

Automated Quantification of Mitral Valve Regurgitation based on Normalized Centerline Velocity Distribution

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Abstract

Previous echocardiographic techniques for quantifying valvular regurgitation are limited by factors including uncertainties for orifice location and a hemispheric convergence assumption that often results in over- and underestimation of flow rate and regurgitant orifice area. Using computational fluid dynamics simulations, these factors were eliminated, allowing a more accurate assessment of regurgitation. A model was developed to allow automated quantification of regurgitant orifice diameter based on the centerline velocity data available from color M-mode echocardiography. The model, validated using *in vitro* unsteady flow data, demonstrated improved accuracy for orifice diameter ($y=0.95x+0.38$, $r=0.96$) and volume ($y=1.18x-4.72$, $r=0.93$).

1. Introduction

Accurate assessment of valvular regurgitation severity is of paramount importance, particularly for mitral regurgitation in which early diagnosis and correct timing for surgical intervention has become essential [1]. Despite evidence showing the accuracy of different quantitative methods [2-4], the proper quantification of mitral regurgitation remains an unresolved issue in the setting of a busy echocardiography laboratory. Complex and time-consuming features of previously validated methods have limited their widespread clinical use.

The Proximal Isovelocity Surface Area (PISA) method is a two-dimensional color Doppler echocardiographic technique for quantifying valvular regurgitation [4]. The technique is, however, limited by three assumptions. First, the method is based on the assumption of hemispherical isovelocity contours proximal to the orifice. Volumetric flow (Q) at any hemisphere is then calculated by the formula, $Q = 2 \pi r^2 v$ (Equation 1) where r is the radius of the hemisphere and v is the velocity at that hemisphere. The regurgitant orifice area (ROA) can be estimated by dividing the calculated flow rate by the peak velocity (v_p) obtained using continuous-wave Doppler; $ROA = Q / v_p$ (Equation 2).

However, due to the finite size of the orifice, the isovelocity contours flatten out as the orifice is approached, leading to an underestimation of the flow, depending on the selected value of the Nyquist velocity.

The second assumption of the approach is that the location of the orifice is known and used to determine the radius of the hemisphere (r). However, an accurate location is difficult to obtain and this has a major impact on the estimation of the flow rate since the value of r is squared. The third assumption is that the orifice is located in a flat ($\alpha=180$ degree) plane. While a correction factor has been previously shown to partially correct for this [5], the importance of local orifice geometry should not be neglected. A further limitation of the method is that these estimates of Q and ROA are made from a single moment in time and do not, therefore, demonstrate continuous, dynamic changes, an important issue in mitral valve prolapse and functional mitral regurgitation where ROA may vary several-fold during systole [6].

Figure 1 demonstrates the significant underestimation (up to 50%) of the flow near the orifice where the contours are not hemispherical (solid line). The figure also demonstrates the magnitude of errors made by mislocating the orifice by one millimeter.

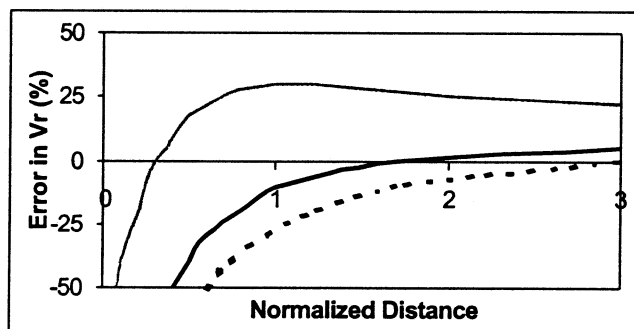


Figure 1. Error made by PISA in estimation of regurgitant volume (V_R) as a function of the normalized distance of the aliasing boundary from the orifice assuming the correct value of the radius r (solid line), 1mm overestimation of the radius (gray line) and 1 mm underestimation of the radius (dashed line).

The purpose of this investigation was to develop a technique that provides accurate estimation of orifice diameter and regurgitant flow using Doppler echocardiographic data without the aforementioned assumptions of the PISA technique. Data from computational fluid dynamics simulations were used to create a mathematical model describing the flow convergence and this model was validated using data obtained from *in vitro* experiments.

