Improved Non-Contact Heart Chamber Modeling Using Catheter Mediated Ultrasound Returns

Derrick Chou[1], Jaume Coll-Font[1], Lea Melki[1], Wilson W Good[1], Steve Yon[1]

[1]Acutus Medical Inc., Carlsbad Ca. USA

Abstract

Non-contact (inverse) techniques for mapping of cardiac electrical activity require the existence of an accurate surface representation, typically in the form of a triangulated mesh. One approach for surface mesh generation employs ultrasound reflected from the endocardium. Transmitted from a catheter within the heart chamber, localized reflections form a shell of points descriptive of the shape of the interior surface of the heart. The existence of significant variance in the position of ultrasound reflections discourages the use of conventional meshing techniques. A surface reconstruction technique which is robust in the presence of positional variance and sensitive to peripheral heart structures is required. A Poisson equation relating a 3-D scalar function to the normal of the (as yet) unknown surface yields an iso-surface as the desired anatomic boundary. Evaluation of the Poisson-based surface technique is accomplished by consideration of the mesh obtained from in-vitro acquisition of ultrasound from polymer left and right atrium targets. Error between the computed mesh vertices and the target surface was ~1.5 mm average, and the technique is sensitive to surface structures in all orientations.

1. Introduction

Non-contact or inverse mapping of cardiac electrical activity requires the existence of an accurate representation of heart chamber geometry, typically in the form of a triangulated mesh, onto which computed electrical properties may be displayed. One approach for generation of heart chamber geometry, implemented in the Acutus AcQMap system, employs ultrasound transducers on a catheter within the heart to determine the position of the chamber wall. The Acutus AcQMap catheter transmits and receives ultrasound pulses which are localized via an A-mode methodology, relative to known catheter position, based on assumed acoustic speed and measured travel time. 48 transducers positioned uniformly around the nearly spherical catheter sample the boundary with a frequency > 50 Hz, and movement of the catheter, including translation and rotation to ensure adequate sampling of peripheral structures, assures rapid accumulation of a shell of surface position estimates.

Creation of a triangulated 2-D surface mesh from the ultrasound shell is complicated by, e.g., error in the estimated position of the catheter, wall motion during respiration and cardiac cycles, and inadequate catheter motion leading to regions of low sample density. Consequently, commonly employed surface / mesh construction techniques such as marching cubes or alpha shapes are not applicable to most ultrasound data sets. Figures 1A and 1B show a typical clinical ultrasound sample cloud and a cross sectional view.

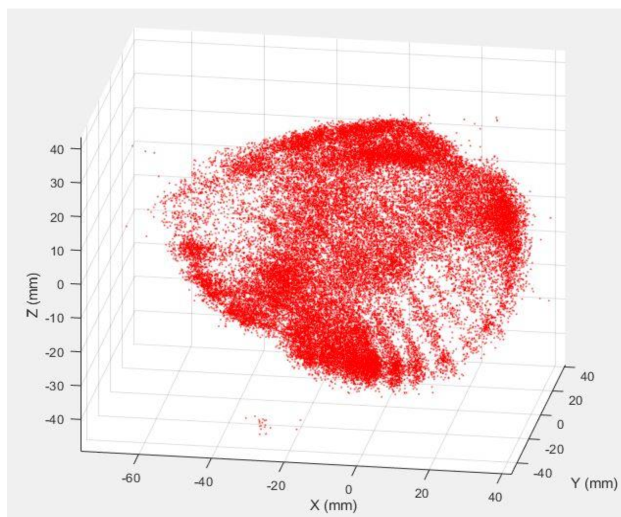

Figure 1A. Typical clinical ultrasound cloud, LA, viewed from patient front upper left. Striations are the path of a single transducer beam under catheter rotation.

What is desired is a smooth, closed mesh robust to positional noise and variable sample density but sensitive to peripheral structures. Also desired is some visual indication of local ultrasound sample density for the purpose guiding ultrasound acquisition.

