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Analysis of Left Atrial Respiratory and Cardiac Motion for Cardiac Ablation Therapy

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Abstract

Cardiac ablation therapy is often guided by models built from preoperative computed tomography (CT) or magnetic resonance imaging (MRI) scans. One of the challenges in guiding a procedure from a preoperative model is properly synching the preoperative models with cardiac and respiratory motion through computational motion models. In this paper, we describe a methodology for evaluating cardiac and respiratory motion in the left atrium and pulmonary veins of a beating canine heart. Cardiac catheters were used to place metal clips within and near the pulmonary veins and left atrial appendage under fluoroscopic and ultrasound guidance and a contrast-enhanced, 64-slice multidetector CT scan was collected with the clips in place. Each clip was segmented from the CT scan at each of the five phases of the cardiac cycle at both end-inspiration and end-expiration. The centroid of each segmented clip was computed and used to evaluate both cardiac and respiratory motion of the left atrium. A total of three canine studies were completed, with 4 clips analyzed in the first study, 5 clips in the second study, and 2 clips in the third study. Mean respiratory displacement was 0.2 ± 1.8 mm in the medial/lateral direction, 4.7 ± 4.4 mm in the anterior/posterior direction (moving anterior on inspiration), and 9.0 ± 5.0 mm superior/inferior (moving inferior with inspiration). At end inspiration, the mean left atrial cardiac motion at the clip locations was 1.5 ± 1.3 mm in the medial/lateral direction, and 2.1 ± 2.0 mm in the anterior/posterior and 1.3 ± 1.2 mm superior/inferior directions. At end expiration, the mean left atrial cardiac motion at the clip locations was 2.0 ± 1.5 mm in the medial/lateral direction, 3.0 ± 1.8 mm in the anterior/posterior direction, and 1.5 ± 1.5 mm in the superior/inferior directions.

1. Introduction

Atrial fibrillation (AF) is a condition of the heart in which the atrial beat rapidly and irregularly, with the arrhythmogenic trigger often located in the pulmonary veins.¹ In image-guided cardiac ablation therapy, a catheter is inserted into the left atrium to deliver radiofrequency energy to the endocardial tissue aiming to either isolate the AF trigger in the pulmonary veins or alter the arrhythmic substrate. The procedure is often guided using surface models built from high-resolution, preoperative CT or MRI scans. One of the challenges in guiding a procedure from a preoperative model is properly synching the preoperative models with cardiac and respiratory motion.²⁻⁴ Various motion compensation models have been proposed; however, validation of these models remains a challenge. In this paper, we describe a methodology for evaluating cardiac and respiratory motion in the

left atrium and pulmonary veins of a beating canine heart. This analysis is valuable for both quantification of left atrial motion as well as serving as a ground truth dataset for validating computational motion models.

2. Methods

Canine studies were conducted according to a protocol approved by the Mayo Foundation Institutional Animal Care and Use Committee. After obtaining access to the left atrium through transseptal catheterization, cardiac catheters were used to place metal clips in the left atrium and pulmonary veins of the canine heart under fluoroscopic and ultrasound guidance. Clips were placed within and near the pulmonary vein ostia and left atrial appendage. A contrast-enhanced, 64-slice multidetector CT scan was collected with the clips in place. Helical CT scanning was performed 10-20 seconds after intravenous injection of 40 mL of contrast media at a rate of 4 mL/s. The CT scan was reconstructed at 5 phases of the cardiac cycle at both end-inspiration and end-expiration. Next, each clip was segmented from the CT scan as shown in Figure 1 at each of the five phases of the cardiac cycle (0%, 20%, 40%, 60%, 80%) at both end-inspiration and end-expiration. The centroid of each segmented clip was computed and used to evaluate both cardiac and respiratory motion of the left atrium and pulmonary veins. A total of three canine studies were completed. In each study, we attempted to place five clips; however, since the endocardial surface of the left atrium is smooth, some of the clips did not attach resulting in fewer than 5 clips in some studies. In total, we evaluated 4 clips in the first study, 5 clips in the second study, and 2 clips in the third study.

3. Results

3.1 Respiratory Motion

In Figure 2, plots of the respiratory motion versus each of the five cardiac phases are given for two of the canine studies. Each plot represents the change in either the x, y, or z direction between end-expiration and end-inspiration. Individual clips are colored separately and the mean across all clips is colored in solid black. As seen in the two plots on the left, minimal medial lateral displacement is observed between end inspiration and end expiration. The middle plots demonstrate that the left atrium has an anterior displacement upon inspiration. One clip (colored red) in the first canine had a slight posterior motion upon inspiration. This clip was located in the right superior pulmonary vein which may have undergone a different displacement than the left atrium during respiration. Plots on the right indicate an inferior motion upon inspiration. As seen in the plots, respiratory displacement was consistent across cardiac phase. When averaged across the 11 clips in the three different studies, mean respiratory displacement was 0.2 ± 1.8 mm in the medial/lateral direction, 4.7 ± 4.4 mm in the anterior/posterior direction (moving anterior on inspiration), and 9.0 ± 5.0 mm superior/inferior (moving inferior with inspiration).