2. Methods

2.1. Fluid dynamics modeling

2.1.1. Simulations of valvular regurgitation

An axi-symmetric fluid dynamics model of mitral valve regurgitation was developed in a computational fluid dynamics (CFD) software package (Fluent 5.3, Fluent Inc., Lebanon NH). Simulations were performed under steady flow conditions for orifice diameters (d) ranging from 2 to 9 mm. Flow conditions were adjusted so that the pressure drop across the valve changed from 50 to 120 mmHg, resulting in peak flow velocities (v_p) from 3 to 6 m/s. Calculations were also performed for wall constraints from 100 to 240 degrees. A total of 160 simulations were performed.

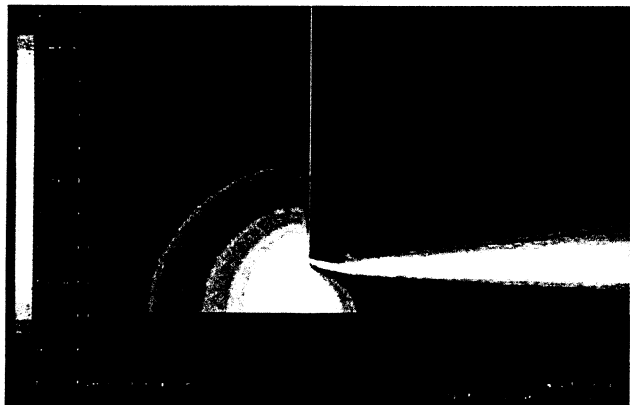


Figure 2. Contour plot of the velocity field for regurgitation through a 5 mm orifice with a peak velocity of 2.74 m/s after solving the Navier-Stokes equations using the CFD software.

The velocity data obtained from this computational model was then used to analyze the theoretical performance of the PISA method (Figure 1) and for the generation of a new, more accurate method to quantify mitral regurgitant orifice area. Figure 2 shows a typical result obtained from the computational fluid dynamics model with flow from left to right and the centerline flow along the bottom edge (axis of symmetry). Note the flattening of the isovelocity contours as flow converges proximal to the orifice. Centerline velocity profiles from all cases were extracted from CFD results and imported into a customized analysis program developed in LabVIEW (National Instruments, Austin TX) for post processing.

2.1.2. Normalized velocity distribution model

To develop the mathematical model of flow convergence, velocity profiles were normalized by the peak velocity along the centerline. Using the diameter of

the orifice, centerline coordinates were also normalized. Normalization of both velocity and distance allowed all flow convergence profiles to be described by a single equation, as the normalized profiles were very similar as shown in Figure 3. Note that the peak velocity appears slightly beyond the orifice, and the normalized velocity at the orifice was approximately $0.6v_p$ in all cases.

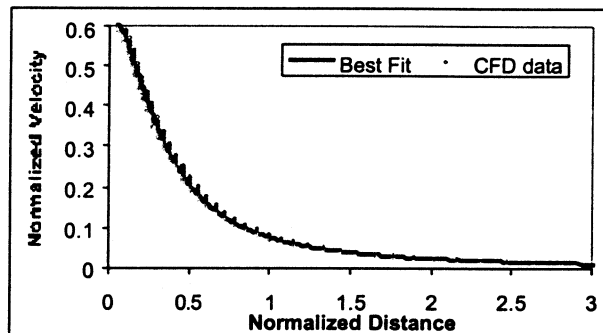


Figure 3. The data obtained from the CFD model for the $\alpha = 180$ degrees, $d = 2-9$ mm, $v_p = 3-6$ m/s after being normalized shows how all these cases can be described by a single fit.

Nonlinear curve fitting analysis was performed to determine the parameters (a_1, a_2, a_3) that provide the best-fit relationship between the normalized velocity (v/v_p) and the normalized distance (r/d) as shown in Equation 3. The proposed model depends on the normalized velocity distribution (NVD) along the centerline. Equation 3 also contains the variable r_0 , the location of the orifice along the centerline.

$$\frac{v}{v_p} = \frac{a_1}{1 + a_2 \left(\frac{r - r_0}{d} \right)^{a_3}} \quad (3)$$

The fitting analysis provided an overall best fit determined with $a_1 = 0.6$, $a_3 = 1.8$. Data analysis demonstrated a linear relationship between a_2 and the angle α ($a_2 = \alpha / 18 - 1.8$). For the flow rate, a similar strategy was followed. It was found that there exists a non-linear relationship between the flow rate and the product of the regurgitant orifice area and the peak velocity:

$$Q = b_1 \frac{\pi}{4} d^2 v_p \quad (4)$$

The parameter b_1 was best described by an inverse relationship with α ($40/\alpha + 0.4$).