 ISSN: 2325-887X DOI: 10.22489/CinC.2022.404

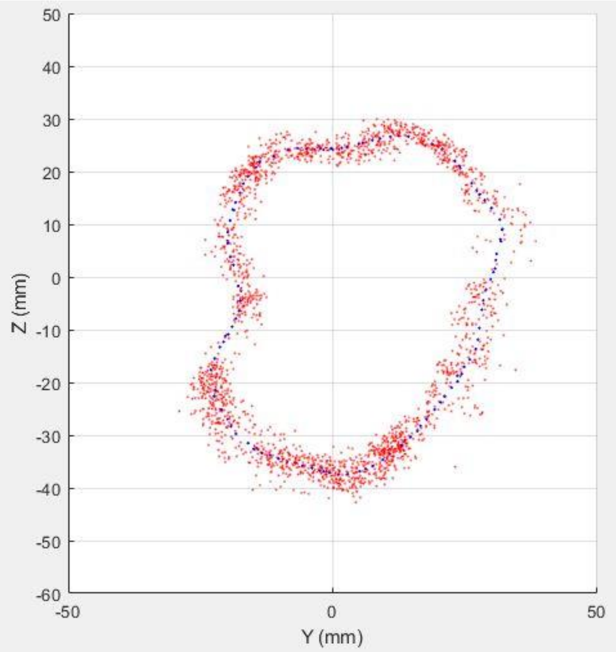

Figure 1B. Cross section of the ultrasound shell (red points) in Figure 1A, as viewed from patient left. 10 – 20 mm wall thickness and significant density variation is common. Blue points are an average wall position.

2. Method

Ultrasound points are accumulated into pre-defined spatial voxels for the purpose of eliminating extreme density variations which may occur during intervals when catheter motion stops. Occupied voxels are assigned unit density, while density values in unoccupied voxels are computed by an iterated diffusive process [1].

Each occupied voxel is assigned a 'normal' vector which approximates the local orientation of the desired surface. An empirically observed property of the method described here is that the solution is robust with respect to normal orientation, and a simple radius vector from the centroid of the ultrasound samples is generally sufficient.

Now postulate the existence of a function ϕ in $\mathbb{R}^3$ which assumes the value 1 interior to the eventual boundary, and 0 outside, and require

$$\nabla\phi = \vec{n} \qquad \text{Eq. 1}$$

Equation 1 is poorly posed since the curl of the gradient must vanish identically, but the curl of the normal is not similarly constrained. To remove this inconsistency, apply the gradient operator to each side of Equation 1 such that

$$\nabla\cdot\nabla\phi = \nabla\cdot\vec{n} \qquad \text{Eq. 2}$$

The governing Poisson equation (Equation 2) is solved discretely by positioning radial basis functions in each occupied voxel and computing the associated weights by an inverse method. The desired final surface is chosen as the closed iso-surface of the solution defined by

$$\phi = 0.5 \qquad \text{Eq. 3}$$

A triangulated mesh is created by standard techniques on the iso-surface solution. The Poisson-based surface reconstruction, originally developed by Kazhdan et al. [2] has been found to be robust with respect to ultrasound wall thickness and density variations.

An approximation to local ultrasound density is assigned to each mesh vertex by interpolation from the diffused voxel density. During ultrasound acquisition, local density may be incorporated in the developing mesh as shading and / or transparency to guide the operator toward more uniform sampling.

3. Results

The capability (accuracy) of the Poisson based surface generation method is evaluated by application to an ultrasound cloud obtained with the Acutus AcQMap system using polymer models of human LA and RA in an isotonic blood analog. The final mesh is compared to the known geometry by evaluating the mean normal offset between the Poisson mesh and a mesh created from the polymer model. The LA model, ultrasound, and final Poisson based mesh are shown in Figure 2A through 2C, and the corresponding results for the RA model are shown in Figure 3A through 3C.

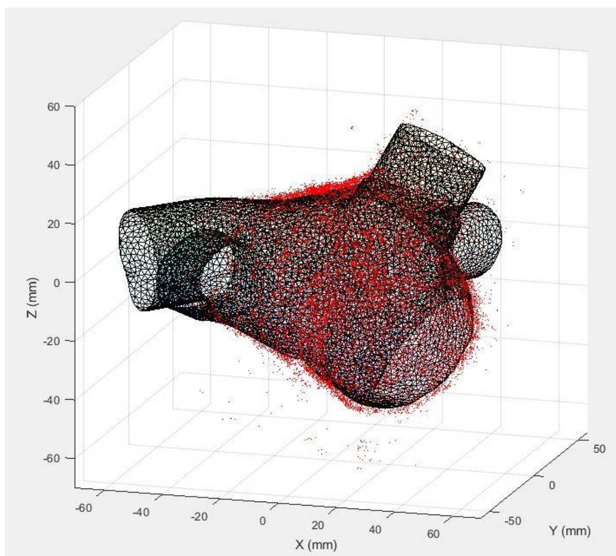

Figure 2A. Mesh representation of the LA model, and ultrasound (red) generated by the Acutus AcQMap system.