3.2 Cardiac Motion

Plots of cardiac motion of each clip for one of the canine studies is shown in Figure 3. For these plots, the motion for each clip was normalized to its centroid and the 3D motion is projected to the x,y, and z axes. From these plots, we see that the magnitude and overall

pattern of motion is similar across the collection of clip locations for this study. Cardiac motion across all studies and clip locations is summarized in Tables 1 and 2. In these tables, cardiac motion is reported as the maximum displacement in the x,y, and z directions. At end inspiration, the mean left atrial cardiac motion was 1.5 ± 1.3 mm in the medial/lateral direction, 2.1 ± 2.0 mm in the anterior/posterior and 1.3 ± 1.2 mm superior/inferior directions. At end expiration, the mean left atrial cardiac motion was 2.0 ± 1.5 mm in the medial/lateral direction, 3.0 ± 1.8 mm in the anterior/posterior direction, and 1.5 ± 1.5 mm in the superior/inferior directions. The motion for the third canine study is higher than that for studies 1 and 2. In the third study, the two clips were placed closed to the left atrial appendage which may undergo larger cardiac motion.

4. Discussion

In this work, we evaluated respiratory and cardiac motion of the left atrium and pulmonary veins using fiducial clip markers. In the evaluation of respiratory motion, we found a mean inferior displacement of 9.0 mm, a mean anterior displacement of 4.7 mm, and negligible medial/lateral motion with inspiration. While not directly comparable to human studies, we did find general agreement with these results to patient studies of respiratory motion of the left atrium. In a free breathing patient study using magnetic resonance imaging,⁵ mean left atrial motion was found to be 10.2 mm in the superior/inferior direction, 2.4 mm in the anterior/posterior direction, and 2.0 mm in the left/right direction. Another patient study which used end-inspiration and end-expiration computed tomography scans,⁶ assessed each of the pulmonary vein ostial centers and found inferior displacements ranging from 12.7 to 16.1 mm and anterior displacements ranging from 6.5 to 11.9 mm upon inspiration. As in our study, this study also found negligible motion in the medial/lateral direction.

In our study of left atrial cardiac motion, we found the mean left atrial cardiac motion at the clip locations was 1.5 mm in the medial/lateral direction, 2.1 mm in the anterior/posterior direction and 1.3 mm in the superior/inferior directions at end inspiration. At end expiration, mean left atrial cardiac motion at the clip locations was 2.0 mm in the medial/lateral direction, 3.0 mm in the anterior/posterior direction, and 1.5 mm in the superior/inferior directions at end expiration. Motion at the two respiratory phases was very similar and likely within the margin of error, although this would need to be validated in a larger study. Previous work evaluating cardiac motion of the left atrium,⁷ utilized patient magnetic resonance imaging data. In this study, three dimensional motion was estimated by finding anatomical landmarks across the left atrium and at the pulmonary vein ostia. The authors of this study found that motion was highly variable across the left atrium, with less motion at the pulmonary vein ostia and larger motion in other regions of the left atrium. Three dimensional motion at the pulmonary vein ostia ranged from 1.9 to 2.7 mm across the different pulmonary veins, while mean motion at the anterior left atrium, mitral annulus and left atrial appendage was found to be 8.7, 12.5, and 9.8 mm respectively. In our study, most of the clips were placed at the pulmonary vein ostia, as these are the regions of highest interest for the application of cardiac ablation therapy. The overall magnitude of motion found in our study is consistent with the motion of the pulmonary vein ostia reported by Patel *et al.*. In addition, the larger motion observed in the third canine study which had clips placed in and near the left atrial appendage is also consistent with the study of Patel *et al.*

We plan to extend this work to include a larger number of animal studies with clips placed more broadly across the left atrium and pulmonary veins. This will provide the ability to quantitatively assess differential motion across different regions of the left atrium. Overall, this study will be valuable for both quantification of left atrial motion as well as serving as a ground truth dataset for assessing computational motion models.

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Figure 1. Segmentations of the metal clips from the CT scan. Clips were placed within and near and the pulmonary veins and left atrial appendage.

Figure 2.

Respiratory motion of each clip versus the five cardiac phases across two canine studies. Each clip is colored separately and the mean across all clips is colored solid black. Motion is with reference to end expiration and is plotted separately for the x, y, and z directions. x increases from right to left (medial to lateral), y increases from posterior to anterior, and z increases from inferior to superior.

Figure 3.

Cardiac motion of each clip for one canine at end inspiration. Each clip is colored separately and the mean motion is shown in black. In the top figure, the 3D motion is projected to the medial/lateral and inferior/superior directions. In the bottom figure, the 3D motion is projected to the anterior/posterior and inferior/superior directions.

Table 1

Cardiac motion of each clip at end inspiration across the three canine studies. N indicates the number of clips evaluated in each study. Motion is given as maximum displacement in the x (medial/lateral), y (anterior/posterior), and z (superior/inferior) directions.

Inspiration	<i>x</i> (mm)	<i>y</i> (mm)	<i>z</i> (mm)
Canine 1 (N=4)	1.2 (0.6)	1.3 (0.9)	1.4 (1.2)
Canine 2 (N=5)	1.0 (0.8)	1.1 (0.5)	0.7 (0.4)
Canine 3 (N=2)	3.3 (2.4)	5.9 (1.3)	2.5 (1.9)
Mean (N=11)	1.5 (1.3)	2.1 (2.0)	1.3 (1.2)

Table 2

Cardiac motion of each clip at end expiration across the three canine studies. N indicates the number of clips evaluated in each study. Motion is given as maximum displacement in the x (medial/lateral), y (anterior/posterior), and z (superior/inferior) directions.

Expiration	<i>x</i> (mm)	<i>y</i> (mm)	<i>z</i> (mm)
Canine 1 (N=4)	2.8 (1.5)	2.7 (1.0)	2.0 (1.8)
Canine 2 (N=5)	0.9 (0.4)	1.9 (0.6)	0.8 (0.2)
Canine 3 (N=2)	3.2 (1.9)	6.3 (0.2)	2.4 (2.4)
Mean (N=11)	2.0 (1.5)	3.0 (1.8)	1.5 (1.5)