

# Computational Cardiac Modeling Based on Transesophageal Echocardiographic Imaging

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Cardiac surgery remains a therapeutic mainstay for cardiovascular disease. Reconstructive by nature, virtually all cardiac operations require an accurate understanding of the complex 3-D structure and function of

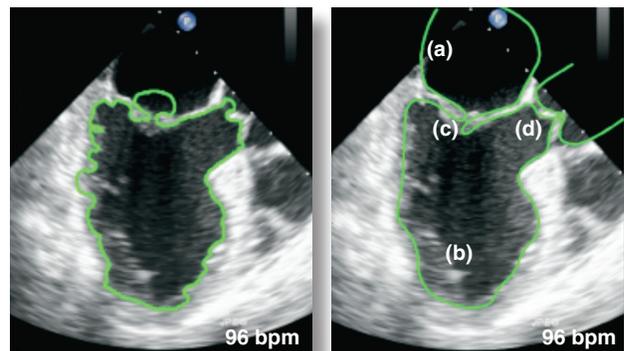
that uniquely “mechanical” vital organ, the heart. Because most cardiac reconstructive operations (e.g., valve repair) are performed on a flaccid, empty heart under cardiopulmonary bypass, accurately predicting how surgical modifications will behave under physiologic conditions is often challenging for cardiac surgeons.

We describe the design of a biomechanical model of the left ventricle complex to assist in virtual surgery and pre-operative surgical planning. We specifically focus on the problem of hemodynamic computational modeling in the left heart complex and the recovery of an anatomical model of the valve and left heart chambers. The novelty of our approach lies in the exploitation of prior patient-specific data resulting from image analysis of transesophageal echocardiographic (TEE) imagery. Most prior work in heart computational modeling does not include patient-specific data, with some very recent exceptions that exploit computed tomography (CT), a modality that provides much higher spatial resolution. When compared with traditional 3-D imaging approaches such as magnetic resonance imaging (MRI) or CT, TEE promises to become a preferred modality for intraoperative use because it is portable, flexible, real time, and non-ionizing. In addition, several models of 4-D ultrasound platforms (3-D spatial + time) were recently released.

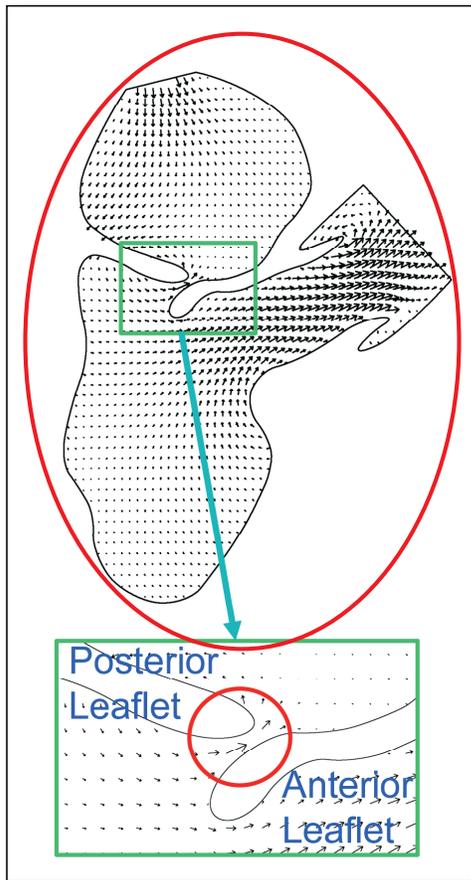
Our approach recovers kinematic and anatomical information in the form of left heart chambers and

valve boundaries through a level-set-based, user-in-the-loop segmentation on 2-D and 3-D TEE (Fig. 1). The resulting boundaries in the TEE sequence are then interpolated to prescribe the motion displacements in a computational fluid dynamics (CFD) model implemented by using finite element modeling (FEM) applied on arbitrary Lagrangian–Eulerian (ALE) meshes.

