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# 비반구 유동모델과 영역기반 윤곽선 기법에 기초한 자동근위 등속표면적의 결정 및 혈류량 추정

진경찬*, 조진호**

*경북대학교 센서기술연구소, **경북대학교 전자·전기공학부, 의공학과

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# Automatic Proximal Isovelocity Surface Area Determination using Non-hemispherical Flow Model and Region Based Contour Scheme for Blood Flow Rate Estimation

K.C. Jin*, J.H. Cho**

*Sensor Technology Research Center, Kyungpook National University
** Dept. of Biomedical Eng., School of Electronic and Electrical Eng., Kyungpook National University

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**요 약** : 순간적으로 승모판에서 혈류가 역류하는 영역을 측정하기 위해서, PISA 방법이 자주 이용되고 있다. 이 방법은 물질보존법칙에 근거하여, 구멍을 통과하는 유체량을 isotach 표면적과 이에 대응하는 속도의 곱으로 구하는 것이다. 이러한 PISA 방법에서 사용되는 유동모델은 반구모델과 비반구모델의 형태인데, 이는 isotach 표면적이 반구이거나 비반구임을 가정하여 계산된 것이다. 이러한 isotach 모델링에서는 isotach의 높이와 폭의 결정이 유체량을 추정하는데 아주 중요한 변수가 된다. 본 연구에서는 in-vitro 칼라 도플러 영상으로부터 PISA 영역을 추정을 위하여 영역기반을 근간으로 하는 비반구모델에 대한 표면적 추정 방법을 제안하였다. 이 방법의 타당성을 알아보기 위해 180개의 칼라 도플러 영상에 대해 isotach의 높이와 폭을 추정한 결과, 기존의 에지기반방법이 19개 영상에서 에러를 가지는 반면, 제안한 방법에서는 에러영상이 없음을 알 수 있었다.

**Abstract** : Blood measurement of the instantaneous mitral effective regurgitant orifice (ERO) has become feasible with use of the proximal isovelocity surface area (PISA) method. This method is based on conservation of mass, where the flow rate through the orifice is calculated as the product of the isotach surface area and the speed across the isotach. In a hemispherical or a non-hemispherical model of PISA flow model, the flow rate is calculated assuming that the surface of the isotachs have a hemispherical or a non-hemispherical shape. In this isotach modelling, the height and the width of isotach are important parameters which can determine the flow rate. In this paper, to estimate the surface area of the PISA envelope, we proposed the region based contour extraction technique in the non-hemispherical flow model with in-vitro color Doppler images. To validate the proposed method, we tested with the total 180 color Doppler images, and evaluated that the proposed method has no missed frame, whereas the edge based scheme has 19 missed frames in the total 180 frames.

**Key words** : Mitral regurgitation, Blood flow rate estimate, Echocardiography

## INTRODUCTION

Mitral regurgitation is most often caused by rheumatic heart disease, a type of degeneration of the valve, or dysfunction of the muscles that control the closing of the valve. Moreover, a heart attack may result in mitral

통신저자 : 진경찬, (702-701) 대구시 북구 산격동 1370
경북대 공대 7호관 센서기술연구소
Tel. (053)950-6571, Fax. (053)950-6827
E-mail. jkc@strc.knu.ac.kr

insufficiency if a portion of the heart that supports the position of the valve is disrupted

To decide the timing of surgery appropriately, the accurate quantification of mitral regurgitation is necessary. Although several quantitative methods exist involving angiography, echocardiography, and magnetic data, echocardigraphy remains still primarily a subjective assessment of the clinician

Mele *et al.* [1] has suggested that imaging the jet width and area in mitral regurgitation may be the most appropriate region to apply color flow mapping, however, this zone can only be imaged completely in the short axis view, which is difficult to measure, and requires several measurements to fully describe the area. As well, like other measurements of jet morphology, this method only provides an index of the severity of mitral regurgitation rather than a true quantitative measure of regurgitant volume or flow rate.

