Introduction

Clinicians today prefer echocardiography with Doppler as a noninvasive detection modality for mitral regurgitation (MR). Physical examination of the patient coupled with the analysis of the echocardiogram can give cue to the clinician about the presence of MR. However, assessing its severity calls for diagnostic methods that employ qualitative as well as quantitative metrics.

Proximal isovelocity surface area (PISA) method, which analyzes the proximal isovelocity hemispheric surface area of the flow convergence on the ventricular side, has been widely accepted by clinicians as a means for grading MR severity. Doppler-visualized PISA surface is assumed to be hemispheric in shape, and the quantity of blood flowing from the left ventricle (LV) to the left atrium (LA) during mid-systole can be calculated when the radius of the hemisphere shell and velocity at its surface are known. However, the shape of the Doppler-visualized PISA surface is not a hemisphere, but rather, a sphere flattened at the base. In general, hemisphere radius is measured which underestimates orifice area by approximately two-fold.

ABSTRACT

Mitral regurgitation (MR) is a disorder of mitral valve and it is one of the most common causes of cardiovascular morbidity and mortality. Mitral valve allows blood to flow from left atrium, to the left ventricle and Mitral Valve regurgitation results in poor apposition of the valvular leaflets, so that the heart's mitral valve doesn't close tightly, allowing blood to flow backward into the left atrium. Transthoracic Echocardiography (TTE) with Doppler is the widely used non-invasive technology for the detection and evaluation of severity of valvular regurgitation. Proximal isovelocity surface area (PISA) method has been widely accepted by clinicians as a means for grading MR severity. In this paper an alternate method to PISA to automatically quantify mitral valve regurgitation severity is proposed. This work attempts to automatically segment the jet region in color Doppler images using K-Means clustering. Further to quantify mitral regurgitation, jet area parameters and shape features are extracted from the segmented jet region which are then modeled using classifiers such as Support Vector machine (SVM) and Back Propagation Neural Network (BPNN). Quantifying MR with PISA calls for considerable expertise as a number of components must be taken into account to fully assess the severity of mitral regurgitation, however the results of the proposed method indicate that it could be used as an alternate method to automatically assess the severity of mitral regurgitation.

Keywords: BPNN, color Doppler, jet area parameters, K-means, mitral regurgitation, regurgitant jet, shape features, SVM

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The mitral valve and mitral regurgitation

The mitral valve is located between the LA and the LV and is composed of two flaps, as shown in Figure 1.

During systole or LV contraction, the flaps are tightly closed, but in patients suffering from mitral valve prolapse, the valve flaps get enlarged and stretch inward into the LA. During systole, the mitral valve sometimes "snaps" allowing some blood to flow back into the LA and it is called regurgitation.

Because of this leak, the heart pumps lesser blood to remaining parts of the body. This leak has no significance in case of mild MR; however, in cases of moderate or severe MR, to compensate for the leak, the LV exerts itself more to supply blood to other parts of the body. In due course, depending on the volume of blood that is regurgitated, the heart muscle and the circulatory system undergo a series of changes resulting in cardiovascular morbidity and mortality.

Color Doppler echocardiography

Accurate assessment of MR severity is crucial for making decisions regarding surgery, predicting prognosis, clinical decision-making, and for optimizing patient outcomes. Color flow Doppler is the most preferred technique to detect and evaluate MR as shown in Figure 2.

The backflow of blood into the LA from the LV through the mitral valve is displayed in the form of the jet by color Doppler echocardiogram, as shown in Figure 3. MR is visually diagnosed through apical two-chamber and apical four-chamber views, and regurgitation jets are often represented in plain blue hues or high-saturation color mosaics comprising blue, yellow, and orange hues. The region above the regurgitation orifice, where the blood converges to enter the LA though the orifice, is called flow convergence zone and the size of the orifice corresponds to the width of the orifice and volume of the blood flow. The blood enters the LA through a narrow orifice, and here, the velocity of the blood is the highest and this region is called "vena contracta." The width of the "vena contracta" gives an insight to estimate the severity of MR, and it is directly proportional to the width of the regurgitation orifice. The portion of the jet that is seen in the LA is the "jet body." The area and length of the jet body also correspond to the severity of MR.