The agreement between the simulated normalized velocity vs. distance relationship and that described by the mathematical model was very high ($r = 0.997$, $mse = 0.17$). The flow rate (Q) determined from Equation 4 also demonstrated strong agreement with simulated conditions ($r = 0.998$, $mse = 0.01$ ml/s).

2.2. Parameter estimation

An analysis program was developed in LabVIEW to obtain dynamic estimates of orifice diameter, orifice location and flow rate using the temporal information in the Doppler images. Integration of the flow rate over time provides the estimate of regurgitant volume.

The convergence profile (velocity as a function of distance from the orifice) can be obtained from a color M-mode (CMM) Doppler echocardiographic image. Calibration information required for CMM analysis is based on the color bar (velocity lookup table) provided on the image and the corresponding Nyquist velocities, the LabVIEW software determines a velocity distribution ($v[r,t]$) from the raw color image. Temporal and spatial resolutions are extracted from the horizontal and vertical axis of the CMM image.

Continuous wave (CW) Doppler imaging provides the peak velocity for velocity normalization. Peak velocity (v_p) is obtained from the CW image using an edge detection algorithm. The ECG signal is used to synchronize the CMM and CW images, allowing normalization of the convergence profile using the corresponding peak velocity value.

Finally, the angle α can be estimated from the standard 2D ultrasound image. The angle is assumed constant during regurgitation, leaving only the diameter d and the orifice location r_o as unknowns in Equation 3. Nonlinear fitting is performed with this convergence profile to obtain estimates of d , r_o , and Q every 5 ms. V_R is calculated by integration of the flow rate.

2.3. In Vitro data acquisition

An *in vitro* model with a blood analogue fluid was designed to validate the mathematical model. Using Doppler ultrasound equipment (Acuson Sequoia, Mountain View, CA), CMM and CW images were obtained under unsteady flow conditions created by a pulsatile flow pump. Figures 4 and 5 demonstrate typical Doppler images from the ultrasound machine. The pressure drop across the orifice was recorded using (Marquette Tram System, Milwaukee, WI) and the instantaneous flow rate was measured using a flow probe (Transonic HT207, Ithaca, NY) at the pump outlet. The flow signal was then integrated and used as a reference standard for comparison with the estimated V_R .

In total, 40 different data points were obtained. The orifice diameter varied from 2 to 9 mm, heart rate between 50 and 70 beats per minute and peak pressure drop from 50 and 124 mmHg. Acquired *in vitro* data was processed using the LabVIEW program to obtain d and Q as functions of time. Orifice diameters were computed as

the mean value of the time varying signal. Q was integrated to obtain V_R . For comparison, the standard PISA technique was applied to the *in vitro* data. Regression analysis was performed to evaluate the accuracy of the NVD method. Paired t-tests were performed to compare the results with the PISA technique. A p-value of 0.05 was considered significant.

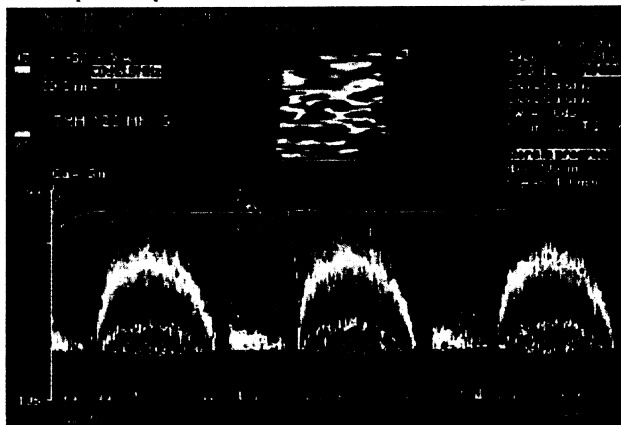


Figure 4. A typical color M-mode (CMM) Doppler image.

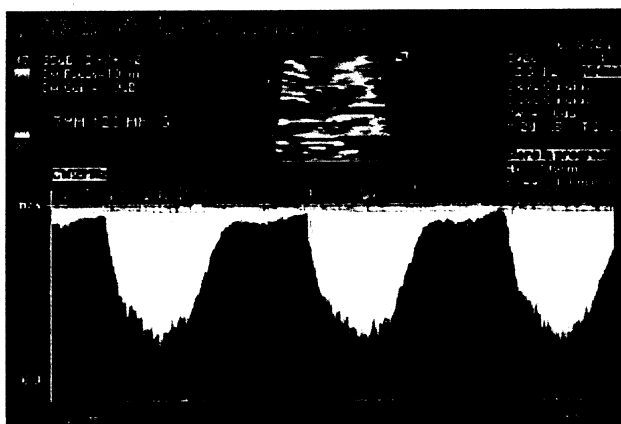


Figure 5. A typical continuous-wave (CW) Doppler image.