In Figures 2A and 3A, we observe that ultrasound points are distributed around the physical surface, both internal and external, due to localization errors inherent in transducer position and orientation. Thickness of the distribution is typically 5 – 10 mm, and significant gaps due, e.g., to poor sampling technique or actual openings in the heart chamber are common. Figures 2B and 3B show the Poisson generated surface shaded by local ultrasound density. The Poisson solution is robust with respect to small regions of poorly localized ultrasound as seen, e.g., below the valve plane in Figure 2B. In under sampled regions (e.g. near the right PV in Figures 2A, 2B), the Poisson surface is closed but may not follow the actual boundary. However, with sufficient sampling, peripheral structures such as vein ostia are well modeled. Regions of low density, such as the valve plane and vein openings, are clearly distinguished by color from higher density regions. In use, the dark shading is intended to guide the user toward more effective sampling by translation and rotation of the AcQMap catheter toward regions of low density.

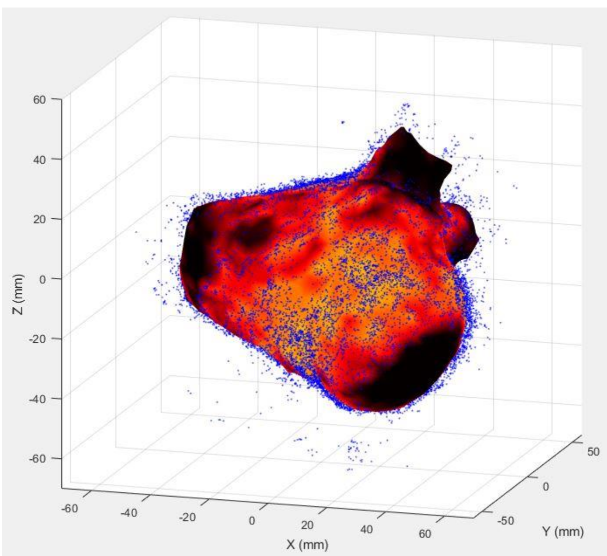

Figure 2B. Ultrasound points (blue) from the LA model and Poisson-generated surface. Dark areas indicate low ultrasound density.

Quantitative comparison between the model surface and the Poisson generated mesh, for the purpose of evaluating ‘accuracy’ of the Poisson based mesh, is obtained by computing the normal distance between each (Poisson) vertex and the model mesh. Rejecting regions of the Poisson mesh which are incomplete due to inadequate sampling, the average normal offset is ~1.5 mm.

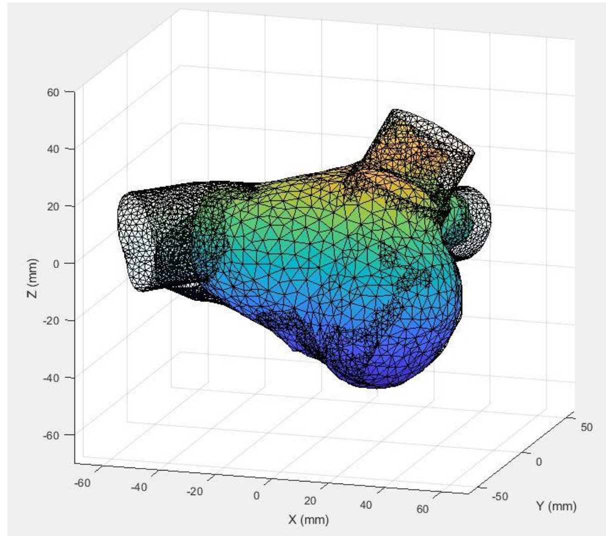

Figure 2C. Mesh representation of the LA model and Poisson generated surface. The Poisson mesh is shaded for clarity. The Poisson surface closely approximates the actual model surface, including in the pulmonary veins, but is closed, necessitating an additional hole cutting step if openings are required.

