Volumetric Intravascular Ultrasound Visualization Using Shape-based Nonlinear Interpolation

Y. Rim\textsuperscript{1}, D. D. McPherson\textsuperscript{1}, and H. Kim\textsuperscript{1}
\textsuperscript{1}Department of Internal Medicine, The University of Texas Health Science Center at Houston, Houston, Texas, USA

Abstract - Intravascular ultrasound (IVUS) has been utilized primarily to evaluate plaque formation of the coronary and carotid arteries. Several studies have reported three-dimensional (3D) IVUS image reconstruction algorithms to better provide anatomical information of the arterial wall structure. However, most of previous 3D IVUS studies provided unrealistic morphology and acoustic information in the arterial wall due to the low quality of input image data and the linear interpolation algorithm. In the present study, we proposed an improved algorithm to generate intermediary slices using a shape-based nonlinear interpolation method, and created volumetric 3D IVUS images using radio frequency (RF) raw IVUS signal data of a porcine femoral artery. Both arterial structure and acoustic intensity information of the intermediary slice were created by the cubic spline interpolation. This novel volumetric 3D IVUS visualization strategy has the potential to improve vascular ultrasound imaging for better determination of atheroma distribution in the arterial structure.

Keywords: Intravascular ultrasound (IVUS), Shape-based nonlinear interpolation, Volumetric visualization, Three-dimensional ultrasound, Intermediary slice, Acoustic intensity.

1 Introduction

Clinical procedure of the intravascular ultrasound (IVUS) has been utilized to identify the pathological alterations of atherosclerotic plaque by evaluating acoustic intensity information of the cross-sectional images of the artery [1-3].

Comparison of the relatively proximal vascular segment to distal segments in the standard clinical procedure of IVUS requires a repeated review of sequentially recorded cross-sectional two-dimensional (2D) IVUS images to determine the spatial relation of the regions of interest (ROI) [1]. Therefore, it is often difficult for clinicians to determine the type and morphology of atherosclerotic plaque or lesion within the arterial wall [4]. IVUS imaging can demonstrate a series of cross-sectional images of the arterial wall structure in the longitudinal direction using a pull-back device with IVUS catheter. This sequential imaging of 2D IVUS images can provide three-dimensional (3D) IVUS visualization.

Two methodologies have been commonly utilized to create 3D IVUS imaging. A popular method is simply to generate a longitudinal cut-view of the artery showing acoustic intensity information of the arterial wall along the blood flow direction [5]. However, this method only creates another 2D image inside the arterial wall along the longitudinal direction, and thus cannot provide comprehensive information pertaining to spatial plaque distribution over the entire arterial structure. The other popular technique for 3D IVUS is to focus on creating anatomically realistic arterial border of the lumen and media-adventitia contour using a smooth 3D surface reconstruction algorithm [6]. But detailed information of acoustic intensity distribution through the arterial wall structure is discarded in this technique once surface rendering is performed.

Several studies have reported three-dimensional (3D) IVUS image reconstruction algorithms to better provide anatomical information of the arterial wall structure and overcome the limited 3D visualization capability of currently available commercialized IVUS systems [1, 6-8]. An early study demonstrated a computer-automated 3D reconstruction method to generate a tangible format with a series of 2D IVUS images using linear interpolation method, and compared the reconstructed 3D images to the sequential images obtained during IVUS examination [1]. Another study introduced a shape-based interpolation method of multi-dimensional grayscale images to create coarser and finer discretized images to combine images of the same ROI from two independent image modalities [9]. Although previous studies on 3D IVUS reconstruction presented 3D images of arterial structure, most of the 3D images had unrealistic morphology and acoustic information in the arterial wall due to the linear interpolation to create intermediary slices and the low quality of input image data from video tapes.

We have recently proposed a volumetric 3D IVUS visualization methodology for early and inflammatory arterial atheroma characterization [10]. Volumetric 3D images can provide both visualization of the 3D arterial structure and acoustic intensity distribution for plaque and atheroma detection. However, linear interpolation was utilized in the volumetric 3D IVUS visualization. In order to
quantitate the geometric characteristics of plaque volume and atheroma formation, an improved volumetric 3D IVUS visualization method is required to more distinctly demonstrate acoustic intensity information overlaid on a 3D structure image of the artery.