To detect and extract the jet area for grading the MR, color segmentation using K-means clustering with histograms in hue-saturation-value color space is proposed. To acquire better color representation, the color histogram bins and gray histogram bins are separated.

In this work, color Doppler echocardiogram images are used to classify MR into three different categories, namely mild, moderate, and severe. For this, first, the jet region is segmented from the color Doppler images using our earlier proposed methodology, and using the segmented jet area, parameters, such as jet area perimeter, shape index, stroke volume (SV), and ejection fraction, are calculated. The calculated parameters are classified using backpropagation neural network (BPNN) and support
vector machine (SVM) classifier to evaluate the severity of the MR as mild, moderate, or severe.

**Proposed Methodology**

The block diagram of the proposed system is shown in Figure 3.

**Segmentation of the jet area by K-means clustering**

To start with the proposed method the color Doppler echocardiogram video is converted into frames, and the artifacts such as labels and wedges present in the image are eliminated as they may hinder the segmentation process. As we are interested only in the region containing the heart, the rectangular region of interest (ROI) that is the region containing the heart alone is selected by cropping the image using the value (135 105 775, 575) where (135,105) represents the top left (x, y) coordinates of the ROI triangle and 775 is the height and 575 is the width of the rectangle containing the heart region in the echocardiogram image. These values were arrived at, after empirically in our previous work,[12] after analyzing a number of color Doppler echo images. This rectangular region in each frame is then segmented using K-means clustering, and the mosaic pattern corresponding to the regurgitant jet is extracted using thresholding. The extracted mosaic pattern from all the frames is converted back to video for the convenience of a clinician.

K-means clustering is an unsupervised classifier, which classifies the features into K number of clusters, where K is a positive integer.[13] Clustering is done by minimizing Euclidean distance between data and corresponding cluster centroids. Then, the segmented region is converted to grayscale image, and since the pixel value of the jet area to be segmented lies between 240 and 250, the threshold is applied to extract the jet area alone. Sample frames and corresponding segmented regions are shown in Figure 4. Then, the frames containing the segmented jet area are converted back into video to help the clinicians to visualize the MR jet. Table 1 shows the comparison of jet area calculated by echocardiographer and the automatically segmented jet area by the proposed method. From Table 1, it could be seen that the difference of the manually segmented and the automatically segmented jet area is minimal and acceptable. The proposed method almost satisfies the clinical results and could be effectively employed to segment MR jet region in color Doppler echo images.

Then, from the segmented jet region, parameters such as volume, area, and jet area ejection fraction are calculated. Furthermore, shape features, namely perimeter and shape index are calculated to improve the diagnostic accuracy.

**Extraction of jet area parameters**

The volume of the jet area can be calculated as follows:

$$\text{Volume} = \frac{7.0}{2.4 + D^2}$$

(1)

Where “D” is the equivalent diameter.

The largest jet area volume (LJAV) and the smallest jet area volume in a cardiac cycle are calculated from the segmented jet area. The difference between them gives the SV, i.e., \( \text{LJAV} - \text{LJSV} \), and the ratio of SV to the LJAV gives the EF, i.e., the amount of blood regurgitated[9] and is given by:

$$\text{JAEF} = \frac{\text{LJAV} - \text{LJSV}}{\text{LJAV}}$$

(2)

JAEF can be used by the cardiologist to determine the severity of the MR.

**Table 1: Comparison of jet area segmented manually by a cardiologist and with the proposed method**

| Sample frame number | Jet area segmented automatically JA (pixels) | Jet area segmented manually JC (pixels) | Difference |JA-JC| (pixels) |
|---------------------|--------------------------------------------|----------------------------------------|------------|------|-----------|
| 1                   | 4670                                       | 5144                                   | 474        |      |           |
| 2                   | 1271                                       | 1178                                   | 93         |      |           |
| 3                   | 2324                                       | 2456                                   | 132        |      |           |
| 4                   | 1302                                       | 1289                                   | 13         |      |           |