The quantitative Doppler method, which consists of measuring the forward flow through the regurgitant valve and subtracting it from the net forward output of the heart, has been validated clinically by Ascah *et al.* [2] and is often used as the gold standard for evaluating mitral regurgitation This method has been found to be a more accurate way of quantifying regurgitation, but is rarely applied clinically since several measurements in multiple imaging windows must be made. Additionally, evaluations made using this method can be time-consuming since significant care must be taken in the measurements as there are many sources of error that can propagate through the calculation.

A newer approach based on PISA measurements has been validated in-vitro and clinically [3,4]. The PISA method has the advantage of being independent of machine settings and it examines the relatively orderly flow upstream of a regurgitant orifice In this method, flow rate is calculated from conservation of mass by multiplying the surface area of an isotach by the speed of the flow passing through it. The primary difficulty of the current approach using the PISA concept relates to the model required to describe the local and global geometry of the isotach from the isovelocity contour. In the model of PISA, the flow rate is calculated assuming that the surface of the isotachs has a hemispherical [5] or a non-hemispherical shape [6]. In two flow models, the non-hemispherical flow model can produce the more exact result in flow rate estimation. In these modelling, the width and the height of PISA are important parameters, which can determine the regurgitant flow rate

Once color Doppler image has been acquired, several processing are required to facilitate the surface estimation of PISA model The edge based contour extraction, proposed by Mcleod [7], can estimate simply the edge of PISA envelope, but that may lead to wrong PISA contour since the pixels of image tend to link to allow for problems such as gaps along the PISA contour.

To estimate PISA envelope more exactly, we proposed the region based scheme [8,9] using mean shift procedure(MSP), reaction-diffusion(RD) smoothing and elliptic fourier descriptor(EFD) estimation This extraction method is based on the contour curvature. Finally, we evaluated this method could extract the PISA envelope more exactly than the edge based scheme.

## EDGE BASED SCHEME

To estimate the edge as the PISA envelope, Mcleod proposed the automatic PISA envelope extraction using the edge based scheme The scheme needs several imaging procedures which are edge branching, gaps connecting occurring along the PISA contour, edge trimming and multiple boundaries identification.

In the edge branching, the branching occurs when an edge forks in two directions, since the linking algorithm can choose only one path to follow. This results in a Y shaped contour being recorded as two distinct edges instead of one. To avoid errors resulting from this problem, the endpoints of each edge are examined to determine whether any of their joined into a new edge, and the data arrays of the two original edges are removed

When noise is not entirely removed from the image, gaps may appear along the PISA contour The presence of these edges means that the PISA envelope is represented by two or more separate edges rather than a single continuous edge. In these cases, the height and the width of the envelope can no longer be determined exactly. To obtain a single edge that corresponds to the true size and shape of the PISA contour, the endpoints of each edge record which are compared to the endpoints is less than the specified original edges are removed. To achieve optimal results, a technique which is called recursively with an increasing threshold was used. In some cases, the edge surrounding the PISA envelope may extend into the regurgitant jet, or into other areas of the image such as sector markings. The presence of these extended contours results in errors when reading the height and the width of the PISA envelope. When this occurs, edges must be trimmed according to an algorithm based on a knowledge of the general mushroom shape of the PISA envelope. More than one edges in an image will meet the threshold requirements chosen for identifying the PISA envelope. When this occurs, the correct edge is selected using secondary identification methods based on the four locator points of each edge.

## PROPOSED REGION BASED SCHEME

This method is based on the contour curvature and shape property. During MSP, the PISA envelope is extracted, in RD smoothing, the envelope is smoothed and EFD is able to estimate the PISA envelope. From the extracted PISA envelope, the flow rate can be estimated by conservation law. The main flowchart is shown in Figure 1.

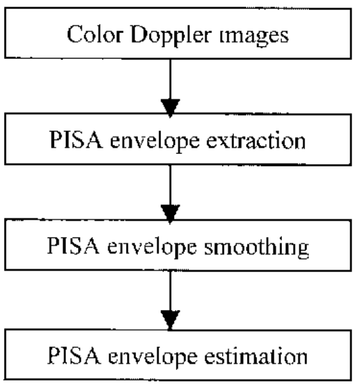


Fig. 1. The flowchart of PISA envelope determination based on region based scheme

### 1. MSP envelope extraction

In color Doppler image region, the image feature spaces derived from real flow image most have a complex structure and is sensitive to noise The significant features whose recovery is necessary for PISA region detection, correspond to clusters in this space. The number of clusters, their shape and rules of assignment have to be discerned solely from the color Doppler image data.

