

INCREASING TEMPORAL RESOLUTION OF 3D TRANSESOPHAGEAL ULTRASOUND BY RIGID BODY REGISTRATION OF SEQUENTIAL, TEMPORALLY OFFSET SEQUENCES

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ABSTRACT

A description of mitral valve function requires both an accurate anatomical description of the three-dimensional (3D) structure as well as a description of the leaflets' rapid motion. Current two-dimensional (2D) ultrasound imaging is unable to capture the 3D anatomy and 3D imaging suffers from severely reduced temporal resolution. We present a method to utilize two sequential 3D transesophageal echocardiographic (TEE) ultrasound acquisitions with a temporal delay to create a dataset that captures the 3D anatomical description of the valve and has a higher temporal resolution. The enhanced dataset should provide better information for modeling the motion of the mitral valve.

Index Terms— image registration, 3D ultrasound imaging, mitral valve, leaflet dynamics

1. INTRODUCTION

Mitral valve modeling as a method to improve and assist mitral valve repair surgeries has been pursued for over 30 years [1]. The complex 3D anatomy of the mitral valve apparatus and the rapid motion of the leaflets make it difficult to understand the abnormal structural relationships of a dysfunctional mitral valve from standard 2D echocardiographic images [2]. Newer technologies including 3D transesophageal echocardiographic (TEE) imaging allow for better imaging of the mitral valve though the process of extracting valve motion from these datasets remains to be fully explored [3,4]. In particular, for biomechanical modeling of the valve, leaflet dimensions, motion trajectories, and locations of chordae tendinae attachment are critical to capturing the leaflet dynamics and reproducing them in simulations [5].

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3D TEE acquisitions that include the papillary muscles and the entire valve apparatus result in image sequences with temporal resolutions that are much lower than those obtained with 2D echocardiography. For example, a 3D TEE image sequence that is optimized for mitral valve imaging can achieve approximately 39-59 Hz sampling rate. The achievable frame rate is primarily depending on the imaging depth (7-17 cm), which is determined by the underlying anatomy. A sample set of 2D image planes extracted from one such dataset can be seen in Figure 1. Note the large displacement of the mitral valve leaflets in this image series. Even after optimization of the imaging protocol, the maximum frame rate achieved in patients, for a given depth, is currently insufficient for accurate imaging of valve dynamics [5,6]. To achieve the long-term goal of using 3D TEE acquisitions to generate models of valve dynamics, increased temporal resolution is necessary.

As described in Figure 2, acquiring two separate 3D volumetric sequences with different temporal offsets from the detected QRS complex can be used to increase the temporal resolution of the dataset. However, the interval between the two acquisitions, albeit short, can lead to rigid body motion due to TEE probe migration leading to misalignment between the two volumes. The goal of this work is to efficiently combine two time-shifted datasets to yield a single high temporal resolution dataset that could be used for automated motion detection and deformation field determination.

2. METHODS

2.1. Data Acquisition

Real-time 3D TEE full volume imaging data of normal and abnormal mitral valves were acquired in 5 patients using an iE33 console fitted with an X2-T Live 3D TEE probe (Philips Medical Systems, Bothell, WA). During a single

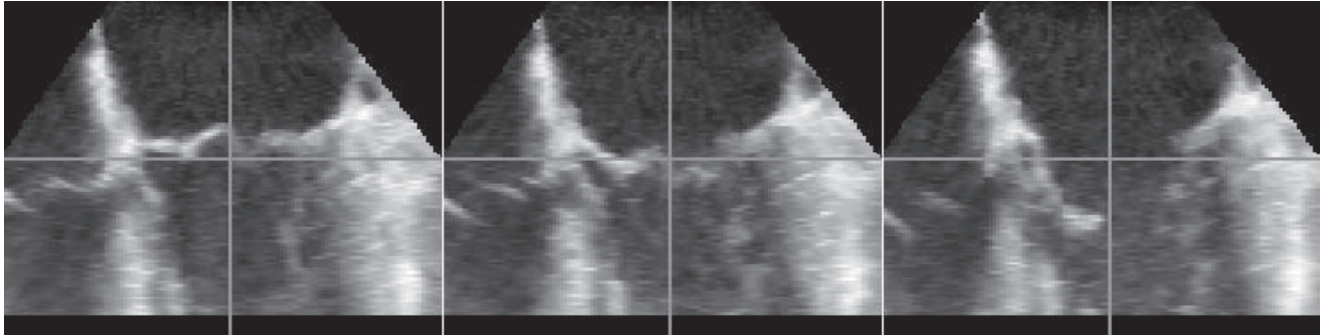


Figure 1: 2D cross-sections through the mitral valve during valve opening. The trace demonstrates 3 temporally contiguous frames obtained from a single 3D TEE acquisition.