In the present study, we proposed an improved algorithm to generate intermediary slices between adjacent slices using the shape-based nonlinear interpolation method and create a volumetric 3D IVUS image using raw radio frequency (RF) IVUS signal data of a porcine femoral artery. Since the distance between neighboring pixels in a cross-sectional image is usually smaller than the distance between the images leading to non-isotropic voxel dimensionality between neighboring pixels, this often yields deterioration in the quality of the 3D image [11]. Therefore, increasing the level of discretization between the acquired 2D IVUS images may provide improved quality of the consequent volumetric 3D IVUS image of the arterial structure. We compared the improved volumetric 3D IVUS images created by the proposed shape-based nonlinear interpolation method with those created by the linear interpolation in previous studies.

2 Materials and Methods

We developed a straightforward algorithm to convert a series of raw RF IVUS signal data into a fully volumetric 3D visualization (Fig. 1). The entire protocol including 2D image reconstruction from raw RF signal data, border tracing, segmentation, sequential alignment of 2D images, and intermediary slice generation was conducted in a single image processing platform. Volumetric visualization of 3D IVUS images was performed using ImageJ, an open-source Java-based image processing software provided by the National Institutes of Health (NIH).

2.1 Volumetric 3D IVUS Visualization

An atherosclerotic Yucatan miniswine atheroma model (20 kg, Sinclair Research Center Inc., Columbia, MO) was used. The animal protocol was approved by the Institutional Animal Care and Use Committee of The University of Texas Health Science Center at Houston. Following full anesthesia, the right femoral artery was exposed with groin incisions, and an arteriotomy was performed. A 5F sheath was inserted in the femoral artery. A high frequency (20 MHz, 3.5F) IVUS imaging catheter was utilized connected to a Volcano s5i IVUS Imaging System (Volcano Co, Rancho Cordova, CA). The IVUS catheter was inserted through the arterial segment past the region of interest. The IVUS catheter was withdrawn using an automatic pullback device at a constant speed of 0.5 mm/s, while IVUS images and raw RF signal data of the arterial segment were continuously recorded. A total of 256 scan lines with 1,024 sampling data per each scan line were recorded (dynamic range of 40-60 dB). Since there was no curvature in the arterial segment evaluated, it was assumed that the direction of pullback of the IVUS catheter was parallel to the longitudinal direction of the artery. Electrocardiogram (ECG) was synchronized with IVUS imaging in real time thus serving as a time reference for systolic and diastolic phases while recording the RF IVUS signal data. In order to construct 2D grayscale images from the raw RF signal in beam space, the pre-determined cutoff threshold (1,050 mV) was applied to the RF signal data to create 2D IVUS images comparable to that directly generated from the Volcano IVUS system. The enveloped amplitude (i.e., acoustic intensity) under the threshold value was utilized to reconstruct grayscale images in beam space. In this beam space, x- and y- axes refer to radial and circumferential directions, respectively.

The reconstructed image in beam space was transformed to the Cartesian coordinate system for standard vascular imaging. A graphical user interface (GUI)-based image processing system was developed for interactive tracing and segmenting procedure under MATLAB (Mathworks Inc., Natick, MA) platform.

Figure 1. Protocol of the volumetric 3D IVUS visualization
The endothelium/atheroma border and the outer edge of the dense adventitia in each image were manually segmented, and a series of segmented RF data set in the ROIs were placed in tomographic sequence for intermediary slice generation. The extracted RF signal data of the ROIs were utilized to generate intermediary slices using the shape-based nonlinear interpolation method.

2.2 Shape-based Nonlinear Interpolation

Fig. 2 demonstrates the algorithm to generate intermediary slices between 2D IVUS image slices (collected and segmented from original raw RF data) using the shape-based nonlinear interpolation. The basic concept in this shape-based nonlinear interpolation method is to interpolate the vascular structure geometry using three neighboring slices (Step 1, Fig. 2). We first applied the cubic spline interpolation method to obtain the segmented ROI of the arterial wall along the longitudinal direction using the traced 20 cross-sectional IVUS image data. The interpolation was performed on the 256 scan lines along the circumferential direction between original slices, and the boundary information was calculated along the same 256 scan lines in the intermediary slices. Next, nonlinear acoustic intensity interpolation was performed (Step 2, Fig. 2). The segmented ROI of the arterial wall in each slice contains acoustic intensity distribution profile. This information was utilized to interpolate acoustic intensity distribution within the ROI in the consequent intermediary slice using the cubic spline interpolation.