Whereas the parametric model, such as gaussian mixture, introduces severe artifacts since then the shape of the delineated clusters is predefined, the non-parametric cluster analysis uses the modes of the underlying probability density to define the cluster centers and the valleys in the density to define the boundaries separating the clusters To estimate the probability density for low to medium data sizes, kernel estimation is a good practical choice. It is simple, and for kernels obeying mild conditions the estimate is asymptotically unbiased, consistent in a mean-square sense, and uniformly consistent in probability We used the kernel estimation based clustering as density gradient estimation which is detected with the hill climbing MSP [10].

Let $\{X_i\}_{i=1..n}$ be an arbitrary set of $n$ points in the $d$-dimensional Euclidean space $R_d$. The multivariate kernel density estimate obtained with kernel $K(x)$ and window radius $h$, computed in the point $x$ is defined as

$$\overline{f}(x) = \frac{1}{nh^d} \sum_{i=1}^{n} K\left(\frac{x - X_i}{h}\right) \quad (1)$$

For Epanechnikov kernel, the density gradient estimate becomes

$$\hat{\nabla} f(x) = \frac{1}{n(h^d c_d)} \frac{d+2}{h^2} \sum_{X_i \in S_h(x)} [X_i - x] = \frac{n_x}{n(h^d c_d)} \frac{d+2}{h^2} \left( \frac{1}{n_x} \sum_{X_i \in S_h(x)} [X_i - x] \right) \quad (2)$$

where the region $S_h(x)$ is a hypersphere of radius $h$ having the volume $h^d c_d$, centered on $x$, and containing $n_x$ data points The last term in equation (2)

$$M_h(x) = \frac{1}{n_x} \sum_{X_i \in S_h(x)} [X_i - x] = \frac{1}{n_x} \sum_{X_i \in S_h(x)} X_i - x \quad (3)$$

is called the sample mean shift. Equation (3) shows that an estimate of the normalized gradient can be obtained by computing the sample mean shift in a uniform kernel centered on $x$. The mean shift vector has the direction of the gradient density estimate at $x$ when this estimate is obtained with the Epanechnikov kernel. Since the mean shift vector always points toward the direction of the maximum increase in the density, it can define a path leading to a local density maximum.

### 2. RD envelope smoothing

We considered a shape represented by the curve $C_0(s) = (x_0(s), y_0(s))$ undergoing a deformation, where $s$ is the parameter along the curve, $x_0$ and $y_0$ are the cartesian coordinates and the subscript $_0$ denotes the initial curve prior to deformation. Let each point of this curve move by some arbitrary amount in arbitrary directions. This evolution [11] is then described as

$$\frac{\partial C}{\partial t} = \alpha(s,t)\overrightarrow{T} + \beta(s,t)\overrightarrow{N} \qquad (4)$$
$$C(s,0) = C_0(s)$$

where $\overrightarrow{T}$ is the tangent, $\overrightarrow{N}$ is the outward normal, $s$ is the parametrization, $t$ is the time duration of the deformation and $\alpha, \beta$ are arbitrary functions.

To interpret the morphological operations like smoothing PISA shape, we considered the following deformation, as shown in equation (5) which is based on the RD, is the general propagation rule for a closed curve in time along its normal direction

$$\frac{\partial C}{\partial t} = (\beta_0 - \beta_1 k)\overrightarrow{N} \qquad (5)$$
$$C(s,0) = C_0(s)$$

where $\beta_0$ describes a deformation that is a constant motion along the normal, or constant deformation, $\beta_1$ describes a deformation that is proportional to the curvature along the normal or curvature deformation and $k$ means gaussian curvature.

