Respiratory Motion Correction for Geometrically Correct Three-dimensional Reconstructions of Coronary Arteries

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Abstract

By fusing intravascular ultrasound (IVUS) with biplane angiography, geometrically correct three-dimensional (3D) reconstructions of coronary arteries can be produced. Spatio-temporal localization of the IVUS transducer is challenging due to cardiac and respiratory motion. Since cardiac motion can be eliminated via ECG-gating, the aim of this project was to develop a scheme for respiratory motion correction of the 3D transducer path.

A model-based technique was used to eliminate respiratory motion in transducer paths reconstructed from biplane angiography in three pullbacks. Although biplane angiography is the current standard, alternate technology for spatio-temporal localization, will potentially allow inexpensive, real-time 3D reconstruction with no ionizing radiation. The model-based respiratory motion correction has the potential to aid in real-time clinical 3D reconstruction of coronary artery anatomy.

1. Introduction

Intravascular ultrasound (IVUS) has become increasingly recognized as a powerful tool with the potential to characterize atherosclerotic lesion geometry and composition. While angiography provides two-dimensional (2D) projections of the complex coronary arterial tree, IVUS provides direct visualization of the arterial wall. However, there is no indication of spatial arrangement or orientation of tomographic IVUS image slices.

Performing an IVUS pullback, where the catheter is withdrawn from a distal position during imaging, can generate sequential image data sets. Early attempts at 3D reconstruction simply involved stacking these images. However, the natural curvature of the coronary arteries was not reflected in these reconstructed models. To provide spatial arrangement, orientation, and curvature, previous researchers have developed techniques to combine IVUS and angiography. Two main procedures for fusion of IVUS and biplane angiography have been used: either using a set of pre-pullback angiograms to define the path of the transducer pullback [1, 2] or tracking the transducer during the pullback [3].

The assumption that the transducer follow the path of the catheter outline in the pre-pullback angiograms may not hold for *in vivo* applications due to cardiac and respiratory motion. There also may be non-uniform distances between IVUS image frames, even while using constant-speed automated pullback devices [1]. These assumptions are not necessary for spatio-temporal tracking of the IVUS transducer during the pullback. However, the cardiac and respiratory motion complicate this approach *in vivo*. Since the cardiac motion can be overcome using an ECG-gated acquisition, the aim of this study was to investigate the elimination of respiratory motion from 3D transducer paths.

2. Methods

We have previously developed a technique for fusing IVUS and biplane angiography for geometrically correct 3D reconstruction of coronary arteries [3, 4]. The process used spatio-temporal tracking of the IVUS transducer to provide the 3D backbone for placement of the outlines detected in the IVUS images.

2.1. 3D reconstruction

There are three steps in the reconstruction process. First, the path of the IVUS transducer was determined using biplane angiography. Then, the IVUS frames acquired at all time points were segmented to determine luminal and external elastic membrane (EEM) borders. Finally, the correct angular orientation around the transducer path was determined, and the IVUS contours were placed perpendicular to the transducer trajectory, completing the reconstruction.

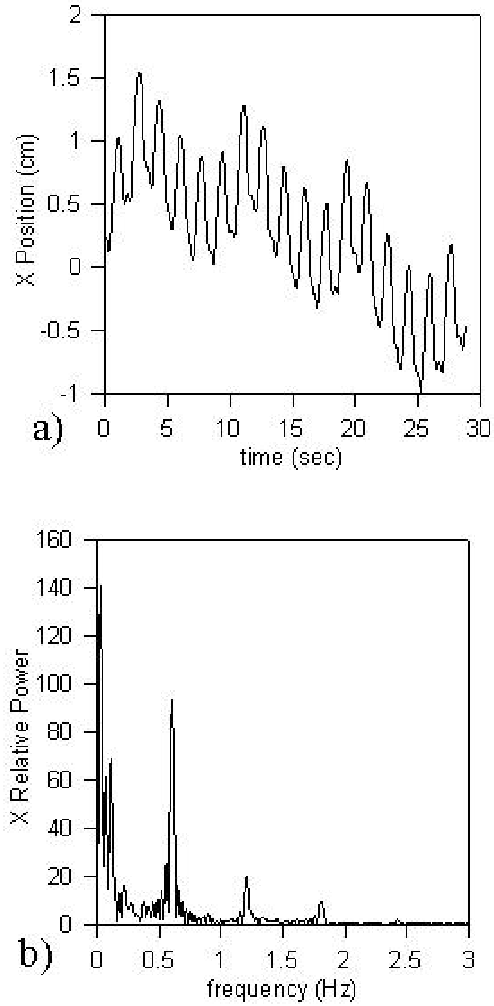

Figure 1. (a) Plot of transducer X position vs. time and (b) its fast Fourier transform.

