CHAPTER 4

AN EFFICACIOUS APPROACH FOR THE QUANTIFICATION OF MITRAL REGURGITATION USING IMAGE PROCESSING AND PROXIMAL FLOW CONVERGENCE METHOD

4.1. Introduction

Mitral Regurgitation also called Mitral Insufficiency (MI) or Mitral Incompetence is a Valvular heart disease. When this Valvular heart disease occurs, the heart valve that is mitral valve does not function properly as it causes abnormal leaking of blood to regurgitate into the left atrium of the heart, thereby the blood volume and pressure are increased [57]. When the blood pressure in the left atrium increases, correspondingly the blood pressure in the pulmonary veins gets abruptly increased. Due to this action, the left atrium gets enlarged for accommodating the extra blood leaking back from the ventricle. This tremendously enlarged atrium often beats rapidly in an irregular pattern and it is one of the disorders called atrial fibrillation. In atrial fibrillation, the effectiveness of heart’s pumping is reduced because the fibrillating atrium is trembling rather than pumping. This results in the prevention of normal blood flow through the atrium and some times blood clots are produced inside the chamber. When a blood clot breaks loose, it is pumped out of the heart causing blocking an artery and likely causing a stroke or other harm.

Severe regurgitation may lead to failure of heart. Due to the severe regurgitation, congestion or fluid accumulation may cause in the lungs because of increased pressure in the atrium, or the reduced forward flow of blood from the ventricle to the body deprives organs of the proper amount of blood [14]. When certain patients are doing exercise or exert by themselves or they lie down at night, the patients feel short of breath. To avoid waking up in the middle of
the night due to feeling of short breath, the patients might need to sleep with their heads lifted up. Additional worsening of heart failure, the left ventricle might evenly dilate and weaken. Some of the symptoms of this disease are patients may get tired easily and feel weak; they can notice swelling in their ankles and feet owing to fluid accumulation in these areas [22].

Mitral Regurgitation leads to valvular heart disease. In Mitral Regurgitation, the severity of the regurgitation is the main or key determinant of advancement to left ventricular dilatation and dysfunction. Therefore to evaluate the advancement of disease, the accurate or exact measurement of Regurgitant Volume in patients with MR is significantly noted and this will establish the optimal time needed for surgical repair or replacement. For accessing the Mitral Regurgitation a number of analytical approaches and diagnostic methods have been proposed. So far all the existing methods have exposed a restriction in one form or the other [7]. In table 4.1 the various aspects of Echocardiography and Doppler parameters used in evaluation of MR severity are illustrated. Figure 4.1 shows Color Doppler Echocardiographic image of MR jet in the parasternal long axis view (zoomed) showing three components of regurgitant jet.

Figure 4.1 Color Doppler Echocardiographic MR image in parasternal long axis (zoomed) view showing vena contracta, flow convergence and jet area in the left atrium.

Table 4.1 Echocardiographic and Doppler parameters used to evaluate MR severity: Utility, Advantages, and Limitations
<table>
<thead>
<tr>
<th>Structural parameters</th>
<th>Utility/advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA and LV size</td>
<td>Enlargement sensitive for chronic significant MR. Normal size virtually excludes significant chronic MR.</td>
<td>Enlargement seen in other conditions. Normal in acute significant MR.</td>
</tr>
<tr>
<td>MV leaflet/support apparatus</td>
<td>Flail valve and ruptured papillary muscle specific for significant MR.</td>
<td>Other abnormalities do not imply significant MR.</td>
</tr>
<tr>
<td>Doppler parameters</td>
<td>Simple, for mild or severe central MR; evaluates spatial orientation of jet.</td>
<td>Lead to technical, hemodynamic variation; significantly underestimates severity in wall-impinging jets.</td>
</tr>
<tr>
<td>Jet area-Color Flow</td>
<td>Simple, quantitative at mild or severe MR.</td>
<td>Not useful for multiple MR jets;</td>
</tr>
<tr>
<td>Vena contracta width</td>
<td>Quantitative; Presence of flow convergence at Nyquist limit of 50-60 cm/s alerts to significant MR. Provides both lesion severity (EROA) and volume overload (R Vol).</td>
<td>Less accurate in eccentric jets; not valid in multiple jets. Provide peak flow and maximum EROA.</td>
</tr>
<tr>
<td>PISA method</td>
<td>Quantitative, valid in multiple jets and eccentric jets. Provides EROA, RF and R Vol.</td>
<td>Measurement of flow at MV annulus less reliable in calcific MV and /or annulas. Not valid with concomitant significant AR unless</td>
</tr>
<tr>
<td>Flow quantitation-PW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet profile-CW</td>
<td>Simple, readily available</td>
<td>Qualitative; complementary data.</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Peak mitral E velocity</td>
<td>Simple, readily available, A-wave dominance excludes severe MR.</td>
<td>Influenced by LA pressure, LV relaxation, MV area, and atrial fibrillation.</td>
</tr>
<tr>
<td>Pulmonary vein flow</td>
<td>Simple, Systolic flow reversal for severe MR.</td>
<td>Influenced by LA pressure, atrial fibrillation. Not accurate if MR jet directed into the sampled vein.</td>
</tr>
</tbody>
</table>