JA- Jet area segmented automatically, JC - Jet area segmented manually
Extraction of shape features
Since the severity depends on JAV, the shape features are calculated from the segmented jet area with the largest volume in such a way, an average of each shape feature is calculated from LJAV frame to LJSV frame and a feature vector is formed. The LV shape index is sensitive to deviation of shape from a circular one and it depends on area and perimeter of the jet area boundary. The shape index is calculated as follows:

\[
LV \text{ Shape Index} = \frac{4\pi (\text{Area})}{(\text{Perimeter})^2}
\]  

The other shape features such as area, perimeter, equivalent diameter, minor axis length, major axis length, solidity, and eccentricity of the segmented area are also calculated. Calculating the distance between each adjoining pair of pixels around the border of the jet area region gives the perimeter.

Classification
The extracted jet area parameters such as JAV, jet area ejection fraction along with the shape feature area, perimeter, equivalent diameter, minor axis length, major axis length, solidity, and eccentricity are then fed to the SVM and BPNN classifier for classifying the condition as mild MR, moderate MR, and severe MR. The literature reveals that SVM and BPNN classifiers give excellent classification performance in medical image analysis, and as such, they are chosen to grade MR in this work.

The BPNN consists of an input layer, one or more hidden layers, and an output layer. BPNN learns from the training samples presented in the input layer. The input data navigate through the hidden layers which are multiplied with predefined weights, and the results are produced at the output layer. The results obtained are compared with the desired output, and the difference between the two is the error, which is then propagated backward through the network to the input layer. As the error is propagated backward, the weights connecting the neurons are adjusted by the backpropagation algorithm. The process is repeated until the desired output is obtained or the error is negligible. BPNN is elaborately discussed.

SVM is a supervised learning algorithm, for two classification problems in the simplest form. The principle of SVM is to find the hyperplane and the support vectors, which are samples that lie on or near the hyperplane. The hyperplane is chosen in such a way that the distance between the two classes is maximized, which helps SVM to model the two different classes from the training samples. SVM easily classifies linearly separable samples; however, when the samples are linearly inseparable, then the kernel functions such as Gaussian radial basis function, polynomial (inhomogeneous), polynomial (homogeneous), and sigmoid kernel could be used to separate the two classes. An intuitive explanation of SVM is given.

Results and Discussion
A database of 70 Doppler echocardiogram videos with MR disease (20 – mild, 30 – moderate, and 20 – severe) videos acquired using Philips iE33 xMATRIX echo system from the division of cardiology, Raja Muthiah Medical College Hospital, Annamalai University, is used for this study. Each video is up to 2 s having 26 frames/s.

The echocardiogram video or sequence is given as input to the proposed system, and the jet area is segmented using color-based segmentation using K-means clustering algorithm. Sample frames and corresponding segmented regions are shown in Figure 5.

From the segmented jet region parameters such as volume, area, and jet area ejection fraction are calculated. Furthermore, shape features such as perimeter, equivalent diameter, minor axis length, major axis length, solidity, and eccentricity of the segmented area are calculated. The extracted features are fed to BPNN classifier and in this work; the number of neurons in the input layer is nine. The hidden layer neurons are fixed to 50 after empirically analyzing the count. The output layer consists of three neurons which are nothing, but the MR severity grades mild, moderate, and severe. The features are also fed to the SVM classifier for classifying MR into any of the three classes, and for this, the radial basis function kernel of SVM is used.

Figure 5: (a) Original frames extracted and (b) segmented jet area
The performance of BPNN and SVM classifier in grading mitral valve regurgitation is given in Table 2. From the table, it could be seen that SVM with an accuracy of 90%, sensitivity of 85.1%, and specificity of 92.31% outperformed BPNN in correctly classifying the MR into mild, moderate, and severe.

Conclusion

In this article, an alternate method to PISA to automatically quantify mitral valve regurgitation severity was proposed. This method employs K-means clustering algorithm to perform color-based segmentation of the regurgitant jet region. From the segmented region, jet area parameters and shape parameters were extracted, which were modeled using SVM and BPNN classifiers to quantify the MR severity into mild, moderate, and severe. The results obtained indicate that the proposed work could be used as an alternative method to assess the severity of mitral valve regurgitation.

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Conflicts of interest
There are no conflicts of interest.

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