Ultrasound in Med. & Biol., Vol. 41, No. 1, pp. 251–267, 2015

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2014.09.001

● *Original Contribution*

# SEMI-AUTOMATED SEGMENTATION AND QUANTIFICATION OF MITRAL ANNULUS AND LEAFLETS FROM TRANSESOPHAGEAL 3-D ECHOCARDIOGRAPHIC IMAGES

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(*Received* 23 *December* 2013; *revised* 18 *August* 2014; *in final form* 2 *September* 2014)

**Abstract—Quantification of three-dimensional (3-D) morphology of the mitral valve (MV) using real-time 3-D transesophageal echocardiography (RT3-D TEE) has proved to be a valuable tool for the assessment of MV pathologies, but of limited use in clinical practice because it relies on user-intensive approaches. This study presents a new algorithm for the segmentation and morphologic quantification of the mitral annulus (MA) and mitral leaflets (ML) in closed valve configuration from RT3-D TEE volumes. Following initialization, the MA and the ML and the coaptation line (CL) are automatically obtained in 3-D. Validation with manual tracings was performed on 33 patients, resulting in segmentation errors in the order of 0.7 mm and 0.6 mm for the MA and ML segmentation, in addition to good intra- and inter-observer reproducibility (coefficients of variation below 12% and 15%, respectively). The ability of the algorithm to assess different MV pathologies as well as repaired valves with implanted annular rings was also explored. The reported performance of the proposed fast, semi-automated MA and ML quantification makes it promising for future applications in clinical settings such as the operating room, where obtaining results in short time is important. (E-mail: enrico.caiani@polimi.it) © 2015 World Federation for Ultrasound in Medicine & Biology.**

*Key Words:* **Mitral valve, Echocardiography, Mitral annulus, Mitral leaflets, Block-matching, Graph-based segmentation, Mitral valve quantification.**

## INTRODUCTION

The mitral valve (MV) is located in the left atrioventricular groove and prevents the systolic backflow from the left ventricle (LV) to the left atrium (LA). The mitral annulus (MA) is one of its anatomic components, a fibroelastic ring with a three-dimensional (3-D) saddle shape to which the anterior and posterior mitral leaflets (ML) attach (Muresian 2009). The quantification of MA and ML morphology is valuable for the diagnosis, treatment and follow-up of patients with MV disease (Vergnat et al. 2011; Grewal et al. 2009; Maffessanti et al. 2011). Transthoracic echocardiography is the standard imaging modality used to evaluate patients with MV disease. Recently, the advent of real-time 3-D transesophageal echocardiography (RT3-D TEE) has enabled a more accurate morphologic and quantitative assessment of the MV apparatus, compared with conventional two-dimensional (2-D) or transthoracic 3-D ultrasound techniques, thus becoming the clinical standard for the pre-operative assessment of the MV (Grewal et al. 2009; Maffessanti et al. 2011). Despite its extended use, quantification of morphologic MA and ML parameters from RT3-D TEE data sets remains a challenge, and commonly it is performed using strategies that rely on manual and time-consuming segmentation procedures (Vergnat et al. 2011; Watanabe et al. 2006; Song et al. 2006).

Several semi-automatic approaches have been proposed to obtain more reproducible results and less cumbersome analyses. Schneider et al. (2010) proposed a semi-automatic method for the segmentation of the MA during systole, with the hypothesis that the annulus lies in the region where the thin-tissue of the leaflets is attached to the thicker-tissue of the ventricular walls. However, such an assumption is not valid in the anterior