### 3. EFD envelope estimation

The analysis of the PISA shape is based on fourier descriptors which are made invariant to changes in location, orientation and scale. Several representations are possible using an arc length $S$ parameterization of the chain-encoded contour. We followed the approach of Kual *et al.* [12] and expanded the function $x(s)$ and $y(s)$ separately to obtain the EFD. The EFD corresponding to the $n$-th harmonic of a contour composed $K$ points are given by

$$a_n = \frac{S}{2n^2\pi^2}\sum_{i=1}^{K}\frac{\Delta x_i}{\Delta s_i}\left[\cos\frac{2n\pi s_i}{S} - \cos\frac{2n\pi s_{i-1}}{S}\right]$$
$$b_n = \frac{S}{2n^2\pi^2}\sum_{i=1}^{K}\frac{\Delta x_i}{\Delta s_i}\left[\sin\frac{2n\pi s_i}{S} - \sin\frac{2n\pi s_{i-1}}{S}\right] \qquad (6)$$
$$c_n = \frac{S}{2n^2\pi^2}\sum_{i=1}^{K}\frac{\Delta y_i}{\Delta s_i}\left[\cos\frac{2n\pi s_i}{S} - \cos\frac{2n\pi s_{i-1}}{S}\right]$$
$$d_n = \frac{S}{2n^2\pi^2}\sum_{i=1}^{K}\frac{\Delta y_i}{\Delta s_i}\left[\sin\frac{2n\pi s_i}{S} - \sin\frac{2n\pi s_{i-1}}{S}\right]$$

where

$$s_i = \sum_{j=1}^{i}\Delta s_j, \quad S = \sum_{i=1}^{K}\Delta s_i$$

$$\Delta s_i = \sqrt{(\Delta x_i)^2 + (\Delta y_i)^2}$$
$$\Delta x_i = (x_i - x_{i-1}), \quad \Delta y_i = (y_i - y_{i-1})$$

In equation (6), $\Delta x_i$ and $\Delta y_i$ represent the changes in the $x$ and $y$ projections of the chain code as the $i$-th contour point is traversed. By contrast to the use of the cumulative angular function where the truncation of the fourier series can yield open curves, the curve reconstructed from the EFD is always closed. And the larger the number of ellipses involved, the more accurate the representation becomes.

## HEMISPHERICAL AND NON-HEMISPHERICAL FLOW MODEL

When flows are visualized using color Doppler imaging, only the axial component of velocity is measured and the envelopes visualized are actually isovelocity contours. These isovelocity contours are easily identified as there is a distinct blue red color shift once the aliasing velocity has been exceeded. By changing the aliasing velocity, multiple isovelocity contours can be measured.

To calculate the surface area of an isotach from the PISA envelope, a model describing the flow geometry is required since the imaged width of the PISA envelope is less than the width of the isotach, as seen in Figure 2.

The hemispherical model avoids this problem by assuming that the surface of the isotach have a hemispherical shape. Surface area can then be calculated by taking a single measurement along the centerline, $R_A$ in Figure 2, where speed and velocity coincide. The hemispherical model can lead to significant underestimation of flow rate since isotach geometry is hemispherical only in regions far from the orifice, and tends to flatten out near the orifice as shown in Figure 2(b).

Recently, Iwanochko *et al* proposed the non-hemispherical flow model using the half-height and half-width of PISA envelope. Using this model, they showed that the accuracy of the calculated flow rate was significantly improved compared to the results from using the hemispherical model.

As seen in Figure 2(a), isotachs radiate out from the orifice forming hemispherical shells and the surface area for these isotachs is simply represented by

$$A = 2\pi R_A^2 \qquad (7)$$

where $R_A$ is the axial radius of the isotach. Thus, the

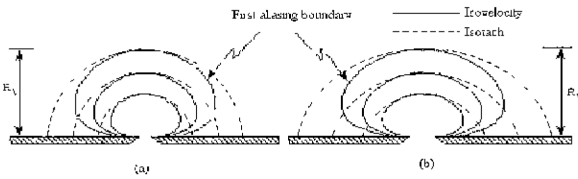


**Fig. 2.** Axial components of velocity for an infinitesimally small orifice (a), and for a finite sized orifice (b)

flow rate can then be calculated as the product of the surface area and the velocity at the aliasing boundary.

