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영역기반 윤곽선 기법과 표면 분할 유동모델에 기반한 근위 등속 표면적 기법을 이용한 혈류량 추정

(Blood Flow Rate Estimation using Proximal Isovelocity Surface Area Technique Based on Region-Based Contour Scheme and Surface Subdivision Flow Model)

陳 景 贊*, 曺 辰 鎬**
(Kyung-chan Jin and Jin-ho Cho)

요 약

PISA 방법은 주로 승모판에서 역류하는 혈류량을 측정하기 위해 사용되고 있다. 이 방법은 PISA isotach의 기하학적 모양에 대한 모델링에 관한 것이다. PISA의 일반적인 유동모델은 isotach의 표면이 수식적으로 반구이거나 비반구임을 가정하여 계산된 것이지만, 본 논문에서는 영역기반방법으로 isotach를 추정한 후, 타원체의 높이에 기초한 실제적인 표면분할 유동모델을 이용하여 유체량을 추정하였다. 제안한 방법을 평가하기 위해, 30cm^3/sec-60 cm^3/sce의 실제 유량을 가지는 동적인 180개의 유동영상에 대해서 기존 방법들과 비교하였다. 실험한 결과, 반구 유동모델의 유체량 평균이 29 cm^3/sec로 실제 유체량 평균보다 35 %정도 적게 추정을 하였고, 제안한 방법의 평균은 45 cm^3/sec으로 비반구 유동모델의 평균과 같았고, 유체량 변화파형도 유사한 결과를 가짐을 알 수 있었다.

Abstract

The proximal isovelocity surface area (PISA) method is an effective way of measuring the regurgitant blood flow rate in the mitral valve. This method defines the modelling required to describe the geometry of the isotach of the PISA. In the normal PISA flow model, the flow rate is calculated assuming that the surface of the isotach is either hemispherical or non-hemispherical numerically. However, this paper evaluated the estimate flow rate using a direct surface subdivision flow model based on the height field after isotach extraction using a region-based scheme. To validate the proposed method, the various PISA flow models were compared using pusatile color Doppler images with flow rates ranging from 30 cm^3/sec to 60 cm^3/sec flow rate. Whereas the hemispherical flow model had a mean value of 29 cm^3/sec and underestimated the measured flow rate by 35%, the proposed model and non-hemispherical model produced a same mean value of 45 cm^3/sec, moreover, both flow models produced a similar pulsatile flow rate.

I. Introduction

The accurate quantification of mitral regurgitation is an important clinical objective for diagnosing and monitoring mitral regurgitation, which is most often caused by rheumatic heart disease or the dysfunction of the muscles that control the closing of the valve.

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* 正會員, 慶北大學校 電子工學科
(Dept. of Electronic Eng., Kyungpook National University)
** 正會員, 慶北大學校 醫工學科
(Dept. of Biomedical Eng., Kyungpook National University)

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Ascah *et al.*[1] clinically validated the quantitative Doppler method, which consists of measuring the forward flow through the regurgitant valve and then subtracting it from the net forward output of the heart. This method is often used as the basic standard for evaluating mitral regurgitation, however, it is rarely applied clinically, since several measurements in multiple imaging windows must be made and significant care must be taken when making the measurements.

Mele *et al.*[2] suggested that imaging the jet width and area of the mitral valve as an alternative method of evaluating the mitral regurgitation. However, this method is difficult to measure, and requires several measurements to fully describe the area. Moreover, this method only provides an index of the severity of the mitral regurgitation rather than a true quantitative measure of the regurgitant flow rate.

A more recent approach based on PISA measurements has been validated.[3] 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, the flow rate is calculated from the conservation of the mass by multiplying the surface area of an isotach by the speed of the flow passing through it. Isotach is isovelocity contour distorted by the transducer beam. The primary difficulty of an approach that uses the PISA concept relates to the model that is required to describe the local and global geometry of the isotach from the isovelocity contour.

Accordingly, to estimate the PISA isotach of color Doppler images in an in-vitro test, Mcleod[4] proposed an automatic PISA determination using an edge-based scheme. This method can effectively and usefully extract the edge, that is, the isotach contour, however, there still may be errors in the edge linking, trimming, gaping, and multiple boundary treatment.

In the conventional PISA flow model, the flow rate is calculated assuming that the surface of the isotachs is either hemispherical[3] or non-hemispherical.[5] In-vitro tests have shown that the hemispherical flow model can underestimate the flow rate, whereas the non-hemispherical model can estimate more accurately.

In this paper, to extract the PISA isotach exactly and model the PISA isotach surface physically, it is proposed that the determination of the PISA is based on a region-based scheme and a subdivision flow model. The region-based scheme is based on the curvature of the cross-section contour in the PISA isotach, and the surface subdivision method[6] is used for the surface area calculation.

The proposed method was evaluated using in-vitro pulsatile color Doppler images and produced similar results to the non-hemispherical flow model, whereas the hemispherical PISA flow model underestimated by more than 35%.

Ⅱ. Method

Once a color Doppler image has been acquired, some processing relating to isotach contour estimation is required to physically model the surface area calculation of the PISA flow model. The edge based scheme proposed by Mcleod, produces a false PISA contour as the image pixels tend to be linked to allow for problems such as gaps along the PISA contour. To alleviate this problem caused by the edge based scheme, a region-based scheme is proposed which uses a mean shift procedure (MSP), reaction-diffusion (RD) smoothing, and elliptic fourier descriptor (EFD) estimation.[7]

After extracting PISA envelope, a model describing the flow geometry is required. Until now, there are two PISA flow models assuming that the 3D surface of the isotach is hemispherical or non-hemispherical. These models are based on numerical rather than physical geometric modelling.