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annular portion, which prevents the correct application of a thin-tissue detector and an evolving contour to segment the MA. In Schneider et al. (2012), the previous approach is extended to the dynamic segmentation of the MA (from diastole to systole), using a modified optical flow approach; however, the method relies on the same assumptions of the morphology of the MA near the anterior annular portion. Pouch et al. (2012) combine an active contour guided segmentation followed by a deformable model approach to segment both the MA and ML, but an adequate orientation of the MV within the pyramidal volume data set is required to achieve accurate segmentations, thus limiting the applicability of this approach. Burlina et al. (2010), Schneider et al. (2011) and Mansi et al. (2012) made use of model-based methods that incorporate geometric, morphologic or mechanical constraints that were dependent on the training sets and therefore could not be fully verified in the presence of MV pathologies. Ionasec et al. (2010) made use of machine learning techniques to delineate the 4-D MA; the method is accurate and has been thoroughly tested (1516 RT3-D TEE data sets), but it requires an extensive training database of manually delineated features, which makes it both dependent on the training sets and inaccessible to most. In addition, none of the proposed methods fully computes and exploits the local morphology of ML thickness and tenting, thus limiting the clinical applicability of those approaches.

In this article, we thoroughly describe and validate a novel semi-automated approach that requires minimal user interaction for segmenting the MA, the ML and the CL from RT3-D TEE data sets in the closed MV configuration (systolic phase), which allows the computation of novel quantitative parameters, such as regional leaflet thickness and regional tenting height. The accuracy and reproducibility of the MA and ML segmentation and of the computed parameters were tested on a heterogeneous data set of 33 patients; additionally, the potential clinical applicability of this approach in the presence of MV pathologies was also tested. Preliminary results of the proposed approach on a smaller group of patients were presented in Sotaquira et al. (2013).

## METHODS: MITRAL VALVE SEGMENTATION

The proposed method operates on the RT3-D TEE image by first deriving the MA from a set of user-defined points, and then constructing the ML 3-D surface in a fully automated fashion. For MA detection, we propose a modified block-matching algorithm inspired by the work of Nevo et al. (2007), able to track in 3-D space the position of the annular points starting from the set of annular locations defined by the user. This modified algorithm involves the use of image cross-correlation and the enhancement of annular locations using morphologic operations. Next, using a graph-based approach, the ML is automatically delineated from the set of detected annular points. Finally, the 3-D polygonal mesh representations of both MA and ML are computed, including a semi-automatic procedure for the coaptation line detection, and the set of morphologic parameters is then quantified.

Figure 1 depicts the flow chart for the proposed algorithm. Such steps are described in detail in the following sections.

### *Manual initialization*

After selecting a frame at closed valve (end-systole), the user navigates the 3-D volume and selects three points: one at the anterior (A) and posterior (P) annular locations and one in the left atrium (LA) (Fig. 2a). The mid-point between A and P defines the origin of the coordinate system. The axis in the longitudinal direction, perpendicular to the axis connecting A and P and pointing in the atrial direction, is then used to obtain a stack of 36 rotational cut-planes (inter-plane angular spacing of 5°). The LA point ensures that each plane in the stack is correctly oriented in 2-D space (*i.e.,* with the LA lying on top of the valvular plane and the LV on the bottom), regardless of the orientation of the MV within the acquired 3-D volume.

Finally, the user subsequently defined an additional set of 6 annular points:

- Antero-lateral (Al) and Postero-medial (Pm) points, selected from a cut-plane orthogonal to that containing the A and P points and passing through the origin of the coordinate system (Fig. 2b);
- 4 points on the anterior portion of the MA on four cut-planes in the stack, symmetrically positioned (at ± 15° and ± 30°) around A (Fig. 2c).

### *Mitral annulus segmentation*

Given the stack of 36 rotational cut-planes and the eight previously initialized annular points, the task is to locate in 3-D space the remaining 64 annular points $P_i$ ($i = 1...64$) on the non-initialized semi-planes (each of them consisting of one half of the original cut-planes, and thus containing one annular point). For each of these semi-planes, a region-of-interest (ROI) is automatically selected and centered on the initialized point in the semi-plane closer to $P_i$ (Fig. 3a). A region-of-search (ROS) is automatically defined on the semi-plane containing $P_i$ (centered on the ROI position) (Fig. 3b) and a weighted normalized cross-correlation (WNCC) (Bohs and Trahey 1991) between ROI (the template) and ROS images is then computed (Fig. 3c), where the weight corresponds to a Gaussian function. The ROI size was defined heuristically and set to 24 × 28 mm$^2$,