# Automatic Systole-Diastole Classification of Mitral Valve Complex from RT-3D Echocardiography based on Multiresolution Processing

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## ABSTRACT

Mitral valve repair is one of the most prevalent operations for various mitral valve conditions. Echocardiography, being famous for its low-cost, non-invasiveness and speediness, is the dominant imaging modality used for carrying out mitral valve condition analysis in both pre-operative and intra-operative examinations. In order to perform analysis on different phases of a cardiac cycle, it is necessary to first classify the echocardiograhic data into volumes corresponding to the systole and diastole phases. This often requires tedious manual work. This paper presents a fully-automatic method for systole-diastole classification of real-time three-dimensional transesophageal echocardiography (RT-3D-TEE) data. The proposed method first resamples the data with radial cutting planes, segments the mitral valve by thresholding, and removes noise by median filtering. Classification is then carried out based on the number of identified mitral valve regions. A multiresolution processing scheme is proposed to further improve the classification accuracy by aggregating classification results obtained from different image resolution scales. The proposed method was evaluated against the classification results produced by a cardiologist. Experimental results show that the proposed method, without the use of computationally intensive algorithms or the use of any training database, can achieve a classification accuracy of 91.04%.

**Keywords:** RT-3D Echocardiography, Mitral Valve, Systole-Diastole Classification, Cardiac Cycle, Ultrasound, Multiresolution

## 1. DESCRIPTION OF PURPOSE

*Lup-dub* is the distinctive sound that echoes throughout our entire life. Anatomically, it is the heart-beating sound produced by two groups of valves, namely the atrioventricular valves and the semilunar valves. Beating along with the group that produces the first *lup*, the rhythmically repeated opening and closing of the mitral valve allows oxygenated blood to flow from the left atrium to the left ventricle. Acting as a one-way door, another vital role of the mitral valve is to prevent any backflow of blood. The mitral valve is composed of the anterior mitral leaflet and the posterior mitral leaflet. In a normal functioning mitral valve, the coaptation of the anterior and posterior mitral leaflets must be tight enough to prevent blood from flowing back into the left atrium during systole.[1] Certain mitral valve conditions such as mitral regurgitation, mitral valve prolapse, or mitral stenosis, may cause inaccurate or improper opening or closing of the mitral valve during a cardiac cycle.

Mitral valve repair is a preferential choice over mitral valve replacement for various pathological conditions of the mitral valve.[2,3] In mitral valve repair pre-operative procedures and intra-operative settings, two-dimensional (2D), three-dimensional (3D) and real-time three-dimensional (RT-3D) transthoracic echocardiography (TTE) and transoesophageal echocardiography(TEE) are widely adopted non-invasive imaging modalities for quantifying the conditions severity, progression and repercussion.[4–8] In their review, Wong et al. also suggested that cardiac surgeons should be familiar with the various echocardiographic views for making optimal assessment of annulus dilation, pinpointing the ruptured chordae, spotting perforations of a leaflet, identifying the papillary muscle dysfunction, analyzing the LV function and calcification, and determining the thickening of the subvalvular apparatus.[9]

Observation and assessment based on different phases of a cardiac cycle is often required. For example, patients with classic Barlow's Disease would have mitral regurgitation at mid-to-late phase of the systole, whereas patients with fibroelastic deficiency with flail leaflets would have mitral regurgitation throughout the systole.[10] In order to make such investigative and objective measurements of the systolic or diastolic functions of the left atrium and left ventricle using RT-3D-TEE/TTE, much repetitive and manual work must be done.[11,12] With RT-3D-TEE/TTE, part of the pre-operative

echocardiographic measurements is to manually select the left ventricular end-systolic and end-diastolic volumes for other quantitative analysis of the mitral valve complex such as volume calculations, contour tracing, color-kinesis or mitral annulus identification.[13–16]

An automatic algorithm for rapid online analysis of the mitral valve anatomy and function is particularly useful during interventional procedures, when therapeutic decision needs to be made within minutes or even seconds. A combination of methods that searches for the correlation coefficients of the pixel intensity peaks within a manually defined region-of-interests in each time-step from 2D echocardiograms was proposed.[17] Graser et al. then proposed a method that could automatically detect a cardiac cycle on RT-3D-TEE correctly with an accuracy of 78%.[18]

In this paper, a method for automatic detection of the cardiac cycles from RT-3D-TEE images of the mitral valve is proposed. Specifically, our proposed work is able to automatically and accurately classify whether a 3D-TEE volume is in systole or diastole of a cardiac cycle.