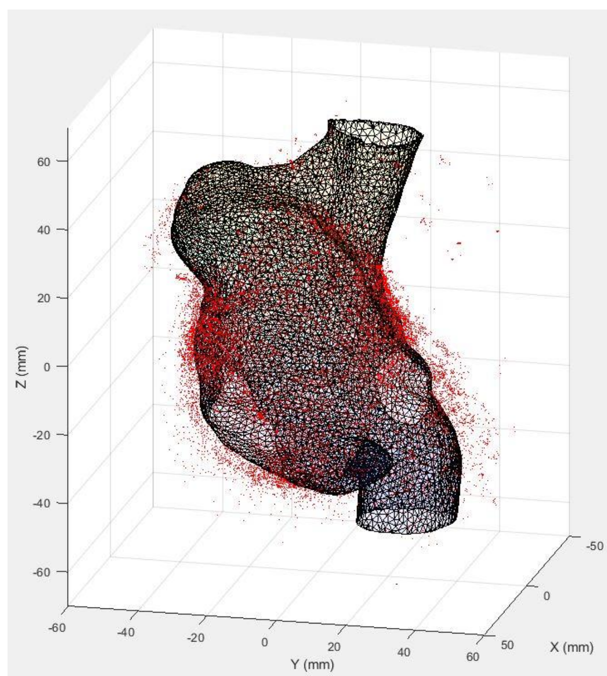

Figure 3A. Mesh representation of the RA model and ultrasound shell (red) generated by Acutus AcQMap system.

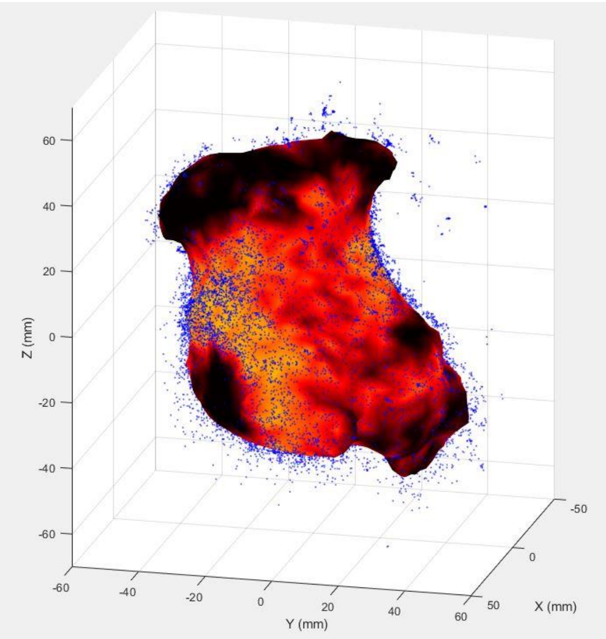

Figure 3B. Ultrasound points (blue) from the RA model and Poisson-generated surface. Dark areas indicate low ultrasound density.

4. Conclusions

With appropriate acquisition of ultrasound points, the left and right atrial models are reproduced with similar accuracy by the AcQMap system and the Poisson based surface reconstruction technique.

In clinical use, left and right atrial reconstructions generated by the AcQMap system exhibit detail and fidelity to the ultrasound points similar to the results presented here.

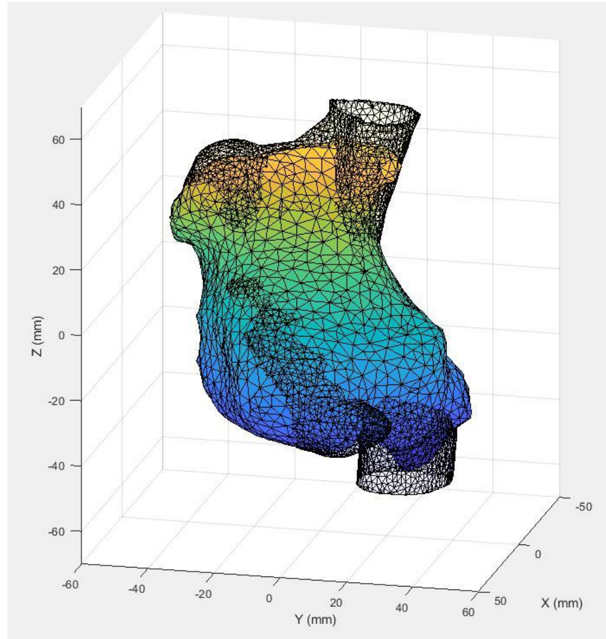

Figure 3C. Mesh representation of the RA model and Poisson generated surface. The Poisson mesh is shaded for clarity. The Poisson surface closely approximates the actual model surface except in regions with inadequate ultrasound sampling.

References

[1] Hornung, Alexander, and L. Kobbelt. "Robust Reconstruction of Watertight 3D Models from Non-uniformly Sampled Point Clouds Without Normal Information", *Eurographics Symposium on Geometry Processing*, Polthier and Sheffer, ed., 2006.

[2] Kazhdan, Michael, M. Bolitho, and H. Hoppe, "Poisson Surface Reconstruction," *Eurographics Symposium on Geometry Processing*, Polthier and Sheffer, ed., 2006.

Address for correspondence:

Steve Yon
2210 Faraday Ave. #100
Carlsbad CA 92008
steve.yon@acutus.com