3. Results

Accurate estimation of orifice diameter was achieved using the NVD method without assumptions of orifice location and hemispherical isovelocity contours. Figure 6 shows the comparison of estimated orifice diameter with measured diameter ($y = 0.95x + 0.38$, $r = 0.96$, S.E. = 0.42 mm). Figure 6 also demonstrates the underestimation of the PISA method (Equation 1) even after inclusion of the angle correction [5]. A paired t-test comparison indicates a significantly better result from the NVD method ($p < 0.0001$).

V_R was calculated by integration of the flow of the NVD model (Equation 4). Figure 7 displays the correlation between the derived regurgitant volumes and

those measured by the flow probe. The NVD method demonstrated a strong agreement with the measured values ($y = 1.18x - 4.72$, $r = 0.93$, S.E. $7.7 = \text{mL/beat}$). This estimate was significantly ($p < 0.0001$) better than V_R derived by PISA ($y = 0.61x - 1.58$, $r = 0.72$, S.E. $= 9.3 \text{ mL/beat}$).

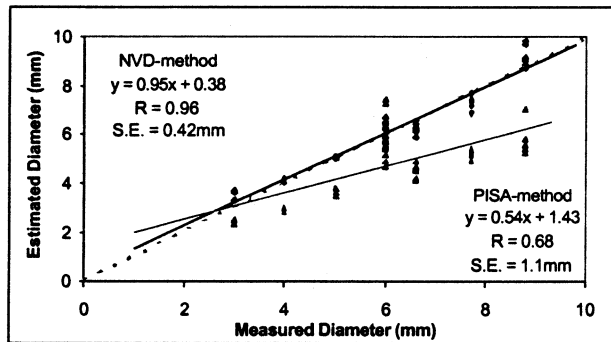


Figure 6. Estimated diameter from the NVD-model (black) and the PISA-method (gray) compared to actual diameter of the phantom used in the *in vitro* experiment.

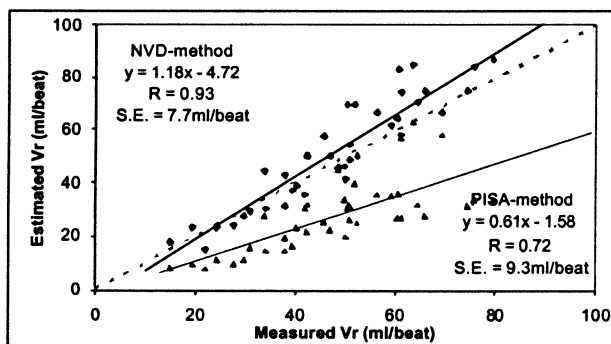


Figure 7. V_R estimated from the NVD model (black) and the PISA method (gray) vs. flow probe measurement.

4. Discussion and limitations

Results show that orifice diameter and regurgitant volume can be estimated with significantly greater accuracy using the normalized velocity distribution (NVD) model than by using the PISA method. Both parameters can be estimated with less error and have a greater correlation with the measured values.

Even though this method eliminates some limiting factors of the PISA method for quantifying the size of the regurgitant lesion, this new technique still has two assumptions in common with the PISA method. Both models assume a symmetrical proximal convergence zone, but in patients this is not always the case. Additional CFD simulations could potentially provide models of more complex valvular geometries, however, the complexity might increase significantly and limit clinical use. Secondly, the orifice is considered to be circular. Even though the orifice shape has a significant

impact on the result, previous studies have shown that the effect of orifice geometry is of higher order, causing minor errors, if biplanar measurements are performed [7].

5. Conclusions

Our results demonstrate that the NVD method can be used for a more accurate and reliable assessment of ROA and V_R . This improvement over the standard proximal convergence technique results from removing assumptions made for (a) isovelocity contours shape and (b) known location of the orifice. In addition, the improvement in accuracy was achieved without consuming greater time due to the automated processing. Further validation with *in vivo* data is planned to demonstrate applicability in clinical evaluation of valvular regurgitation.

References

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