Ultrasound in Med. & Biol., Vol. ■, No. ■, pp. 1–17, 2014

0301-5629/$ - see front matter

ELSEVIER

http://dx.doi.org/10.1016/j.ultrasmedbio.2014.07.014

● *Original Contribution*

FULLY AUTOMATIC DETECTION OF SALIENT FEATURES IN 3-D TRANSESOPHAGEAL IMAGES

Ariel H. Curiale,[*†] Alexander Haak,[‡] Gonzalo Vegas-Sánchez-Ferrero,[*] Ben Ren,[‡] Santiago Aja-Fernández,[*] and Johan G. Bosch[†]

[*] Laboratorio de Procesado de Imagen, ETS Ingenieros de Telecomunicación, Universidad de Valladolid, Valladolid, Spain; [†] Thoraxcenter Biomedical Engineering, Erasmus University Medical Center, Rotterdam, The Netherlands; and [‡] Department of Cardiology, Thoraxcenter, Erasmus University Medical Center, Rotterdam, The Netherlands

(*Received* 31 *January* 2014; *revised* 10 *July* 2014; *in final form* 27 *July* 2014)

Abstract—Most automated segmentation approaches to the mitral valve and left ventricle in 3-D echocardiography require a manual initialization. In this article, we propose a fully automatic scheme to initialize a multicavity segmentation approach in 3-D transesophageal echocardiography by detecting the left ventricle long axis, the mitral valve and the aortic valve location. Our approach uses a probabilistic and structural tissue classification to find structures such as the mitral and aortic valves; the Hough transform for circles to find the center of the left ventricle; and multidimensional dynamic programming to find the best position for the left ventricle long axis. For accuracy and agreement assessment, the proposed method was evaluated in 19 patients with respect to manual landmarks and as initialization of a multicavity segmentation approach for the left ventricle, the right ventricle, the left atrium, the right atrium and the aorta. The segmentation results revealed no statistically significant differences between manual and automated initialization in a paired *t*-test ($p > 0.05$). Additionally, small biases between manual and automated initialization were detected in the Bland–Altman analysis (bias, variance) for the left ventricle (−0.04, 0.10); right ventricle (−0.07, 0.18); left atrium (−0.01, 0.03); right atrium (−0.04, 0.13); and aorta (−0.05, 0.14). These results indicate that the proposed approach provides robust and accurate detection to initialize a multicavity segmentation approach without any user interaction. (E-mail: ariel@lpi.tel.uva.es) © 2014 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Initialization, Segmentation, Active shape models, Ultrasound, Transesophageal echocardiography, Hough transform, Multidimensional dynamic programming, Gamma mixture model.**

INTRODUCTION

Echocardiography is one of the most relevant non-invasive diagnostic tools for real-time imaging of cardiac structure and function. Significant advances in 3-D transthoracic echocardiography (TTE) and 3-D transesophageal echocardiography (TEE) have made this modality a powerful tool in the clinic. Real-time 3-D TEE, for instance, has become the standard echocardiographic modality for visualization of structures in the atrial and valvular regions of the heart (Ahmed et al. 2003; Flachskampf et al. 2010). It is also commonly used for establishing the diagnosis of the mitral valve, describing the precise anatomy, and for visualizing mitral regurgitant jets in mitral valve prolapse and functional mitral regurgitation (García-Orta et al. 2007; Salustri et al. 1996).

A global quantification of the cardiac function is highly desirable to treat different kinds of pathologies. For this purpose, identifying salient structures in an objective, reproducible and automated way is a prerequisite. Three-dimensional echocardiography (3-DE) can provide accurate and reliable measurements for volumetric analysis and functional assessment of the right and left ventricles (Grapsa et al. 2010; Muraru et al. 2010; Shimada and Shiota 2011; van den Bosch et al. 2006). However, the complexity of cardiac anatomy, poor contrast, noise and motion artifacts makes the segmentation a challenging task.

Most segmentation approaches to the right and left ventricles depend on an appropriate initialization step (Jain et al. 1998). Many model-based left/right ventricle segmentation approaches have been studied (Petitjean

Address correspondence to: Ariel Hernán Curiale, Laboratorio de Procesado de Imagen, ETSI Telecomunicación Edificio de las Nuevas Tecnologías, Campus Miguel Delibes s/n, Universidad de Valladolid, 47011 Valladolid, Spain. E-mail: ariel@lpi.tel.uva.es

and Dacher 2010; Pham et al. 2000): active contours method (Kass et al. 1998), level-set method (Osher and Sethian 1988), active shape models and active appearance models (Cootes et al. 1995, 2001). Unfortunately, all these models have exhibited a strong dependence on the initial model placement. In general, the effect of an improper initialization is convergence to an undesired local minimum. Also, and despite the efforts of the research community and medical vendors, global quantification and volumetric analysis typically remain a time-consuming task and heavily rely on user interaction. For example, the time required to accurately extract the most common volumetric indices for the left ventricle for a single patient is in the range 5–6 min (Hascoët et al. 2010; Soliman et al. 2007). Thus, there is still a significant need for tools allowing fully automatic 3-D quantification.