breath hold two separate sequences were acquired, each lasting 7 heartbeats. For a single 3D acquisition, the iE33console partitions the scan into 7 spatial segments, each spanning a single beat but reconstructed into a single volume. The consecutive acquisitions were obtained and temporally offset from the detected R-peak. The second sequence trigger was delayed by approximately one half of the frame duration (10 ms) and the frame rate and all other imaging parameters were maintained to ensure maximal similarity to the first sequence. Accurate reconstruction of each individual 3D dataset was confirmed visually to avoid “stitching” artifacts that sometimes result when inter-beat physiological changes occur within the 7 heartbeat acquisitions. The time between the start of the two separate acquisitions was <30 seconds to minimize physiological parameter variations. Of the 5 patients investigated, 3 had normal valve function and two were imaged prior to valve repair surgery.

2.2. Rigid Registration

The differences between the two temporally offset volumetric sequences are assumed to originate from rotation and/or translations of the TEE probe during the interval between acquisitions (~10-15 seconds). Therefore,

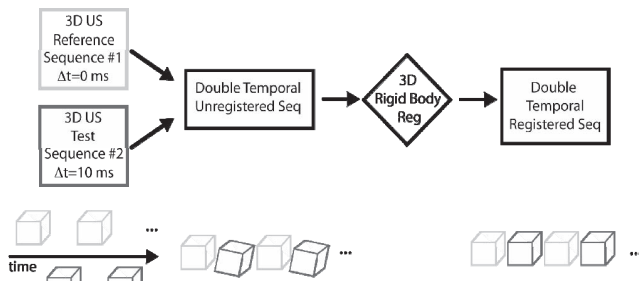


Figure 2: Two temporally offset TEE volumetric sequences are acquired. Though the two 3D sequences are acquired within the same breath-hold, motion may still be an issue. A cross correlation driven 3D rigid-body registration is used to combine the two sequences and a Fourier-based metric is used to determine quality of the inter-sequence registration.

to correctly merge the two volumetric sequences motion, a 3D rigid registration process was implemented to align the sequences (Figure 2).

2.2.1. Selection of the Registration Volumes

To apply a single rigid body transformation to the entire test sequence, the most appropriate time points for a 3D single volume-to-volume registration process must be determined. The test sequence was manually divided into four periods of interest: ventricular filing and atrial contraction, isovolumic contraction, ejection, and isovolumic relaxation [7]. The mitral valve is closed during isovolumic phases, making registration of the mitral valve structure more likely to succeed during these periods. Cross correlation (CC) metric is calculated for temporally adjacent frames of the interleaved sequence to select the reference volume in the first acquisition as well as its corresponding counterpart in the second acquisition. The two volumes with the highest CC value were utilized for the registration processes. Cross correlation was implemented because of its simplicity, quick computation, and popularity in monomodal image registration [8,9].

2.2.2. Manual Registration

3D manual registration was performed by displaying cross-sections of the two volumes chosen through the initial calculation of CC metric evaluation utilizing a laboratory tool. User identified points of interest were utilized to define a translation/rotation which was performed sequentially [10]. Manual registration was repeated until the user was unable to define points that were misaligned on the cross-sections viewed.

2.2.3. Registration using Cross Correlation

A 3D rigid registration algorithm was applied to the volumes determined from the metric evaluation. The rigid registration algorithm used the CC similarity measure calculated on an area slightly larger than the mitral valve