The objective of this Chapter is to obtain a new technique, which is based on an Image processing method. By using the Doppler Echocardiography image via methods like Proximal Flow Convergence, this new technique can precisely calculate the percentage of backward flow of blood, regurgitant flow rate, orifice area and Regurgitant Volume in Mitral Regurgitation. The color Doppler Echocardiographic image with RGB color space is transformed into YCbCr during the preprocessing step and consequently it has been partitioned by using non-linear anisotropic diffusion method, which is used to segment color spaces exactly. The non linear anisotropic diffusion method is used to evaluate the percentage of backward flow of blood. The proximal flow convergence method has been exploited to enumerate Valvular Regurgitation by the examination of the converging flow field proximal to appraise the mildness, severity and eccentricity of a mitral regurgitant lesion. In addition this research provides an assessment of Qualitative and quantitative parameters that are valuable in grading the MR severity and utility, advantages, and limitations of Echocardiographic and Doppler parameters used in determining the severity of Mitral Regurgitation.

The rest of the chapter is organized as follows: The technical terms employed in this
chapter are summarized in Section 4.2. A review of related works concerned to the proposed methodology is shown in section 4.3. The methodology or process used for quantification of MR is discussed in part 4.4. Section and 4.5 concludes the chapter.

4.2. Technical Terms

Echocardiogram - An echocardiogram is an ultrasound test. By using the echocardiogram, the function of the heart is measured. In this, the heart disease, heart valve disease and other heart problems are frequently diagnosed.

Ultrasonography - It is an ultrasound-based diagnostic imaging technique. This technique is mainly used for visualizing subcutaneous body structures including tendons, muscles, joints, vessels and internal organs for feasible pathology or lesions.

Doppler Sonography - with the help of Doppler measurements, the Sonography is improved, which utilize the Doppler Effect to appraise whether the structures (usually blood) are moving towards or away from the probe, and its relative velocity.

Mitral Regurgitation - Mitral Incompetence is a heart disorder. In this regurgitation, when the heart pumps out the blood, the mitral valve does not close correctly. It is the anomalous leaking of blood from the left ventricle, through the mitral valve, and into the left atrium.

Anisotropic diffusion - Another name of anisotropic diffusion is Perona–Malik diffusion. The main goal of this technique is to reduce the noise present in the image.
4.3. Related Works

Plenty of research works have been carried out in the literature for quantification of Mitral Regurgitation and some of them have motivated us to take up this research. A brief review of some of those recent significant researches is presented below:

Choi et al., (2004) [58] have granted a study that was executed to estimate the precision and reproducibility in planning the mitral regurgitant orifice area with the PISA process. This research done on dogs affected by MR and chronic mitral insufficiency was also used for evaluating the result of general anesthesia on mitral regurgitation. By the help of PISA method, the Effective Regurgitant Orifice Area was measured and compared with the measurements concurrently obtained by quantitative Doppler Echocardiography 4 weeks after formation of Mitral Regurgitation. The same method was implemented on 11 patients who were suffering from isolated MR and on 8 Beagle dogs under two diverse protocols of general anesthesia. In association with the quantitative Doppler technique the ERO and RSV by the PISA method have obtained considerable values in experimenting on dogs (r = 0.914 and r = 0.839) and on 11 patients (r = 0.990 and r = 0.996). A significant decrease of RSV was established by the isoflurane anesthetic echocardiography but in fractional shortening (FS), EROA, LV end-diastolic and LV end-systolic volume, there was no significant change.