## 2. METHODS

The end-systolic volume is defined as the last frame before the opening of the mitral valve while the end-diastolic volume is the last frame before the closure for the mitral valve.[19] In the context of image processing, a set of image-slices from the systolic volumes should have a single large region of cardiac tissues (brighter pixels) while another set of image-slices from the diastolic volumes should have two large disconnected regions of cardiac tissues. As illustrated in Figure 1, our proposed method is composed of the two stages, namely i) volumetric data preprocessing and ii) multiresolution based systole-diastole classification.

### 2.1 Volumetric data preprocessing

Every set of RT-3D-TEE data consists of a number of volumes $\Omega_k$ each of which represents a time-step $k$ of a cardiac cycle. Each volume embodies a large number of voxels and each voxel $v_i$ is essentially a numerical value that indicates the intensity of the ultrasound signal in that specific spatial location $(x_i, y_i, z_i)$. Hence, our proposed method starts with a preprocessing stage that begins with a radial-plane cut around the center of each volume $v_c$. Each radial plane $p$ is evenly spaced at an angular offset $\theta$ (Figure 2(a)). Since the normal functioning mitral valve is more or less radially symmetric, the use of radial-plane cut could render a consistent view of the mitral valve complex. For ease of computation, our method defines $\theta$ as $1°$, meaning a total of $M$, defined as 180, symmetrically radial slices will be extracted from each volume. Next, for each radial plane, a binarization filter and a median filter are applied. The binarization filter is a good approach to separate the cardiac tissues from the blood as both masses sit at different bands of pixel intensities while the median filter is efficient at removing random noise that is inherent in the echocardiographic images.

### 2.2 Multiresolution based systole-diastole classification

In this proposed method, the objective of multiresolution processing is to identify the object-of-interests that consistently appear from coarser resolution level to finer resolution level. Here, the object-of-interests are the disconnected cardiac tissues, which also acts as an indicator for the state of the diastole. In the event of a left ventricular systole, the systolic pressure shuts the mitral valve and drives the blood through the now-opened aortic valve to the body, which can confuse our classification. To handle such a case, our proposed method applies a dilation operation to various resolution scales with a linear structural element of proportional size so that the closure of the mitral valve is preserved and at the same time the opening of the aortic valve is disregarded. The linear structural element, when applied, can morphologically minimise the opening induced by the aortic valve. At each resolution level $c$, the number of connected regions, $r_c$, is computed based on a 8-connected neighborhood connectivity. For this proposed method, we use 5 resolution scales at $1/10$, $1/5$, $3/10$, $2/5$ and $1/2$ of its original size(Figure 3 and Figure 4). In order to classify whether a given volume is in diastole or systole, under this multiresolution processing scheme, the proposed method computes the mean number $\mu$ of connected regions of cardiac tissues across all resolution scales with the corresponding weights $\alpha_c$. For simplicity, $\alpha_c$ is set to 1. Finally, our method classifies a volume as diastole only when that volume has a significant number of radial-plane image-slices with two large clusters of pixels and systole otherwise. This is expressed in (1), (2) and (3) where $\Omega_k$, as previously mentioned, denotes the 3D volumetric data at $k$th time-step of a cardiac cycle and $\mu_p$ refers to mean number of connected regions at the $p$th radial-plane image-slice. If the mitral valve complex is anatomically diseased such that the closure cannot be completely sealed at systolic volumes, $\delta$ is a threshold that can be increased to relax the classification contraint in formula 3.