The solution for potential flow through an orifice with the finite size, rather than flow into a point sink, shows that isotachs are hemispherical only at distances far from the orifice Near the orifice the isotachs tend to flatten in the axial direction so that the half-width of the isotach is much larger than the half-height in Figure 2(b)

A non-hemispherical model of the shape suggested by Iwanochko *et al*, assumes that the cross section of the isotach is formed by taking a pair of circular arcs joined by a straight line, shown in Figure 3. The isotach surface is then formed by rotating this cross section about the axis Very close to the orifice, these arcs are centered near the edges of the orifice, while far away they will be centered about the origin The surface area of this isotach is

$$A = \pi r_0^2 + \int_0^{\pi/2} 2\pi(ra)d\theta$$
$$r = r_0 + a\sin\theta,\ r_0 = b - a \qquad (8)$$

which, when integrated and simplified,

$$A = \pi b^2 + (\pi^2 - 2\pi)ab + (3\pi - \pi^2)a^2 \qquad (9)$$

The dimension $a$ may be measured from the Doppler image, however, the dimension $b$ is not directly available since the instrument is sensitive only to the axial component of velocity. Iwanochko *et al.* used 0.62 as the conversion ratio between the measured half-width and the real half-width

For flow into a point sink, the flow is radially inward, with a velocity inversely proportional to the distance from the sink that can be represented by which when multiplied by the aliasing velocity of the instrumentation gives the flow rate

$$Q = (3.14d^2 + 5.97da + 1.37a^2)V_A \qquad (10)$$

where $V_A$ is the aliasing velocity Equation (10) provides a simple means of calculating flow rate, using the imaged half-height and the half-width of the PISA envelope, that accounts for the flattening of isotachs that takes place near the orifice.

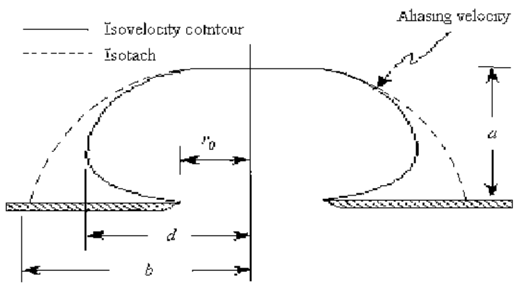


Fig 3 Non-hemispherical model suggested by Iwanochko et al.

## EXPERIMENT AND RESULTS

A clinical trial could not be performed to evaluate the proposed method due to a lack of suitable patients available and the difficulty of implementation in blood flow system, but an introductory examination was done to determine the effectiveness of the region based PISA envelope and to estimate the flow rate in the in-vitro flow images.

To compare the edge based scheme and region based scheme in color Doppler images, we acquired the color Doppler pulsatile images from Mcleod's research at Queen's university. He designed in-vitro flow simulator that provides variable flow rates through orifices of varying diameter. In the simulator, the flow is pressure-driven from the proximal chamber, which is padded with acoustic foam through an orifice plate into the distal chamber To get the pulsatile image, the pulsatile flow were produced with a solenoid valve placed upstream of the receiving chamber. The flow rate was varied from 2.0 to 3.5 L/min (30 to 60 $cm^3$/sec) through orifices and the mean flow rate was measured continuously throughout the acquisition period. The period was 6 seconds and total frame number was 180.

When an PISA envelope fails to be identified in a frame, it is counted as a missed frame, and the value of the calculated flow rate at that point is set equal to the value of the previous frame. In edge based scheme, the numbers of the missed frame are 19 of 180 total frame and in region based frame, the missed frame was not found

### 1. Edge based scheme

The result of the edge based scheme was shown in Figure 4. The extracted edges in Figure 4, describe the PISA isovelocity Figure 4(c) describes the tracking edge error, but the half-height and the half width may be induced correctly. Figure 4(f) shows the false edge image resulting from missed edge branching and gap determination, and good edge contour from edge trimming method was shown as Figure 4(i). Since this edge based scheme is sensitive to the noise present in an image which can make it difficult to identify a continuous contour in edge map, Mcleod performed the filtering during the edge detection by increasing the standard deviation of the gaussian filter. However, over-filtering results in a systemic underestimation of the PISA envelope.

