Co-Registration of Doppler Tissue Synchronization Imaging and Computer Tomography with an Application to Pacing and Cardiac Resynchronization Therapy

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Abstract

Dyssynchronous myocardial contraction can be treated with surgical implant of a pacing device. Integrated information of coronary anatomy and mechanical delay may be extremely beneficial to success of the implant but it is not available in current cardiac imaging modalities. The objective of this study is to investigate the feasibility of a point-merge co-registration approach to overcome the limitation.

This study shows that our method is a reliable and fast tool useful not only to attain optimal left ventricular implantation site but also to better select patients that undergo cardiac resynchronization therapy.

1. Introduction

Dyssynchronous myocardial contraction is a chronic condition of the heart that is a predictor of adverse cardiac events and is associated with a poor prognosis. The condition, which includes patients with both dyssynchronous interventricular activation (a pathological delay between the activation of the left and right ventricles) and dyssynchronous intraventricular activation (the pathological delay between different segments of the myocardium), can be treated with surgical implant of a bi-ventricular pacing device

In fact, resynchronization can be achieved using a special pacing device with an additional lead intravenously implanted through the coronary sinus in order to stimulate the lateral wall of the left ventricle via the lateral or posterolateral branch of coronary venous tree. Unfortunately, a large segment of this patient population (> 30%) are non-responders to therapy and factors that positively predict successful outcome of the surgical therapy have not been fully recognized. Lead position however is believed to be one of the critical factors in determining success of therapy which in-turn is dependant upon technically placing the left ventricular lead, the variability of the coronary venous anatomy and the location of left ventricular mechanical dyssynchrony. Even though the coronary vein anatomy can be determined by multi-slice computed tomography and visual information regarding location of mechanical dyssynchrony can be obtained from ultrasound based tissue synchronization imaging, one of the current limiting factors is the lack of an imaging modality that has both spatial and temporal resolution sufficient to capture and integrate the variability of the coronary venous anatomy together with characteristics of the myocardial dyssynchrony. The objective of this study was to investigate the feasibility of a point merge co-registration approach to overcome this limitation by fusing tissue synchronization images with computed tomography and to provide a novel tool useful not only to better identify responders to resynchronization therapy but also to attain the optimal left ventricular lead implantation site.

2. Methods

The population examined in this study consisted of 5 patients with significant myocardial dyssynchrony. Data from these subjects were acquired using both MSCT (Philips Brilliance CT-64) and Tissue Synchronization Imaging (GE Vivid 7).

2.1. Multi-slice computed tomography

A 40-row or 64-row MSCT scanner (Philips Medical Systems) was used to acquire each volume data set of the chest, covering a volume that included the heart and the coronary sinus with the coronary veins. Patients were asked to hold their breath and a contrast acquisition was performed. Cross-sectional images were reconstructed with a slice thickness of 0.6 or 0.4 mm using an ECG-gated multi-slice reconstruction algorithm to obtain a temporal resolution of 100-150 ms. An experienced reviewer analyzed the data sets, using the original trans-axial images along with multi-planar reconstructions and maximum intensity projection images obtained with the use of commercially available software (Philips Extended Brilliance Workstation).

The reviewer pinpointed the location of the coronary sinus and several points on the lateral and posterolateral branches of the coronary venous tree. An automated segmentation algorithm automatically determined the coronary venous anatomy and saved its geometry in x,y,z coordinate space for later processing.

2.2. Tissue synchronization imaging

Tissue Synchronization Imaging (TSI) is a cardiac imaging modality based on ultrasound that is very effective for visual assessment of left ventricular mechanical dyssynchrony. During a standard color Tissue Doppler echocardiographic acquisition, a signal-processing algorithm processes Tissue Doppler data to automatically detect peak positive longitudinal myocardial velocities and record the time from the QRS as they occur. Each region in the standard grayscale echocardiogram is then color-coded based on the time to peak velocities using shades of green for regions with normal timing, shades of yellow-orange for moderate delay and red for severe delays in peak longitudinal myocardial velocity delays.

In this study, Tissue Synchronization Imaging was obtained on the same day as the MSCT acquisition from both standard transthoracic 3 and 4-chamber apical views.