$$\mu_{k,p} = \frac{\sum_{c=1}^{n} r_c \alpha_c}{n} \tag{1}$$

$$g(\mu_{k,p}) = \begin{cases} 1, & \text{if } \mu_{k,p} >= 2 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$f(\Omega_k) \in \begin{cases} diastole, & \text{if } \frac{\sum_{p=1}^{M} g(\mu_{k,p})}{P} >= \delta \\ systole, & \text{otherwise} \end{cases} \tag{3}$$
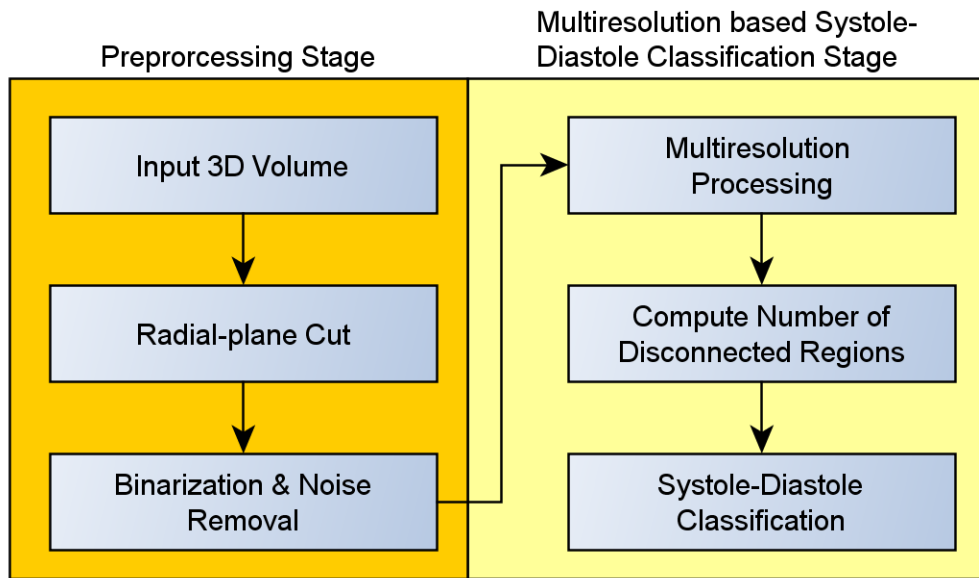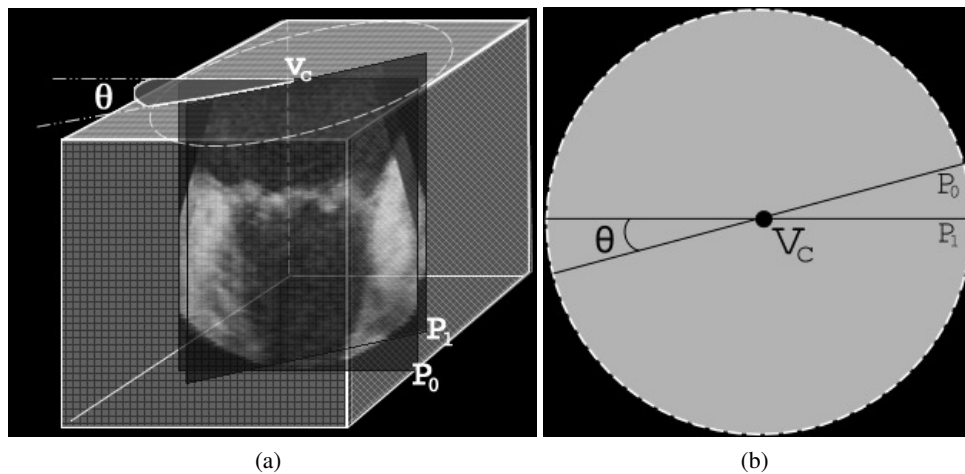


Figure 1. The flowchart of our proposed framework



(a)　　　　　　　　　　　　　　　(b)

Figure 2. An example illustration of two radial-plane cuts, $P_0$ and $P_1$ with angular offset $\theta$ and center $v_c$, derived from the 3D echocardiographic volume of the mitral valve complex. (a) 3D illustration (b) top-view illustration
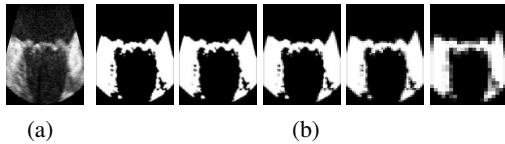
Figure 3. An example illustration of multiresolution processing. (a) Original image in systole (b) Processing under various resolution scales
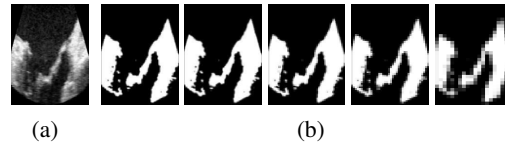


Figure 4. An example illustration of multiresolution processing. (a) Original image in diastole (b) Processing under various resolution scales

## 3. RESULTS

A total of 176 RT-3D-TEE volumes from 5 patients were processed. The dimensions of the volumes were roughly 200x200x200 voxels. And, in our experiments, we have defined $\delta$ to be 0.3 as we observed that the mitral valve can have a partial opening in early-diastole phase and this setting produces reasonable results as shown below.

Our sets of clinical RT-3D-TEE data are all de-identified and are patients with a normal functioning mitral valve. The ground truth was produced by a cardiologist who manually labelled each volume (a time-step) as systole or diastole. We compares our automatic classification results against the ground truth produced by the cardiologist. Table 1 shows how we defined true positive, false positive, true negative, and false negative.