The biplane system was calibrated using a purpose-built calibration object with 8 radiopaque markers of known coordinates. The transducer was manually located in each pair of angiographic images. Using transformation matrices derived from the calibration object, these points were projected to a unique point in three-dimensional space. The sequence of frames generates the sequence of time points and the location of the transducer in three dimensions at each of these points.

The luminal and medial-adventitial borders were segmented with a novel 3D segmentation method. Previous studies by our group have validated this method with both ex vivo and in vivo IVUS images in which the algorithm detected the borders as well as a trained IVUS technician [5].

To determine the proper angular orientation of the IVUS-derived contours, the detected 3D luminal outline was projected onto the two-dimensional contrast angiogram. The projected and the actual angiographic lumens, obtained manually, were compared and an error was calculated. The lumen was rotated 1°and the projection and fit calculation were repeated. This was done through all 360°, and the correct rotational orientation was chosen for each slice as the angle with the minimum error.

The luminal and EEM contours from each IVUS slice, corresponding to the time acquisition points located with biplane angiography, were placed perpendicular to the transducer trajectory with the center of the IVUS image on the path point. The contours for each IVUS image were also rotated by the amount specified by the best-fit determination. The reconstruction technique was previously validated in human and porcine *ex vivo* arteries [3].

2.2. Respiratory motion correction

When tracking the IVUS transducer *in vivo*, motion associated with the cardiac cycle and the respiratory cycle complicate the reconstruction of the transducer path. Three *in vivo* pullbacks, including one left anterior descending artery and two circumflex arteries were performed and complete 3D paths were reconstructed using continuous localization of the transducer by biplane angiography. Figure 1 shows an example plot of the transducer X position versus time for a 30 second pullback. The fast Fourier transform (FFT) of this signal is also plotted.

A model of the X, Y, and Z component motion of the transducer during IVUS pullbacks was constructed. Each component consisted of sinusoids with frequencies for the curvature, the cardiac motion, and the respiratory motion. The z component model is given by Equations 1-4.

$$z_{curv} = \alpha_{curv} \cos(2\pi f_{z,curv} t - \Phi_{z,curv}) \quad (1)$$

$$z_{resp} = \alpha_{z,resp} \cos(2\pi f_{z,resp} t - \Phi_{z,resp}) \quad (2)$$

$$z_{card} = \alpha_{z,card} \cos(2\pi f_{z,card} t - \Phi_{z,card}) \quad (3)$$

$$z = z_{DC} + z_{curv} + z_{resp} + z_{card} \quad (4)$$

There are 10 parameters for each axis, including three amplitudes, three frequencies, three phase shifts, and the DC offset. After estimating the parameters of the z-axis

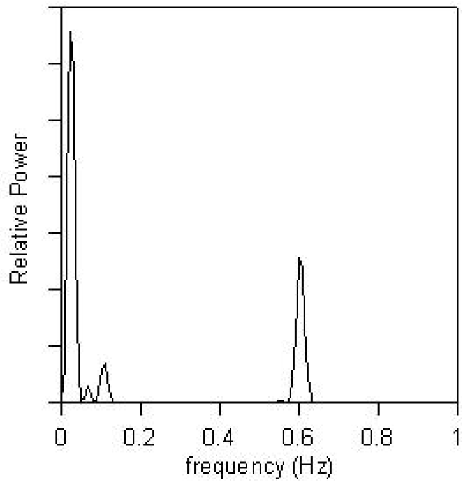

Figure 2. Combined frequency spectra demonstrating three peak frequencies.

model, the z axis path of the transducer path, with only the curvature term can be constructed. The parameters were estimated using a trust region reflective Newton algorithm. To help ensure convergence, the initial frequency values input to the parameter estimation technique were approximated by using the FFT's of the x, y, and z components. The frequency domain signals were multiplied to enhance the three peak frequencies, which were assumed to be the curvature, respiratory, and cardiac frequencies. A plot of the combined frequency spectra is shown in Figure 2, demonstrating the peaks. To determine the frequencies with relative peaks, a threshold was lowered until three values exceed it. The frequency locations of these three values were used as the initial frequencies for the parameter estimation.

3. Results

Three pullbacks, including one left anterior descending artery (LAD) and two circumflex arteries, were performed and complete 3D paths were reconstructed using continuous localization of the transducer by biplane angiography. The agreement between the model and the data was assessed by calculating the squared 2-norms of the residual. A summary of the results is shown in Table 1.

Table 1. Summary of results for three clinical pullbacks.