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2.3. Co-registration

Using custom-made software experienced operators pinpointed the location of pairs of corresponding points in each dataset. These corresponding points were fiducial to the co-registration algorithm and in order to guarantee increased accuracy and reproducibility; the middle of the mitral valve, the middle of the aortic valve and the left ventricular apex were used from the 3-chamber view; the middle of the mitral valve, the middle of the tricuspid valve and the apex were used from the 4-chamber view.

This data was used to numerically derive an optimal 3D transformation to fuse each image data sample MSCT and TSI into a co-registered x,y,z coordinate system.

2.3.1. Homogeneous transformations

In this co-registration algorithm, the basic transformation from one coordinate system to the co-registered x,y,z coordinate system has the form of a 4x4 matrix and we used an homogenous system to transform a vector A in original coordinate system into Vector B in the fused coordinate system. The transformation is performed using a two-step process that involves a matrix multiplication and the homogenization of the resulting vector.

Let

$$M = \begin{bmatrix} m_{1,1} & m_{2,1} & m_{3,1} & m_{4,1} \\ m_{1,2} & m_{2,2} & m_{3,2} & m_{4,2} \\ m_{1,3} & m_{2,3} & m_{3,3} & m_{4,3} \\ m_{1,4} & m_{2,4} & m_{3,4} & m_{4,4} \end{bmatrix}; A = \begin{bmatrix} a_x \\ a_y \\ a_z \\ 1 \end{bmatrix},$$

where M represents the generic transformation and A the generic homogeneous vector

$$B' = M \times A;\ B' = \begin{bmatrix} b'_x \\ b'_y \\ b'_z \\ b'_w \end{bmatrix}; B = \frac{1}{b'_w} \cdot B'; B = \begin{bmatrix} b_x \\ b_y \\ b_z \\ 1 \end{bmatrix}$$

The vector B' is thus obtained by matrix multiplication of M by A. All components of the resulting vector are divided by its fourth component to render the final vector B a homogenous vector.

The matrix M can handle basic operations such as rotation around the x axis $\begin{bmatrix} \cos\alpha & -\sin\alpha & 0 & 0 \\ \sin\alpha & \cos\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$,

rotation around the y axis $\begin{bmatrix} \cos\alpha & 0 & \sin\alpha & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\alpha & 0 & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$, and

rotation around the z axis $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$,

where α is the rotation angle; as well as

translation $\begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$, where Tx,Ty,Tz are the x,y,z components of the translation vector and

scaling $\begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$, where Sx,Sy,Sz indicate the amount of axial scaling, but can also be easily manipulated to store complex transformations equivalent to the application of several intermediate operations. The latter approach was exploited in our implementation in order to efficiently apply an optimal complex transformation with only one matrix multiplication and one scalar multiplication.

2.3.2. Optimal transformation

During the co-registration process, our method implemented a modified version of the Shor's r-algorithm to iteratively search along the descendent gradient the optimal transformation that minimizes the sum of distances between the fiducial points in one modality $P_{2,c}$ and the transformed fiducial marks $P_{1,c}$ in the other modality to be registered.

The minimization of the error function $Err = \sum_{c=1}^{n} \left\| P_{2,c} - T \circ P_{1,c} \right\|$ is subject to constraints that allow discard of unwanted solutions such as, for example, the "*flatten*" transformation.

Once obtained, an optimal transformation is applied to the entire dataset in real time. Our implementation utilizes the Graphics Unit Processor to handle the transformation in hardware and therefore requires no storage of additional data besides the mathematical details of the optimization model used.

An experienced operator reviewed the results of the co-registration and made sure that anatomical detail such as the endocardial border and cardiac valves shown in the fused image were consistent across modalities. In the final stage, the coronary venous anatomy determined from MSCT was co-registered and visualized fused in 3D space with TSI.

3. Results

In all cases the co-registration process was user-friendly, accurate and the duration of the process was less than 5 minutes per case.

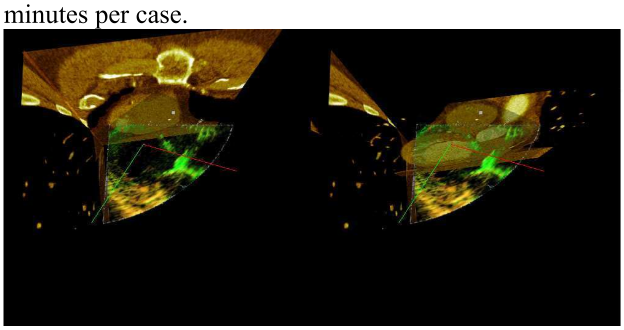

Figure 1 Two cross-sections from the fused CT and TSI rendered in 3D space intersect at apical level (left) and mid-level (right) show consistent endocardial borders, apical and valve locations across modalities.