Preliminary experimental results on clinical cases collected under an Independent Review Board (IRB)



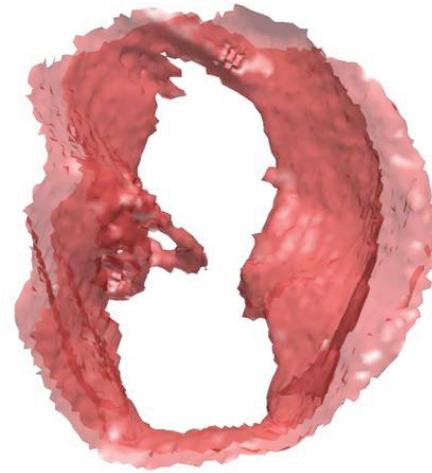
**Figure 1.** First step in creating a cardiac model from ultrasound image data. Automatic (left) boundary segmentation obtained with a level-set method is refined by a user-in-the-loop enhancement (right). Anatomical structure shows (a) left atrium, (b) left ventricle, (c) mitral valve, and (d) aortic valve. (Reproduced with permission from Ref. 1 © 2009, IEEE.)



**Figure 2.** A 2-D blood flow distribution solved with specified boundaries obtained from 2-D ultrasound of a patient. The hemodynamic model correctly predicts a mitral valve insufficiency resulting in regurgitant flow. (Adapted with permission from Ref. 1 © 2009, IEEE.)

are promising, showing that we can recover the 3-D anatomy of a specific patient's mitral valve. Initial results on 2-D FEM hemodynamic modeling also demonstrate that we can correctly predict the patient's regurgitating blood flow during peak systole.

Figure 2 shows 2-D blood flow distribution solved with specified boundaries obtained from 2-D ultrasound of a patient. This patient has a mitral valve insufficiency that results in the regurgitant flow, which the hemodynamic model predicts correctly. 3-D TEE ultrasound images are used to construct a patient-specific anatomical model of the valve (Fig. 3). In a healthy valve, the leaflets would



**Figure 3.** Mitral valve model constructed from 3-D ultrasound data acquired intraoperatively. The data used for reconstruction were obtained during diastole; segmentation used a level-set approach.

make contact and would not permit flow into the atrium during systole.

The proposed methods could also be used to augment TEE rendering and assist cardiologists and clinicians in better assessing pathologies such as heart valve regurgitation by providing a higher-resolution and more complete (i.e., full vectorial) picture of the flow in comparison with the current Doppler echocardiography.

Planned future work includes the following: (i) Refine the existing 2-D TEE image analysis algorithms and extend them to 3-D TEE for computing patient-specific 3-D motion and structure information through automated segmentation, mesh generation, optical flow estimation, and dynamic tracking. (ii) Utilize the mesh-free smoothed particle hydrodynamics (SPH) method to model blood flow. Mesh-free techniques eliminate meshing issues caused by merging two disparate domains, such as the atrial and ventricular cavities, as the mitral valve opens, thus avoiding the splitting of a single domain into two separate domains during valve opening. (iii) Construct a full fluid–structure interaction model of the heart muscle and blood by combining SPH with an FEM or a technique such as smoothed particle applied mechanics (SPAM). (iv) Develop a modifiable computational biomechanical model to predict the mitral valve closure behavior resulting from a virtual surgical reconstruction.

For further information on the work reported here, see the references below or contact [chad.sprouse@jhuapl.edu](mailto:chad.sprouse@jhuapl.edu).

<sup>1</sup>Sprouse, C., Yuh, D., Abraham, T., and Burlina, P., "Computational Hemodynamic Modeling Based on Transesophageal Echocardiographic Imaging," in *Proc. of EMBC 2009, Int. Conf. IEEE Eng. Med. Biol. Soc.*, Minneapolis, MN, pp. 3649–3652 (2009).

<sup>2</sup>Hammer, P., Perrin, D., del Nido, P., and Howe, R., "Image-Based Mass-Spring Model of Mitral Valve Closure for Surgical Planning," in *Medical Imaging 2008: Visualization, Image-Guided Procedures, and Modeling*, M. I. Miga and K. R. Cleary (eds.), Proc. of SPIE, Vol. 6918, SPIE, Bellingham, WA, 69180Q (2008).

<sup>3</sup>Einstein, D., Kunzelman, K., Reinhall, P., Nicosia, M., and Cochran, R., "Non-Linear Fluid-Coupled Computational Model of the Mitral Valve," *J. Heart Valve Dis.* 14, 376–385 (2005).