Ultrasound in Med. & Biol., Vol. 39, No. 12, pp. 2447–2462, 2013

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2013.07.013

● *Original Contribution*

# ENDOCARDIAL SURFACE DELINEATION IN 3-D TRANSESOPHAGEAL ECHOCARDIOGRAPHY

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(*Received* 7 *November* 2012; *revised* 16 *July* 2013; *in final form* 29 *July* 2013)

**Abstract—We describe and compare several methods for recovering endocardial walls from 3-D transesophageal echocardiography (3-D TEE), which can help with diagnostics or providing input into biomechanical models. We employ a segmentation method based on 3-D level sets that maximizes enclosed volume while minimizing surface area and uses a growth inhibition function that includes 3-D gradient magnitude (to locate the endocardial walls) and a thin tissue detector (for the mitral valve leaflets). We also study delineation using a graph cut method that performs automated seeding by leveraging a fast radial symmetry transform to determine a central axis along which the 3-D volume is warped into a cylindrical coordinate space. Finally, a random walker approach is also used for automated delineation. The methods are used to estimate clinically relevant cardiovascular volumetric parameters such as stroke volume and left ventricular ejection fraction. Experiments are performed on clinical data collected from patients undergoing cardiothoracic surgery. Performance evaluation includes comparisons of the automated delineations against expert-defined ground truth using a number of error metrics, as well as errors between automatically computed and expert-derived physiologic parameters. (E-mail: philippe.burlina@jhuapl.edu)** **© 2013 World Federation for Ultrasound in Medicine & Biology.**

***Key Words:*** **3-D Transesophageal echocardiography, Endocardial wall segmentation, Level Sets, Graph Cuts, Random Walker.**

## INTRODUCTION

Segmenting the endocardial wall boundaries has a number of applications in cardiology and cardiothoracic surgery. Automated segmentation can be useful for training purposes, it can help characterize the pathophysiology of cardiovascular diseases and perform diagnostics, it can inform computer-aided minimally invasive interventions and it can aid in pre-operative surgical planning and modeling. An important use case is mitral valve disease (MVD). Surgical interventions for MVD are challenging, and treatment may involve one or more options, including insertion of an annuloplasty ring, reshaping of mitral valve leaflets or the recomposition of mitral valve chordae tendineae. The pre-operative evaluation of these options can be accomplished by simulating their likely outcomes. Recent studies performing biomechanical simulations of the heart have exploited patient-specific anatomy (Burlina et al. 2013; Hammer et al. 2011; Votta et al. 2008). Segmentation of the endocardial walls provides boundary conditions that are necessary for personalized modeling techniques.

Three-dimensional transesophageal echocardiography (TEE) is now being used for clinical, pre-operative and intra-operative cardiac applications. One reason is that it allows for acquisition of 3-D time-varying image sequences at rates up to 90 Hz, a capability that is unparalleled by other modalities and is essential to observing the very rapid motion of some of the left heart anatomic components. However, performing segmentation from 3-D echocardiographic imagery can be complicated by lower spatial resolution (although the resolution of the 3-D ultrasound [US] platform used in this study is on par with other clinical volumetric modalities), degraded contrast (contrast for 3-D TEE is acceptable for the left atrium and mitral valve areas, which are closer to the probe, while lower contrast affects principally the basal and apical areas of the left ventricle), the presence of imaging artifacts (*e.g.,* noise, shadowing and reverberation), cropping of the apical areas and 3-D TEE imaging

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variations dependent on the skills of the ultrasonographer. Acquiring 3-D TEE over one or several heart cycles at these rates also results in large data sets that cannot be practically segmented by a human in a reasonable time frame. It is therefore of interest to seek automated or semi-automated methods that make the segmentation fast and reproducible.