Grossmann et al., (2004) [59] have to appraise whether the fundamental mechanism of Mitral Regurgitation influences the reliability of the Proximal Flow Convergence method to appraise the Regurgitant Volume. In addition there is a comparison between the mode of imaging the flow convergence region and different correction algorithms for calculation of the
Regurgitant Volume. Then by the use of Proximal Flow Convergence method in organic mitral regurgitation, the Regurgitant Volume was overvalued which is irrespective of the application of different correction algorithms or the use of color Doppler M-mode. A sufficiently consistent determination of the Regurgitant Volume by the Proximal Flow Convergence method was probable in functional mitral regurgitation.

In 2007, Stephane Lambert [60] has presented a review that focuses on the use of Proximal Isovelocity Surface Area measurement in intra-operative evaluation of Mitral Regurgitation. The quantitative assessment of the severity of Mitral Regurgitation provided by PISA could be used for clinical decision-making in the operating room. Together with the various mathematical formulas used to calculate the effective mitral regurgitant orifice area, the Regurgitant Volume, and the Regurgitant Fraction, the physical principles behind the PISA method have also been reviewed in their discussion. Graphic and video demonstrations have been utilized to illustrate the presented step-by-step approach. At the end, different limitations and technical considerations related to measurement of PISA in the operating room have been discussed.

Stephane Arques et al., (2009) [61] have obtained the case report. These reports demonstrate the clinical applicability of the Proximal Isovelocity Surface Area method, which are used for identifying, locating and evaluating paravalvular prosthetic mitral regurgitation by transthoracic echocardiography.

4.4. The Proposed Methodology

The most important role of the clinical cardiology is for assessing the severity of Mitral Regurgitation. Mostly clinical decision making depends on its severity. The PISA and image processing methods aid efficiently to get the quantification of Mitral Regurgitation. The
proposed methodology mainly contributes three modules,

i. Preprocessing

ii. Anisotropic Diffusion Segmentation

iii. Mitral Regurgitation quantification and evaluation using PISA method

4.4.1. Preprocessing

In preprocessing stage, the RGB color Doppler images are changed into YCbCr color model. The equations to change RGB into YCbCr color model are as given below:

\[
\begin{align*}
Y &= 0.2989 R + 0.5866 G + 0.1145 B \\
C_b &= -0.1688 R - 0.3312 G + 0.5000 B \\
C_r &= 0.5000 R - 0.4184 G - 0.0816 B
\end{align*}
\]  

Figure 4.2 Preprocessing Output  
(a) Mitral Regurgitation original input image  
(b) Region-of-interest  
(c) YCbCr color space image

4.4.2. Anisotropic segmentation
Followed by preprocessing, in the second, the YC_bCr color image is segmented or partitioned using non-linear anisotropic diffusion method where color spaces are exactly segmented. By this the percentage of backward blood flow in Mitral Regurgitation is evaluated. The families of continuous partial differential equations are discretized by anisotropic diffusion in image processing. These equations simultaneously perform both diffusion and Laplacian processes. Provided that there are no sinks or sources that exist, the subsequent equation formulates the above mentioned process (for any dimension):

\[
\frac{\partial}{\partial t} u(x,t) = \text{div}(c(x,t) \nabla u(x,t))
\]

\(c(x,t)\) controls the diffusion strength. Vector \(x\) indicates the spatial coordinate(s). Variable \(t\) denotes the ordering parameter. The function \(u(x,t)\) is taken as image intensity \(I(x,t)\).

![Figure 4.3 Anisotropic diffusion segmentation output](image)

### 4.4.3. Quantification using PISA method

For the quantification of Valvular Regurgitation, the PFC method using color Doppler [49], [21] has been recognized as a reliable and exact quantitative method. Theoretically the flow convergence region proximal to a discrete regurgitant orifice in a flat planar surface is a
hemispherical volume. The blood flow in this volume is stepped up towards the regurgitant orifice along radial stream lines. Concentric hemispheric shells of equivalent and accelerating velocities (velocity isopleths) [62] comprise this zone of proximal flow acceleration.

