad \dots(2)$$

VTK rendering scene can be divided into two models (operator 3D widget model and renderer data model). To achieve the purpose of updating control information of operator 3D widget model on renderer data model, Callback command is required to activate the response accordingly. *AddObserver* acts as an external module to observe and reflects the real time data model status. In present study, computing 3D measurement of NT is accomplished using *vtkPicker* widget. Observer will convert *vtkPicker* data into geometrical and physical parameters in the rendering scene. Once *vtkPicker* updates its parameters, Observer will update the data simultaneously through establishing interface connection.

Results and Discussion

Results

Developed 3D reconstruction program has to display overall 3D volumetric pregnant mothers' abdomen, which provides comprehensive clinical image information for both internal and external body features. Considering the same organic tissue characteristics of pregnant mother and fetus, color transfer function plays key role to separate 3D fetus from mother's uterus, and adopts the rendering algorithm based on lighting, shading model,

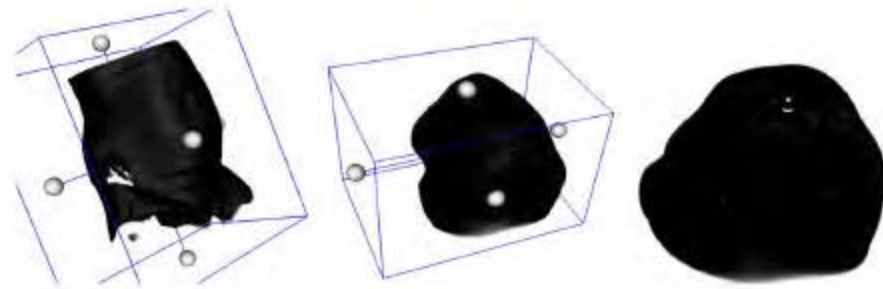


Fig. 5—Effect of color transfer function in 3D reconstruction simulation of volumetric pregnant women abdomen: a) bird-eye view; b) front view; and c) internal body features



Fig. 6—Effect of color rendering in 3D abdomen reconstruction with various view positions

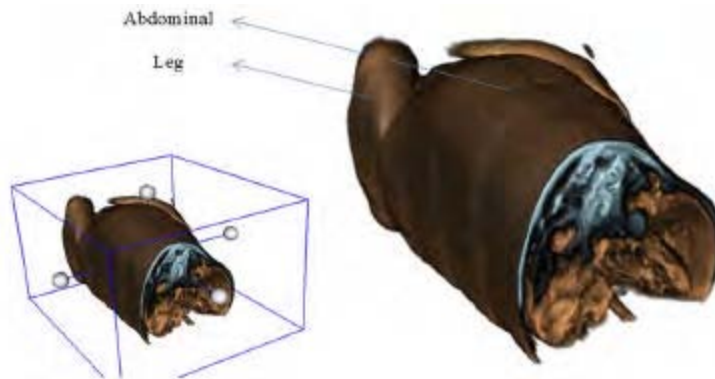


Fig. 7—Interactive virtual cutting plane selection with *vtkBoxWidget* for NT marker assessment

voxels' opacity and ray casting techniques. Initial rendering results without *vtkVolumeProperty* parameters (color and opacity transfer functions) are found to be inappropriate for NT marker assessment (Fig. 5). There is no distinct boundary visual segmentation of fetus from mother's organ or tissue. NT marker will not be seen as it appears at the same visual rendering level with its surrounding voxels. Fig. 6 shows final rendering scene of pregnant mother abdomen in various view positions.

For specific NT marker measurement based on reconstructed 3D model, virtual slider is necessary to cut the view plane and it is crucial to identify and display the best 2D image plane from 3D model. For instance, the best sagittal plane during prenatal screening is

favorable for physician to access NT marker; this is of prime significance that current manual 2D scanning method is restricted to acquire the correct scanning plane of 2D fetal images; if NT marker is not examined in an appropriate plane, measurement would be shorter or longer than normal or in worst case, it does not even exist. Also, if tested images are not in true sagittal view or coincide in suitable plane, NT marker might not appear in appropriate position. This difficulty remains unsolved in cases of current ultrasound prenatal screening protocol.

Based on current 3D MRI findings, physician is aware of their selected 2D plane position. Precise NT thickness measurements are feasible within 3D Euclidean distance measurement. Fig. 7 shows interactive virtual cutting