### 2 Region based scheme

During the region extraction procedure, the cluster number, which means the segmented number of region, is four The extracted region image was shown in Figure 5(b), 5(e) and 5(h). In candidate regions, the PISA region was extracted from the largest red color in RGB region The result of PISA contour is shown as Figure 5(c), 5(f) and 5(i), was processed with RD smoothing and EFD estimation. The trimming method is based on the contour curvature for concave detection. For RD smoothing, RD gaussian was 1.0 and diffusion parameter, $\beta_1$, was 0.1.

### 3. Flow rate estimation

The calculated flow rate using non-hemispherical model for in-vitro experiment was found to be in agreement with measured flow rates In Figure 6, the mean value of flow rate calculated by edge based scheme was 46.9 and standard deviation from mean value was 11.2.

In region based scheme, the mean value was 45.0 and the standard deviation was 11.8. The mean value of edge based scheme is larger than the region based scheme since the RD smoothing using curvature was used to determine the PISA contour. If RD smoothing is not used, the mean value of region based scheme is similar to that of edge based scheme.

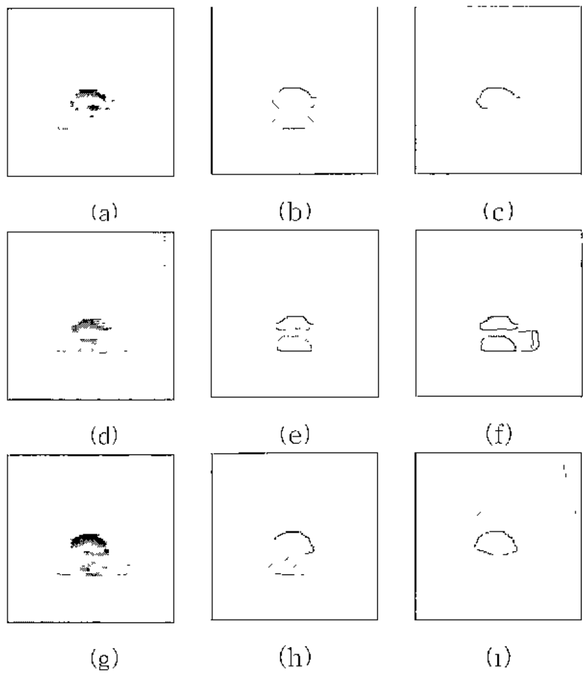

Fig. 4. Edge based PISA envelope: original image (a), (d), (g): the candidate edge (b), (e), (h), and extracted PISA isovelocity contour (c), (f), (i)

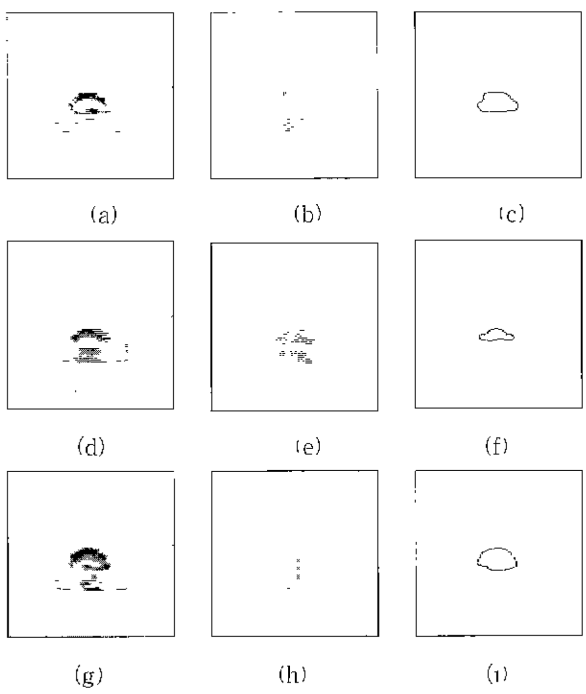

Fig. 5 Region based PISA envelope: original image (a), (d), (g) the candidate region (b), (e), (h), and extracted PISA isovelocity contour (c), (f), (i)