We collected RF data set of the segmented ROIs in 20 IVUS images with a distance of 0.5 mm between images to generate 5 intermediary slice images between adjacent images resulting in a total of 115 cross-sectional images along the longitudinal direction. Acoustic intensity information in the 2D IVUS image data was preserved in the RF data of the segmented ROIs in each slice. In order to interpolate RF data (i.e. acoustic intensity distribution) within the segmented ROIs between 20 slices in a 3D space, we utilized the cubic spline interpolation considering the nonlinearity of the vascular structure geometry and acoustic intensity in the arterial wall. The essential idea of the interpolation is to fit a piecewise function of the form

\[
S(x) = \begin{cases} 
  s_1(x) & \text{if } x_1 \leq x \leq x_2 \\
  s_2(x) & \text{if } x_2 \leq x \leq x_3 \\
  \vdots \\
  s_{n-1}(x) & \text{if } x_{n-1} \leq x \leq x_n
\end{cases}
\]  

(1)

where \( s_i \) is a third degree polynomial defined by

\[
s_i(x) = a_i(x-x_i)^3 + b_i(x-x_i)^2 + c_i(x-x_i) + d_i
\]

for \( i = 1, 2, ..., n-1 \).

The first and second derivatives of these n-1 equations are fundamental to this process, which are

\[
s_i'(x) = 3a_i(x-x_i)^2 + 2b_i(x-x_i) + c_i
\]

and

\[
s_i''(x) = 6a_i(x-x_i) + 2b_i
\]

for \( i = 1, 2, ..., n-1 \).

Using the following four stipulations, we can determine the weights for n-1 equations.

1. The piecewise function \( S(x) \) will interpolate data points.
2. \( S(x) \) will be continuous on the interval \([x_1, x_n]\).
3. \( S(x) \) will be continuous on the interval \([x_1, x_n]\).
4. \( S(x) \) will be continuous on the interval \([x_1, x_n]\).

Figure 2. Intermediary slice generation using the shape-based nonlinear interpolation.
Detailed information of the shape-based nonlinear interpolation procedure is described in Fig. 3. The first step is to register the original 2D IVUS slices in the global coordinate, and align the centroids of the arterial structure on each slice to a centerline. Considering the distance between slices, the interpolated curvatures were created on each of the 256 scan lines by means of the cubic spline interpolation method. Radial distances $r(x_1)$, $r(x_2)$ and $r(x_3)$ on the slice #1, #2, and #3, respectively, were utilized to calculate $r(x)$ on the interpolated intermediary slice. Both inner and outer boundary points of the arterial wall structure on each scan line were generated on the intermediary slices. Since there were a varying number of data points between these two boundary points of the arterial wall structure on each scan line, it is necessary to create the same number of acoustic intensity data points within the ROI along each scan line. Therefore, the acoustic intensity data within the ROI on each scan line were resampled with 100 data points allowing generation of the same number of discretized acoustic intensity data points in the corresponding ROI on the intermediary slices. Nonlinear interpolation of the acoustic intensity values at 100 data points on 256 scan lines was performed to complete the shape-based nonlinear interpolation for both vascular structure geometry and acoustic intensity information.

3 Results

3.1 Intermediary Slice Generation Using the Shape-based Nonlinear Interpolation

Fig. 4 shows the original slices of the porcine femoral artery from the raw RF IVUS data and the consequent intermediary slices created by using the developed shape-based nonlinear (left) and linear interpolations (right). The first, third and fourth row images indicate three original slices, and the second row images demonstrate the intermediary slices between slice #1 and #2 using two different interpolation methods.

The linear interpolation method demonstrated a blur intermediary image calculated by a simple averaging function between the two adjacent slices for both segmentation and acoustic intensity information resulting in an unrealistic image of the arterial intermediary slice. The shape-based nonlinear interpolation method developed in this study, however, provided a clearly reconstructed intermediary slice image with accurately predicted segmentation and acoustic intensity information calculated based on the corresponding information of the three neighboring original image slices. The shadow effect in the linear interpolation method was not observed in the shape-based nonlinear interpolation method. Shape-based nonlinear interpolation method can, therefore, provide better interpolation outcome and generate more realistic geometry of the arterial segment with accurate acoustic intensity values.

![Figure 3. Schematic diagram of the shape-based nonlinear interpolation](image)

![Figure 4. Intermediary slice generation using two different interpolation methods](image)
3.2 Volumetric 3D IVUS Visualization

Volumetric 3D IVUS images reconstructed by the developed shape-based nonlinear interpolation and the conventional linear interpolation methodologies are demonstrated in Fig. 5. Both volumetric 3D reconstruction models were created utilizing the raw RF IVUS signal data from a total of 20 slices, and presented along the longitudinal direction to facilitate 3D visualization. It is clearly observed that the shape-based nonlinear interpolation method provided better demonstration of the 3D structure of the arterial segment and more realistic acoustic intensity distribution compared to the linear interpolation method.