Table 1. Definition of the confusion matrix for the systole-diastole classification evaluation

|  |  | Predicted class | |
| --- | --- | --- | --- |
|  |  | Systole | Diastole |
| Actual Class | Systole | True Positive | False Negative |
|  | Diastole | False Positive | True Negative |

In order to evaluate the effect of the multiresolution processing scheme, we carried out two sets of experiments, one without and one with the multiresolution processing scheme. In the experiment without the multiresolution processing scheme, we simply used the original image scale for systole-diastole classification. Table 2 shows the result without the multiresolution scheme. The average classification accuracy is 79.42% ± 10.59%.

Table 3 shows the result with the multiresolution processing scheme. The average classification accuracy is 91.04% ± 7.84%. In general, our proposed method achieved an accuracy over 92% except for valve #4. We noticed in a few time-steps, the center of the closed mitral valve lies at an off-center location which caused our method to obtain only a partial view of that mitral valve complex after the radial-plane cut phase.

Table 2. Evaluations results for all 5 different valves(from 5 different patients) *without* the multiresolution processing scheme

| Valve | Number of Timesteps | Precision Rate | Sensitivity(Recall Rate) | Specificity | Accuracy |
| --- | --- | --- | --- | --- | --- |
| 1 | 28 | 1.00 | 0.73 | 1.00 | 0.79 |
| 2 | 30 | 0.87 | 1.00 | 0.88 | 0.93 |
| 3 | 20 | 0.69 | 1.00 | 0.64 | 0.80 |
| 4 | 22 | 0.38 | 1.00 | 0.53 | 0.64 |
| 5 | 76 | 0.94 | 0.74 | 0.93 | 0.82 |

Table 3. Evaluations results for all 5 different valves(from 5 different patients) *with* the multiresolution processing scheme

| Valve | Number of Timesteps | Precision Rate | Sensitivity(Recall Rate) | Specificity | Accuracy |
| --- | --- | --- | --- | --- | --- |
| 1 | 28 | 1.00 | 0.88 | 1.00 | 0.93 |
| 2 | 30 | 0.94 | 1.00 | 0.93 | 0.97 |
| 3 | 20 | 1.00 | 0.92 | 1.00 | 0.95 |
| 4 | 22 | 0.83 | 0.77 | 0.77 | 0.77 |
| 5 | 76 | 1.00 | 0.86 | 1.00 | 0.93 |

## 4. CONCLUSIONS

In this paper, we proposed a method that automatically classifies RT-3D-TEE volumes into the systole and diastole phases of the cardiac cycles. To the best of our knowledge, the proposed method is the first to make such a classification fully automatic using the mutliresolution processing approach. With the multiresolution processing scheme and only a few simple image processing operations, our proposed method has achieved an average classification accuracy of 91.04%. Furthermore, we have also illustrated that without the use of computationally intensive algorithms and the need of a training database, we could still achieve an average classification accuracy of 79.42%. We believe that the radial-plane cut during the preprocessing stage has helped to effectively prepare a consistent set of data for the subsequent processing stages. Aside from the accuracy, we notice that, in general, both the precision rate and the specificity are lower without the use of the multiresolution processing scheme. We believe that this is desirable as it proves that the adoption of the multiresolution processing scheme minimizes the number of incorrect classification results. We also observe that the average sensitivity for the evaluation without the multiresolution processing scheme is higher. This may be due to the fact that it is easier to identity a diastole with lower resolution scales than with only its original resolution scale. In other words, the opening between the anterior mitral leaflet and posterior mitral leaflet during diastole, after being preprocessed with a radial-plane cut and a few morphological operations, is much more pronounced at a lower resolution scale.

We find out that one of the possible root causes to the incorrect classifications is largely due to the inherently low contrasts and inconsistent distribution of the speckle noise among intra-patient and inter-patient ultrasound volumes. Nonetheless the misclassifications were only limited to a time step or two within either the diastole or systole phase. There was no misclassification of the whole systole or diastole phase. Hence, to strengthen the classification accuracy, future work could include incorporating contrast enhancement techniques[20, 21] and incorporate prior knowledge that restricts any inconsistent classification in the middle of the systole or the diastole phase of the cardiac cycle.

Working as an automated preprocessing tool, our proposed method can be well adapted into existing mitral valve analytical frameworks that is dependent upon the selected phases of the cardiac cycle. This can greatly and reliably reduce the amount of tedious manual work that the majority of mitral valve pre-operative and intra-operative studies has.

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