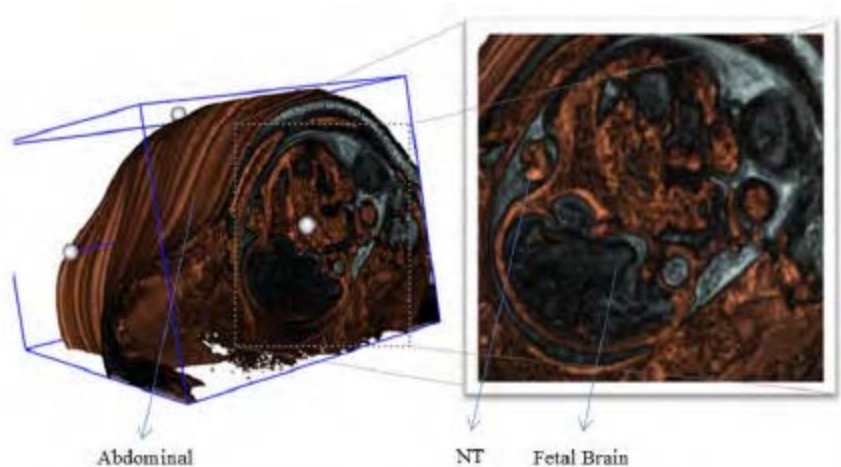


Fig. 8—3D fetus reconstruction in mid-sagittal resliced-view

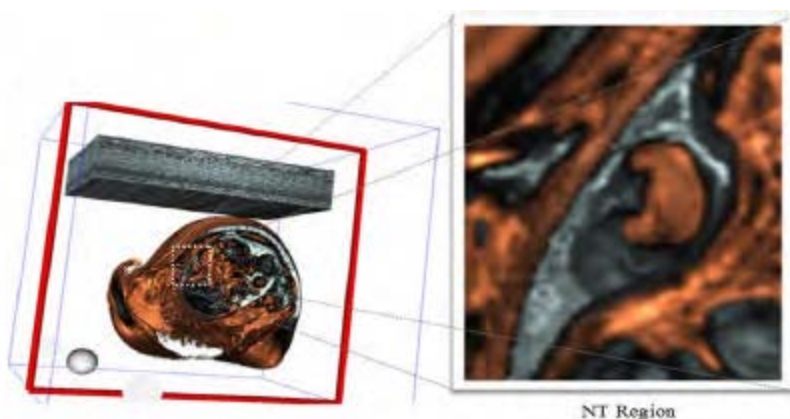


Fig. 9—3D fetus reconstruction in re-sliced view using *vtkPlaneWidget* and its respective NT thickness



Fig. 10—3D NT marker measurement based on two selected points by user manipulation using mouse click and movement triggered event

plane on restructured 3D fetus. At appropriate view plane position, 3D fetus can be seen with excellent NT marker visibility (Fig. 8). Close view of NT marker based

on 3D findings is also illustrated (Fig. 9). 3D NT marker measurement is shown (Fig. 10) based on two points selected corresponding to users' mouse click and movement triggered event. In cases where fetal position did not allow optimal visualization of fetal neck in 2D view, NT was easily obtained in 3D model regardless of fetal position. Obtained 3D images could then be manipulated to get all the desired views for NT measurement. Potential advantages in clinical practice are diagnostic time reduction and exceptional volume data storage, allowing measurements and anatomical survey to be repeated at any time.

Analysis of Results

3D NT marker thickness measurement has been studied based on the developed cell-pick command derived from 3D Euclidean distance. Trial measurements (10) were computed and analyzed by IBM SPSS 19 Statistics software. Statistics analyses show a mean and standard deviation of

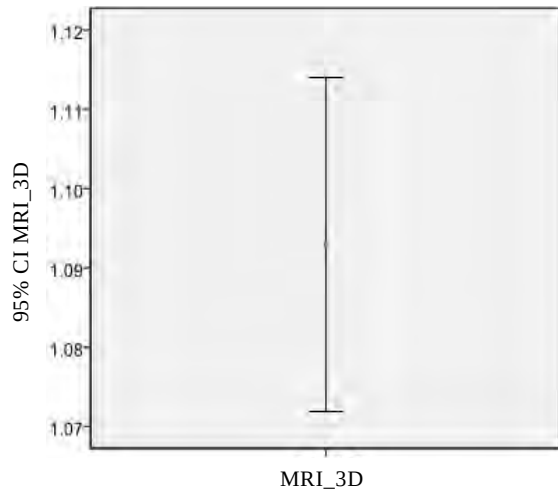


Fig. 11—Error bar of Nuchal Translucency for MRI_3D in mm (sample size, N=10)

1.0929 ± 0.02945 mm, which varies from 1.05561 mm (min.) to 1.13014 mm (max.). It can be seen that 95% confidence interval of MRI_3D for NT thickness measurements (Fig. 11) has small deviation from computed mean.

Discussion

This study demonstrated a feasible method to perform a comprehensive anatomical reconstruction of fetus using 3D MRI volumetric model. Although a complete anatomical survey was more frequently referred to real-time 2D images, examination of 3D volumes, irrespective of fetal position, provided detailed information for an inclusive review of fetal anatomy and NT thickness measurement. If analyzed image planes were not in appropriate position, anatomical marker will not be clearly shown, or it might be measured longer or shorter than its real length. Therefore, it was crucial to identify and display the best 2D image plane from 3D model. Volume rendering was achieved by using algorithms to vary opacity, transparency, and depth in projecting the volume information onto a single image. Fetal head, face, neck, anterior abdominal wall, and stomach could be examined using 3D volumes within suitable color and opacity transfer function. These structures represented main sites, in which fetal abnormalities can be seen in the first trimester. By referring to 2D images, anatomy of these structures could be examined more frequently, but difference compared with 3D volumes was not statistically significant. An advantage of 3D volume reconstruction is that obtained volumes can be

manipulated; by rotating image to a standard orientation (longitudinal, transverse and coronal), desired views can be achieved allowing 3D architecture to be examined in detail (Fig. 9). This is of central importance for measurement of fetal NT thickness for the best sagittal plane by 3D rather than 2D images.

Usage of 3D volumes, however, has some limitations: i) Image processing of the volume data using VTK is prone to consume additional time during examination; and ii) In case proposed 3D reconstructed views were comparable to the respective 2D images, a fine-tuning 3D model would be achieved by suitable color and opacity setting. However, this study shows that 3D volumes can provide maximum information in a very limited reconstruction time using VTK, thus reducing examination time. It also offers a new way of storing and conveying information. 3D volumes in digital format can be sent and examined by a specialist, allowing execution of a virtual scan instead of rescanning the patient. As a result, the pivot in 3D imaging (acquisition time and resolution), have improved the solution of current limitations and enhanced feasibility of 3D volume's routine practice in early pregnancy.

Conclusions

Volume data allow evaluation of a specific point in space from many different orientations by rotating, slicing, and referencing the slice to other orthogonal slices. It also allows for new volume-rendering displays that show depth, curvature, and surface images, which are not available with conventional 2D methods. Implementation of color and opacity settings in 3D models has demonstrated improvement in NT identification.

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