Color flow mapping provides the ability to image one of these hemispheres that match with the Nyquist limit of the instrument. If a Nyquist limit can be selected so that the flow convergence has a hemispherical shape. The flow rate (ml/s) through regurgitant orifice can be computed by multiplying the hemispherical surface with aliasing velocity \( V_a \) as:

\[
FlowRate(Q) = 2\pi r^2 * V_a
\]  

...(4.3)

Now the Regurgitant Orifice Area (ROA) is given by

\[
ROA = 2\pi r^2
\]  

...(4.4)

here \( r \) indicates the radial distance from first alias to the regurgitant orifice. With the assumption, the maximal EROA is derived that the maximal PISA radius happens at the time of peak regurgitant flow and Peak Regurgitant Velocity:

\[
EROA = \left(6.28r^2 * V_a\right) / P_k V_{reg}
\]  

...(4.5)

From the above equation, by using CW Doppler we get the Peak Velocity of the Regurgitant jet (\( P_k V_{reg} \)). The product EROA and the Velocity Time Integral (VTI) are determined to estimate the Regurgitant Volume. This procedure gives maximal EROA than in other approaches. By this fact, the PISA calculation presents an instant peak flow rate. According to the continuity principle, blood flow passes through this specific hemisphere and also flows through the narrowed orifice [54]. Therefore the flow rate through any given hemisphere is equal to the flow rate through the narrowed orifice.

Mathematically,
\[ 2\pi r^2 V_a = A_o \times V_o \quad \ldots (4.6) \]

Here, \( A_o \) indicates the area of the narrowed orifice at the valve (cm\(^2\)), \( V_o \) represents the blood stream peak velocity through this orifice (cm/s). Therefore from the equation (4.6), \( A_o \) can be calculated as:

\[ A_o = \frac{2\pi r^2 V_a}{V_o} \quad \ldots (4.7) \]

As described previously, the Regurgitant Volume through a defected valve and the flow at the regurgitant orifice are equal. Supposing that the regurgitant orifice does not change throughout the period of the regurgitant flow, from the ROA and VTI of the regurgitant signal we can calculate the Regurgitant Volume.

Mathematically,

\[ R_{vol} = ROA \times VTI_{RJ} \quad \ldots (4.8) \]

Here, \( R_{vol} \) indicates Regurgitant Volume (cc), \( ROA \) indicates Effective Regurgitant Orifice Area (cm\(^2\)), \( VTI_{RJ} \) indicates Velocity Time Integral of regurgitant jet signal (cm). The simplified method calculates the Regurgitant Volume when Mitral Regurgitation is unusual. In this case, the ratio between maximum mitral regurgitant velocity and the \( VTI \) of the regurgitant signal is 3.25. Hence the Regurgitant Volume can be calculated from the regurgitant flow rate and the constant.

\[ R_{vol} = \frac{2\pi r^2 V_a}{3.25} \quad \ldots (4.9) \]
Regurgitant Fraction was declared as the percent of Regurgitant Volume \( (R_{vol}) \) divided by the total stroke volume at the mitral annulus level. The Regurgitant Fraction would be illustrated as:

\[
RF = \frac{\text{ForwardFlowThroughTheMitralValve} - \text{FlowThroughTheAorticValve}}{\text{ForwardFlowThroughTheMitralValve}} \quad \text{...(4.10)}
\]

Here \( \text{ForwardFlowThroughTheMitralValve} \) can be found by multiplying the Mitral orifice area \( (2\pi r^2) \) with Diastolic velocity integral and \( \text{FlowThroughTheAorticValve} \) can be found by multiplying the Aortic orifice area \( (\pi d^2/4) \) with Systolic velocity integral and the velocity integral of the regurgitant signal is measured to be 3.25.

The qualitative and quantitative parameters used in grading the Mitral Regurgitation severity are shown in table 4.2. The evaluated parameter values of mild, severe centric (concentrated about a center) and severe eccentric (deviating from a circular path or not having same center) are shown in table 4.3.