![Half-cut](image1)

![Full volume](image2)

(A) Shape-based nonlinear interpolation

![Half-cut](image3)

![Full volume](image4)

(B) Linear interpolation

Figure 5. Volumetric 3D IVUS visualization using the shape-based nonlinear and linear interpolation methods

In particular, the half-cut view of the 3D IVUS image created by the shape-based nonlinear interpolation provided excellent information with smooth acoustic intensity distribution over the luminal surface of the arterial wall where plaques are usually observed (Fig. 5A top). The full volume view of the arterial segment well described the boundary surface of the outer edge of the dense adventitia with corresponding acoustic intensity distribution along the longitudinal direction (Fig. 5A bottom).

On the other hand, the linear interpolation method poorly demonstrated the vascular structure geometry with noticeable discontinuity between slices and striped acoustic intensity distribution in both half-cut and full volume images (Fig. 5B). Due to the blur images with gray shaded areas in the intermediary slices, the morphology of lesion along the longitudinal as well as circumferential directions were not correctly demonstrated leading to unrealistic volumetric visualization of the arterial structure.

4 Discussion

Conventional cross-sectional images of an arterial structure from most of the commercialized IVUS imaging systems can hardly provide comprehensive information pertaining to complex spatial distribution of lesions such as atherosclerosis in a 3D space. Volumetric 3D IVUS visualization of the arterial structure can provide a powerful tool to overcome this limited spatial demonstration issue with 2D IVUS alone. Visualization of both 3D morphology of the arterial structure and corresponding acoustic intensity distribution within the arterial segment can help better understand the extent and stage of plaque formation.

Previous studies have established 3D visualization methods of the vascular structure using 2D IVUS images captured from analog video tapes [1, 6-8]. However, the volumetric 3D reconstruction in these studies demonstrated images with a poorly low resolution as non-isotropic voxel dimensionality was used due to the smaller distance between neighboring pixels than the distance between slice images along the longitudinal direction (blood flow direction). In general, the longitudinal resolution of commercial IVUS imaging systems is much lower than that of the 2D cross-sectional IVUS images. This often yields deterioration in image quality. In order to provide better visualization of volumetric 3D IVUS images, it is imperative to improve interpolation techniques for intermediary slice generation. In the present study, we developed a novel volumetric 3D IVUS visualization strategy to create intermediary slices between original IVUS image slices using the shape-base nonlinear interpolation method.

An important aspect of the volumetric 3D IVUS image reconstruction is to improve image quality of the 3D visualization of the arterial structure. Poor image quality may reduce the accuracy of 3D quantitation and visualization of plaque formation. In most of previous studies, low image resolution has hampered 3D IVUS visualization. In this study, we utilized raw RF IVUS signal data with high resolution to generate intermediary slices between the IVUS image data.
The shape-based nonlinear interpolation method using the cubic spline algorithm was proposed to create vascular structure geometry and acoustic intensity distribution information in intermediary slices between neighboring 2D IVUS slice images. The intermediary slices clearly demonstrated accurately predicted segmentation and acoustic intensity information of the arterial segment. Volumetric 3D IVUS reconstruction with the shape-based nonlinear interpolation provided better visualization of morphology of lesion in the arterial wall with realistic acoustic intensity distribution. In particular, the longitudinal half-cut view of the arterial structure demonstrated excellent continuity between original IVUS slices with respect to both geometry and acoustic intensity information.

There are some limitations in the present study. Manual tracing was performed to segment the endothelium/atheroma border and outer edge of the dense adventitia on the cross-sectional 2D IVUS images along the artery. We are developing a semi-automated image segmentation algorithm for more accurate volumetric 3D visualization and quantitation. In addition, we were not able to perfectly adjust the rotational offset of IVUS catheter probe which can occur during pullback recording. Volumetric 3D IVUS image can be affected by this rotational offset effect.

In summary, we have successfully developed an improved 3D reconstruction algorithm using the shape-based nonlinear interpolation method, and performed volumetric 3D IVUS visualization of a porcine artery. A superiority of the shape-based nonlinear interpolation method over the conventional linear interpolation algorithm in terms of the quality of volumetric 3D IVUS visualization was clearly demonstrated. This novel volumetric 3D IVUS visualization strategy has the potential to improve vascular ultrasound imaging for better determination of atheroma distribution in the arterial structure. Moreover, precise volumetric 3D visualization with accurate acoustic intensity information may improve advanced molecular ultrasound imaging of atheroma components.

5 References