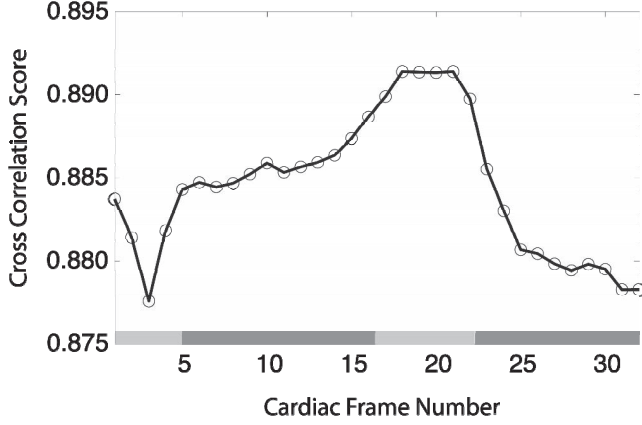


Figure 3: Maximum Cross Correlation Score of mitral valve apparatus with neighboring frames of the unregistered interleaved sequence for Patient 1. Segments of the cardiac cycle that are physiologically more favorable for registration are shown in light gray and include isovolumic contraction or relaxation. Dark gray sections indicate frames occurring during ventricular filing or ejection.

apparatus to prevent the rest of the ventricle from skewing the registration results. The process was optimized by a regular step gradient descent method and the rotation center was selected as the location of the ultrasound probe. The registration algorithm has been implemented in C++ within the framework provided by Insight Segmentation and Registration Toolkit (ITK) [11]. The resulting rigid transformation between the frames was then applied to all the remaining frames of the test sequence.

2.2.3. Registration Evaluation

The success of the registrations was evaluated based on both visual alignment of key structures as well as f_{max} , which was used to quantify the apparent frame-to-frame oscillations and is defined as:

$$f_{max} = \frac{1}{N_{pixels}} \sum_i^{N_{pixels}} |F(i, u_{max})| \quad \text{where}$$

$$F(i, u) = \mathcal{F} \{ I(x_i, y_i, z_i; t) \} \Big|_{u_{max}}$$

where N_{pixels} is the number of pixels in the volume around the mitral valve and u_{max} is the maximum frequency of the Fourier Transform of the pixel intensity value I at pixel (x_i, y_i, z_i) over time. An increase CC score after frame-to-frame 3D registration does not guarantee that the features will align through the sequence of volumes. Therefore, f_{max} is utilized to quantify the amount of oscillation in intensity at the highest frequency.

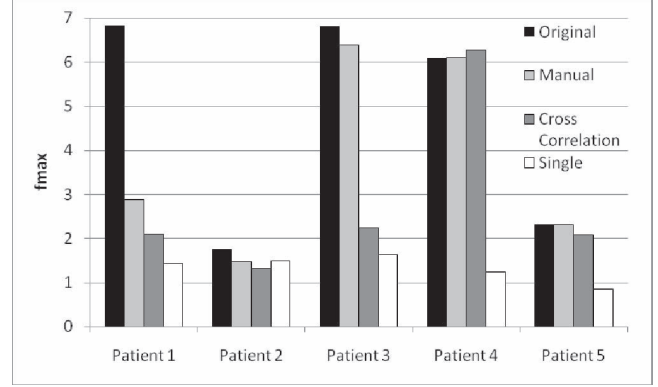


Figure 4: Comparison of f_{max} for the registration of each of $N=5$ patients (top). The original (black), manually registered (light gray), and CC driven registered (dark gray) datasets are shown in comparison to a single, non-interleaved dataset which represents the component of motion at the highest frequencies found inherently in the data.

3. RESULTS

3.1. Selection of Registration Frames

Figure 3 demonstrates the results of the selection of frames based on both the cardiac cycle and the CC metric score for one subject. The best score within the appropriate physiological window (shown in light gray) occurred in the latter stages of relaxation.

3.2. Registration Results Scoring

Figure 4 (top) shows f_{max} after manual and CC driven registration for all patients. The f_{max} of a single acquisition sequence is included to show the relative amount of high frequency motion found in a single dataset. By definition, a single volume fails to capture the high frequency motion of interest, implying that f_{max} for a single dataset is not an exact estimate of the frequency content of an ideal interleaved dataset. In most cases, the original dataset composed of two interleaved acquisitions (black) is misaligned. Manual registration improves the results in some cases (light gray) and CC driven registration improves the registration results in all cases except patient 4 (dark gray). Figure 5 illustrates the results of registration for patient 1. As the f_{max} score indicated in Figure 4, the initial interleaved dataset suffers from a large misalignment. However, as is predicted by the f_{max} score, the CC based registration mechanisms align the images. On average the volumes had displacements of $0.06 \text{ mm} \pm 0.11$ (range 0.05 – 0.42), $0.41 \text{ mm} \pm 0.75$ (range 0.00 – 1.75), $0.03 \text{ mm} \pm 0.05$ (range 0.00 – 0.12), for the X, Y, and Z axes, respectively. Also, the volumes were found to have