## PRIOR WORK

Segmentation is a very important task in medical imaging, and many techniques have been presented over the years (Heimann et al. 2009; Kang et al. 2012; Leung and Bosch 2010; McInerney and Terzopoulos 1996; Noble and Boukerroui 2006; Petitjean and Dacher 2011). As previously mentioned, 3-D US and 3-D TEE have a number of key advantages that make their usage very appealing for segmentation, but the disadvantages of current 3-D US systems (*e.g.,* shadowing, noise and artifacts) require that prior segmentation methods be modified to produce reasonable results.

A number of methods have been developed for 3-D US endocardial border delineation, several of which have been covered in a review by Leung and Bosch (2010). Methods can be divided into four groups, as seen in Kang et al. (2012): (i) boundary-driven techniques, (ii) region-based techniques, (iii) graph-based techniques and (iv) model fitting techniques. Boundary-driven techniques, such as active contours, can sometimes be limited in their ability to describe complex shapes. Region-based techniques, such as level sets, are more flexible than boundary-driven techniques and are also capable of handling noisy data. When applied to 3-D US data, especially data with strong shadowing and artifacts, level sets can overrun important structures or bleed out of the desired regions; we attempted to address these issues in this article via the design of an inhibition function and by automatically learning the number of level set iterations needed. Graph-based techniques segment images on the basis of graph connectivity between seed pixels. Graph cut approaches, such as the method proposed by Boykov and Jolly (2001), can also have issues such as over-running faint structures or over-segmenting desired regions because of strong shadowing; these issues, among others, make the selection of seed points very important. We address seeding in our graph cut method by leveraging the radial symmetry transform, which avoids manual seeding. Random walker segmentation, originally proposed by Grady (2006), also addresses seeding issues to some degree. Finally, model fitting techniques, such as active appearance models and active shape models, require the creation of a model for the desired segmentation target. These models are then iteratively adapted to fit the data. One advantage of these methods is that complex model parameters can be easily extracted once a model is fit to the data. Model fitting techniques can also handle noise and shadowing fairly well. However, model creation is far more complex than the seeding procedure required by other algorithms. Model fitting techniques can also fail if the model is not general enough (*e.g.,* when processing diseased patient data) or under-perform if the model is too general (*e.g.,* a single model created using both normal and pathologic cases).

Our article describes and compares several approaches to 3-D TEE endocardial wall segmentation. One such approach is based on 3-D level sets. Foundational work on level set and recent developments can be found in the work of Caselles et al. (1997), Li et al. (2005), Malladi et al. (2002) and Mumford and Shah (1989). Our article extends the formulation of Li et al. (2005) to three dimensions. The contribution of our study lies in its application to 3-D TEE and the development of a growth inhibition function whose components are designed to address the problem of 3-D TEE-based left endocardial wall segmentation. This is done by using a function that factors in several components to address the specific challenges of this problem: this function combines a *k*-means term and an edge indicator function to handle the endocardial boundaries. One of these challenges is that the level set has a tendency to march over finer structures such as the mitral valve leaflets, and this is even more of a challenge in 3-D TEE, where noise and contrast may enhance this behavior. Our inhibition function therefore includes a term that helps preserve these structures: this is done by an adjunct factor in the form of the structure tensor-based thin tissue detector dedicated to the mitral valve leaflets. Another novel contribution of this study is a graph cut method that avoids manual seeding by leveraging a radial symmetry transform and by converting the US cube into a cylindrical coordinate system. For completeness, a random walker segmentation method is also used for comparison. In addition, we use these automated delineation methods to compute relevant volumetric cardiac parameters. We evaluate performance for the resulting delineation and physiologic parameters by comparison with ground truth derived from expert delineations. This study is a building block along the way of providing a physician the ability to generate 3-D models that are useful for modeling and physiologic parameter estimation that can be used for diagnostics purposes. Preliminary portions of this work have been presented in conference proceedings (Juang et al. 2011; Vyas et al. 2013).

## 3-D LEVEL SETS

### *3-D dynamic surfaces*

We first explain the expanding 3-D dynamic surface approach. We then detail the inhibition function that