Artery	Residual Norm
Circumflex 1	11.52
Circumflex 2	33.65
LAD	16.59

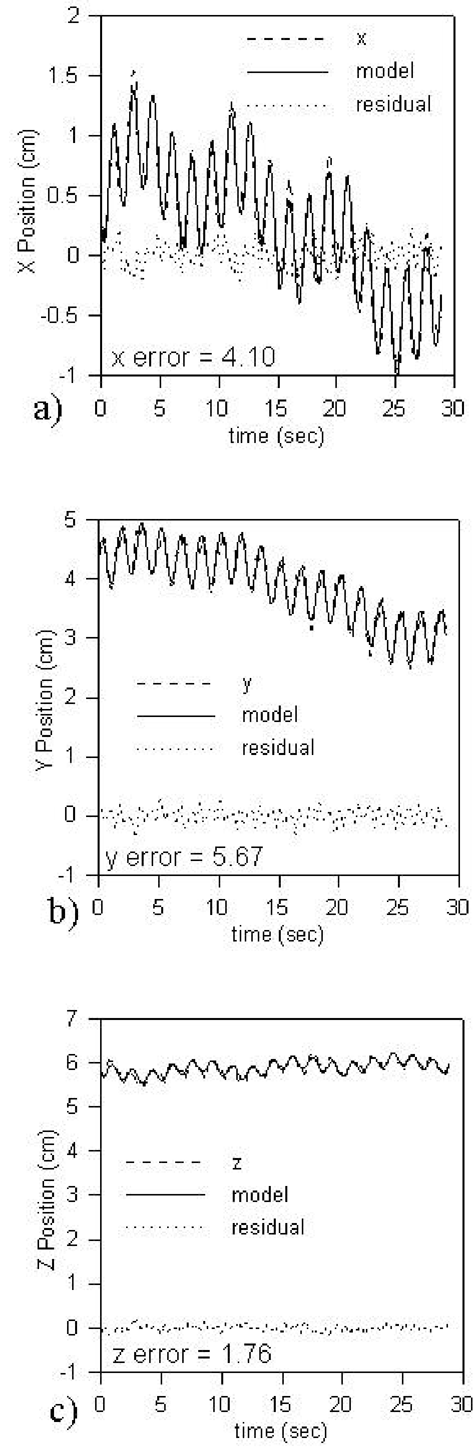

Figure 3. Plots of the signal, the model, and the residual for a clinical pullback. The errors for each component are also presented. Note the different scales on the plots.

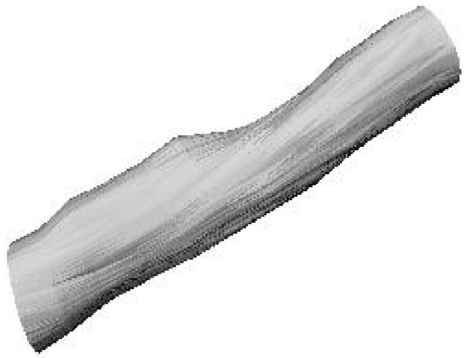

Figure 4. A segment of 3D reconstructed lumen using a motion-corrected transducer path.

As shown in Table 1, the model fit well to all three clinical pullbacks. Figure 3 shows the x, y, and z axis data for the Circumflex 1 pullback. The x error was 4.10, the y error was 5.67, and the z error was 1.76.

A short segment of the 3D reconstructed lumen created using the motion-corrected path of Circumflex 1 is shown in Figure 4.

4. Discussion and conclusions

A model-based technique for respiratory motion correction of 3D reconstructed IVUS transducer paths was investigated. 3D path data from the model using the estimated parameters fit well to experimental data derived from pullbacks using biplane angiography transducer tracking.

Although the model-based motion correction method shows promise, the preliminary assessment performed leaves several questions for future investigation. The technique appeared effective for three *in vivo* pullbacks. However, a much larger number of pullbacks in patients is desired for a more thorough assessment of the model's ability to approximate the 3D motion of the transducer.

Acquiring more data from patients could also help answer other questions. Although low residuals were achieved with the model using the current experimental data, the relationship between the residual and the accuracy of the resulting 3D reconstruction is not known, i.e. how well does the fit need to be for an accurate resulting geometry. More *in vivo* data could elucidate this relationship, but phantom studies could provide a gold standard.

For real-time 3D reconstruction of coronary artery anatomy, minimal post-processing is desirable. The model-based correction scheme is a post-processing step. An alternate is respiratory gating (along with cardiac gating) during the pullback, which would allow real-time acquisition of the 3D curvature information. However, the low frequency of respiration would make the pullback length impractical. Therefore, we envision post-processing correction as a viable trade-off to allow 3D reconstruction as quickly as possible.

Current 3D reconstruction techniques use biplane angiography to provide arterial curvature information. However, the large dose applied to the patient during biplane angiographic imaging and the considerable cost of biplane equipment are significant limitations to the technology. To help move towards more portable and practical real-time 3D reconstruction of coronary arteries, we are investigating alternate transducer tracking technologies, which will require motion correction for the real-time 3D transducer data.

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