Recently, several studies have focused on the reduction of user interaction in different 3-DE segmentation approaches for the mitral valve and left ventricle: Schneider et al. (2010) reduced user interaction to one single point (near the center of the mitral valve) in a mitral annulus segmentation approach, using a thin-tissue detector and principal-component analysis. Pouch et al. (2013) proposed a fully automatic segmentation of the mitral leaflets in 3-D TEE images using multi-atlas joint label fusion and deformable medial modeling. Van Stralen et al. (2008) proposed an automatic method to replace the manual initialization in 3-D TTE segmentation approaches to the left ventricle using the Hough transform (Ballard 1981) for circles and multidimensional dynamic programming (Üzümcü et al. 2006) to detect the left ventricle long axis (LV-LAX). Inspired by this work, Barbosa et al. (2013) introduced an initialization algorithm using the Hough transform for circles and multidimensional dynamic programming in 3-D TTE to realize a fully automatic segmentation scheme for the left ventricle.

The Hough transform for circles has been found to be a powerful tool in providing initialization in a wide range of automated and semi-automated segmentation approaches to the left ventricle (Barbosa et al. 2013; Mitchell et al. 2001; van der Geest et al. 1997; Van Stralen et al. 2008). However, the anatomic pose information derived from these approaches (LV-LAX and mitral valve) does not suffice to initialize our multicavity model because the rotation around the LV-LAX remains unknown. To overcome this problem, we estimate the aortic valve location by using a detector that enhances thin-tissue structures such as the mitral and aortic valves.

Some approaches to classifying structures have been proposed in the literature. Haralick et al. (1983) proposed a classification of local intensity structures based on analysis of the eigenvalues of the Hessian matrix of intensity gradients. Sato et al. (2000) generalized this approach to different types of local intensity structures such as lines, sheets and blobs. Recently, Burlina et al. (2013) combined this generalization with *k*-means clustering to detect sheetlike structures, providing a rough initial segmentation of the mitral valve, which is subsequently refined by user interaction.

The structure classification proposed by Sato et al. (2000) has performed remarkably in detecting lines, sheets and blobs in a wide range of medical images. However, a large number of misclassifications are introduced because of the typical granular pattern known as speckle, which is inherent to ultrasound (US) images. Speckle comes from the random interaction of scatterers within the resolution cell of US images (Wagner et al. 1983). For this reason, in our approach we introduce a probabilistic tissue characterization to prevent misclassifications.

Several statistical models have been proposed for describing the fully formed (or developed) speckle; salient among them is the Rayleigh distribution. Different studies with real acquisitions have indicated that other distributions, like Gamma and Nakagami, approximate the experimental distribution of real US images better than the Rayleigh distribution (Nillesen et al. 2008; Vegas-Sanchez-Ferrero et al. 2012). In our approach we use the Gamma Mixture Model (GMM) in structural tissue classification, because of its successful performance in filtering (Vegas-Sanchez-Ferrero et al. 2010), classification (Vegas-Sanchez-Ferrero et al. 2014) and registration (Curiale et al. 2013) in 3-D US images. However, it is important to note that the proposed methodology is not confined to the GMM model, and any other probabilistic model can be used instead. For example, Linguraru et al. (2007) used a Gaussian mixture model to segment different surgical instruments in 3-D US images.

In contrast to the previous authors, in this work we focus on the reduction of user interaction for a more complex 3-D segmentation approach. Our main goal is to provide the initial anatomic information (3-D position and orientation, 6 degrees of freedom) to initialize a multicavity segmentation approach for 3-D TEE (Haak et al. 2013) without any user interaction. With this aim, we propose a new automatic approach to detect the LV-LAX and the mitral and aortic valve locations. These locations will provide a suitable initialization of the multicavity segmentation method.

The main advantage of the proposed method is its robustness in 3-D TEE images compared with previous methodologies. Note that 3-D structure detection becomes a much more challenging task because many partial cavities are visible in the 3-D image and the left ventricle is not the most prominent; usually only the basal part of the left ventricle is visible (Fig. 1). Additionally, the presence of prominent structures of the mitral valve and aorta and the highly rotational variability make