**Table 4.2 Qualitative and quantitative parameters useful in grading Mitral Regurgitation severity**

<table>
<thead>
<tr>
<th>Structural parameters</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA size</td>
<td>Normal*</td>
<td>Normal / dilated</td>
<td>dilated**</td>
</tr>
<tr>
<td>LV size</td>
<td>Normal*</td>
<td>Normal / dilated</td>
<td>dilated**</td>
</tr>
<tr>
<td>Mitral leaflets or support apparatus</td>
<td>Normal / abnormal</td>
<td>Normal / abnormal</td>
<td>Abnormal/Flail leaflet/Ruptured</td>
</tr>
<tr>
<td><strong>Doppler parameters</strong></td>
<td></td>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>Jet area</td>
<td>Small, central jet (less than 4 cm² or Less than 20% of left atrium area)</td>
<td>Variable</td>
<td>Large central jet (greater than 10 cm² or greater than 40% of left atrium area)</td>
</tr>
<tr>
<td>Mitral inflow-PW</td>
<td>A wave dominant ϕ</td>
<td>Variable</td>
<td>E wave dominant ϕ</td>
</tr>
</tbody>
</table>
Jet density-CW
Jet contour-CW
Quantitative parameters $\psi$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mild</th>
<th>Severe Centric</th>
<th>Severe Eccentric</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of blood flow</td>
<td>3.22</td>
<td>17.10</td>
<td>18.76</td>
</tr>
<tr>
<td>Aliasing velocity(cm/sec)</td>
<td>50</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Peak velocity (cm/sec)</td>
<td>520</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>r(cm)</td>
<td>0.685</td>
<td>1.011</td>
<td>1.245</td>
</tr>
<tr>
<td>Vena Contracta Width(cm)</td>
<td>0.231</td>
<td>0.545</td>
<td>1.185</td>
</tr>
<tr>
<td>ROA(cm$^2$)</td>
<td>2.947</td>
<td>6.41</td>
<td>9.73</td>
</tr>
<tr>
<td>Q(cm$^3$/sec)</td>
<td>147.33</td>
<td>384.6</td>
<td>583.8</td>
</tr>
<tr>
<td>EROA(cm$^2$)</td>
<td>0.2833</td>
<td>0.9628</td>
<td>1.4601</td>
</tr>
</tbody>
</table>

*Unless there are other reasons for LA / LV dilation. Normally 2D values: LV minor axis $\leq 2.8$ cm/m$^2$, LV end-diastolic volume $\leq 82$ ml/m$^2$, maximal LA antero-posterior diameter $\leq 2$ cm/m$^2$, maximal LA volume $\leq 36$ ml/m$^2$ (2,33,35); ** Exception: acute mitral regurgitation; $\xi$ At a Nyquist limit of 50-60 cm/s; Pulmonary venous systolic flow reversal is specific but not sensitive for severe MR. (AHA, ACC and ESC recommended values).

Table 4.3 Measured parameter values of Mild, Severe Centric and Severe Eccentric Mitral Regurgitation.
### Table 1

<table>
<thead>
<tr>
<th>$A_o$ (cm$^2$)</th>
<th>0.2833</th>
<th>0.9628</th>
<th>1.4601</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{vol}$ (ml/sec)</td>
<td>45.33</td>
<td>118.338</td>
<td>179.630</td>
</tr>
<tr>
<td>RF (%)</td>
<td>45.5</td>
<td>49.885</td>
<td>49.93</td>
</tr>
</tbody>
</table>

### 4.5. Conclusions

The fundamental importance of the severity of the disease is decided precisely regarding clinical decision making process for Mitral Regurgitation. The possibility of surgery requires confirmation of severity by a complementary procedure. However Mitral Regurgitation has no gold standard currently, so that it can’t evaluate the quantification of Regurgitant Volume, flow rate and the similar. With the support of PFC method, a new method that safely and accurately calculates MR in theory has been expected in this chapter. In the quantification Mitral Regurgitation Doppler image, a comparatively greater precision was attained on account of anisotropic diffusion segmentation. It is advantageous as I feel that, with the assistance of the flow convergence technique one can conclude the determination of cardiac output non-invasively by Doppler Echocardiography. For the cardiac output measurement several existing procedures joined to establish experimental results.

Most of the diagnostic techniques working on regurgitation have been challenged by the dynamic nature of lesion and the authority of several hemodynamic and physiologic conditions on it. The sequential images are compared quickly for a more precise assessment of interval change in overall above mentioned adaptive methods and for improved timing to carry out the surgery by the assistance of the improvements in digital echocardiography. The growth in the imaging technology would help the accessibility of spatial distribution of the Valvular Regurgitation promptly to progress the calculation of flow convergence, Vena Contracta and regurgitant finally that leads to development in the quantization of Valvular Regurgitation. The
future enhancements of the proposed work may offer a precise non-invasive technique for measuring the Mitral Regurgitation.