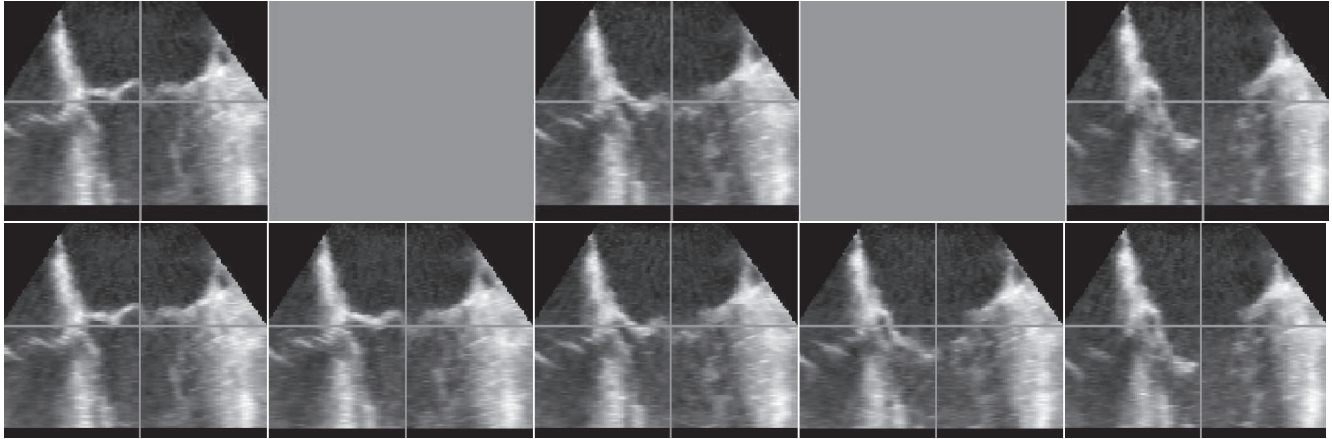


Figure 5: 2D cross-sections through the mitral valve during valve opening. The top trace demonstrates 3 temporally contiguous frames obtained from a single 3D TEE acquisition. The bottom trace shows 5 representative traces from a similar trace after interleaving and rigid-body registration of two separate temporal sequences. As expected, the limited temporal resolution from the single (top) trace fails to capture the dynamics of the leaflets opening. The registered dataset is able to better depict the event.

angular rotations of $3.55^\circ \pm 6.45$ (range 0.03 – 15.00), $0.91^\circ \pm 0.65$ (range 0.15 – 1.93), $3.32^\circ \pm 3.55$ (range 0.20 – 8.38), for the rotation angles.

4. DISCUSSION

Choosing volumes based on the position of the mitral valve and relative ventricular motion should allow for robust registration of two temporal offset sequences. The f_{max} metric, which is based on the strength of the highest frequency component of the temporal Fourier transform on the data, was successfully used to qualitatively assess the relative success of the registration process. The cross correlation driven registration outperformed the manual registration in all of the patients except for patient 4. Visual inspection of the patient 4 data suggests the valve apparatus experiences a large degree of non-rigid deformation between sequences. It appears critical to utilize datasets where the valve and ventricle are in similar configuration. Figure 4 (bottom) illustrates the average f_{max} score for each registration step. Though some of the datasets do not suffer from severe misalignment, the majority of datasets do, making the 3D rigid body registration step necessary for adequate mitral valve motion estimate. We predict that the temporal sampling frequency required for adequate valve motion estimation will increase as the complexity of valve models increases. Hence, registration of more than two datasets into single volumetric sequence is likely in the future.

4. CONCLUSIONS

Due to rigid-body motion of the ultrasound probe during the various 3D TEE acquisitions registration between

volumetric sequences was necessary to generate a single high temporal resolution dataset. The interleaved and registered datasets incorporate both the 3D anatomical mitral valve anatomy as well as an increase in information regarding the leaflets' motion. Increased temporal resolution is a critical step in the development of a description of the leaflet motion that accurately reflects physiological events and will be the input of future modeling work.

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