With a point-merge approach our method was able to use a minimal number of three-pairs of markers to accurately co-register the MSCT, the reconstructed coronary venous anatomy and the TSI.

It enabled not only easy visual determination of the closest coronary vein to the myocardial region with dyssynchrony, but also quantitative assessment with the measurement of the linear distance in 3D space between the targeted left ventricular lead position and the site of latest activation. Last but not least, the method enabled measurement of curvilinear distances and thus accurate assessment of the catheter advancement that was necessary to reach the targeted left ventricular lead position during the implantation.

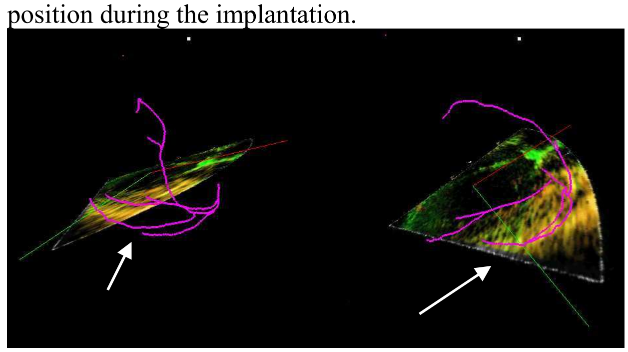

Figure 2. Two different 3D views of the segmented coronary anatomy from Computer Tomography co-registered with the Doppler TSI echocardiographic depiction of the apical 3-chamber view of the left ventricle. This patient was found to have dyssynchrony involving the basal posterior wall (yellow) along with a posterolateral vein (pointed by white arrow) subtending that segment. This image allowed the cardiologist to direct the pacemaker lead to this posterolateral vein in hopes of achieving the optimal clinical result specifically improving ventricular function and ultimately symptomatology.

4. Discussion and conclusions

Despite the attention of many scientists on pacing and cardiac resynchronization therapy drawn by both the severity of the cardiac events associated with myocardiacal dyssynchrony and the high frequency of non-responders to therapy, the prognosis of myocardial dyssynchorny is still challenging to predict.

The variability of coronary venous anatomy as determined by MSCT confirmed that it is not possible to predict apriori the exact spatial relationship between the left ventricular lead position attained using an empirically selected lateral or posterolateral branch to the myocardial segment with dyssynchrony and suggests that only the integrated information of coronary venous anatomy and the site of latest activation could be an enabling factor in predicting and attaining the optimal LV lead position.

Our study shows that the co-registration of coronary vein MSCT and TSI is feasible using a point-merge approach that is reliable, accurate and fast. Our proposed method might greatly benefit implant success in cardiac resynchronization therapy by providing a novel tool with integrated information not currently available in cardiac imaging modalities that is useful to enable positioning a pacing lead to the optimal implantation site. In fact, the newly available quantitative assessment of the linear distance between the site of latest activation from the lateral and posterolateral branch would help with implantation planning by selecting the branch which meets both minimal diameter requirements as well as optimal location relative to the site of ventricular dyssynchrony. The measurement of curvilinear length of the path that the catheter would traverse in the coronary vein enables the assessment distance of catheter advancement necessary during the implantation to reach the optimal implantation site.

Additionally our method can be used to better select patients that undergo intravenous cardiac resynchronization therapy by including only those patients whose coronary venous anatomy is suitable and allows getting sufficiently close to the myocardial region with dyssynchrony.

Although very promising, the results of this study are limited as we did not assess impact on device implant success and clinical outcome of patients with moderate heart failure and myocardial dyssynchrony. Further study is needed to demonstrate effectiveness of this approach.

Acknowledgements

This study was supported in part by the National Space Biomedical Research Institute through NASA NCC 9-58 (Houston, Texas) and the Department of Defense (Fort Dietrich, Maryland, USAMRMC Grant #02360007).

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