## CONCLUSIONS

Non-echocardiographics assesment methods are less common largely because they are either invasive or require dedicated laboratories and technicians, but in

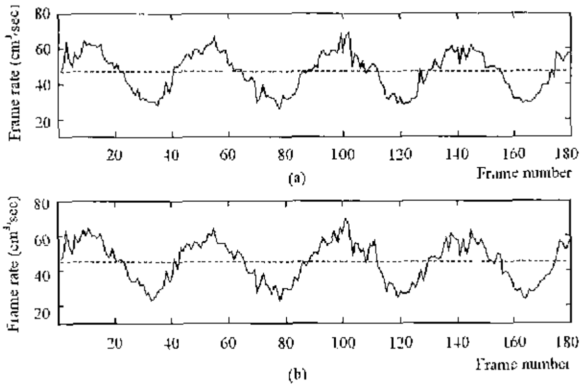


Fig. 6. Calculated flow rate using edge based scheme (a), and region based scheme (b)

comparison to these methods, echocardiography is much less expensive and relatively mobile.

This paper presents an automated extraction of PISA envelope for quantifying valvular regurgitation. The novel aspect of this method is the use of region based scheme to detect PISA envlope from color Doppler images. This region based scheme is more effective method rather than the edge based scheme and we evaluated that this method could produce no missed frame, whereas the edge based scheme has 19 missed frames in total 180 frames. And this method also can be applied to any shape of velocity profile and estimate the flow rate effectively.

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## REFERENCES

1. Mele D., Vandervoort P., and Levine R., "*Proximal Jet Size by Doppler Color Flow Mapping Predicts Severity of Mitral Regurgitation*", Circulation, vol. 91, pp. 746-754, 1995
2. Ascah K.J., Stewart W.J., and Weyman A.E., "*A Doppler-two-dimensional echocardiographic method for quantitation of mitral regurgitation*", Circulation, vol. 72, pp. 377-383, 1985
3. Recusani F., Bargiggia G.S., and Sahn D.J., "*A new method for Quantification of Regurgitant Flow Rate Using Color Doppler Flow Imaging of the Flow Convergence Region Proximal to a Discrete Orifice*", Circulation, vol. 83, pp. 594-604, 1991
4. Rodriguez L., Anconina J., and Thomas J.D., "*Impact of Finite Orifice Size on Proximal Flow Convergence. Implications for Doppler Quantification of Valvular Regurgitation*", Circulation Research, vol 70, pp. 923-930, 1992
5. Bargiggia G.S., Tronconi L., and Montemartini, "*A New Method for Quantitation of Mitral Regurgitation Based on Color Flow Doppler Imaging of Flow Convergence Proximal to Regurgitant Orifice*", Circulation, vol 84, pp 1481-1489, 1991
6. Iwanochko R.M., Hiscoke B., and Sanfilippo A.J., "*In vitro analysis of colour Doppler flow with the use of proximal isovelocity surface area: Improved flow estimates using a nonhemispherical model*", Can. Journal Cardiology, vol. 15, no 1, pp 89-94, 1999
7. Mcleod C.L., "*Automated Image Analysis for Proximal Isovelocity Surface Area Echocardiography*", Master's thesis, Dept. of Mechanical Eng., Queen's University, Canada, 1997
8. Jin K.C., Cho J.H., "*Nonparametric clustering for brain segmentation*", 4th Asia-Pacific conf MBE, pp 336, 1999
9. Jin K.C., Cho J.H., "*STK Feature Tracking Using BMA for Fast Feature Convergence*", Journal of Korean Institute of Telematics and Electronics, vol 38, no. 8, pp. 81-87, 1999
10. Comaniciu D., Meer P., "*Distribution free decomposition of multivariate data*", Pattern analysis and Applications., vol. 2, pp. 22-30, 1999
11. Kimmel R., Bruckstein A.M., "*Analyzing and synthesizing images by evolving curves with Osher-Sethian method*", Int Journal Computer Vision, vol. 24, no 1, pp. 37-55, 1997
12. Kuhl F.P., Gardina C.R., "*Elliptic fourier features of a closed contour*", Computer graphics Image Processing, vol. 18, pp. 236-258, 1982