Therefore, to physically model the surface of the

PISA isotach, a subdivision surface flow model is proposed which is a surface measurement using the height field subdivision of an ellipsoid. The objective is to directly calculate the surface area of the PISA isotach using the total sum of the small surface patch.

1. PISA Envelope determination using region-based scheme

(1) PISA region extraction using MSP

In a color Doppler image region, the PISA region derived from the real image data is close to the red region in an RGB pallette. Using this knowledge, the closest feature space in RGB space is identified. In this method, the number of clusters was set at 4. A cluster means the candidate of cross-sectional region in PISA.

To find out the cluster in PISA image, the modes and valleys in the density is described by the use of density and density gradient. Mode is to define the cluster centers and the valley is to define the boundaries separating the clusters.

When estimating the density gradient, since the mean shift vector[8] always points towards the direction of the maximum increase in density, it can define a path leading to the local density maximum. After the MSP, the number of clusters was calculated.

(2) RD envelope smoothing

This study 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 o denotes the initial curve prior to deformation.

Furthermore, a simple curvature model was selected which captured the morphological operations as well as the smoothing of the PISA shape. In detail, the following deformation was considered.[9]

$$\frac{\partial C}{\partial t} = (\beta_0 - \beta_1 k)\overrightarrow{N}$$
$$C(s,0) = C_0(s) \qquad (1)$$

where β_0 describes a deformation that is a constant motion along a normal, or constant deformation, whereas β_1 describes a deformation that is proportional to the curvature along a normal, or curvature deformation.

(3) EFD envelope estimation

The analysis of the shape of the envelope is based on fourier descriptors which are made invariant to changes in location, orientation, and scale. The approach of Kuhl *et al.*[10] was followed plus the coordinate functions $x(s)$ and $y(s)$ were expanded separately to obtain the EFD.

The EFD is the closed contour which is represented as a composition in the proper phase relationship of ellipses. The larger the number of ellipses involved, the more accurate the representation becomes.

2. Surface subdivision flow model

When flows are visualized using color Doppler imaging, only the axial velocity component is measured, as a result, the envelopes visualized are actually isovelocity contours. These isovelocity contours are easily identified as there is a distinct blue red color shift. From the conservation of mass, the flow rate uses not isovelocity but isotach. 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.

The hemispherical model avoids this problem by assuming that the surface of the isotach is hemispherical. Recently, Iwanochko et al. proposed a non-hemispherical flow model using the height and half-width of the PISA isotach. Using this model, they showed that the accuracy of the calculated flow rate is significantly improved compared to the results using the hemispherical model. However, both of these models are based on numerical rather than physical geometric modelling. Therefore, these methods were evaluated using a physical modelling of the PISA isotach.

(1) Subdivision using height field

One of the main differences between the various subdivision schemes is whether all the vertices of all the successive control meshes obtained throughout the iterative process necessarily belong to the limit surface or not, that is, the difference between an interpolatory and non-interpolatory scheme[6]. Both kinds of scheme are useful for the purposes of LOD(level of detail) generation and hierarchical mesh coding, however, the interpolatory schemes would seem to be a better choice for a surface mesh which is similar to the target object.

A PISA isotach has a kind of hemi-ellipsoidal shape. Therefore, to model the surface area which consists of a polyhedral mesh in an ellipsoid, the subdivision connectivity rule of the boundary curve of an ellipsoid is required.

In the case of a spherical triangle, Arvo *et al.*[11] proposed a sampling algorithm for spherical triangles using Girard's formula, which can be applied to spherical polygons by decomposing them into triangles and applying the subdivision connectivity rule.

In the case of an ellipsoid, since the geodesic curves between the vertices is not the same as in a sphere, the subdivision connectivity rule of the ellipsoidal surface must be based on the height field of the boundary curve.

Given the axis length of the ellipsoid, the height field can be calculated by geometric algebra. Let V_0, V_1, and V_2 be points on the axis-aligned ellipsoid, as shown in Fig. 1, the ellipsoid can then be defined as

$$Y^T D Y = 1 \qquad (2)$$

where T denotes the transpose and D is a diagonal matrix whose diagonal entries are all positive. The planar triangle containing the vertices can be parameterized using.

$$X(s,t) = V_0 + s\times E_0 + t\times E_1 \qquad (3)$$

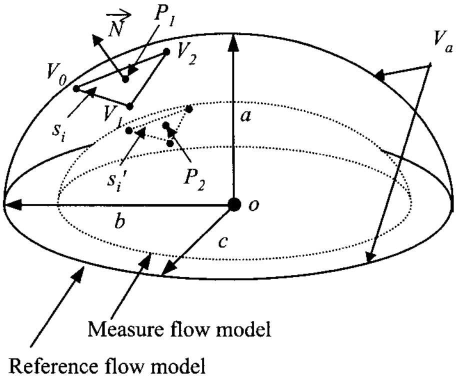


그림 1. 기준 모델과 측정 유동 모델을 이용한 표면 분할 모델

Fig. 1. Surface subdivision flow model using reference flow model and measured flow model.

where $E_0 = V_1 - V_0, E_1 = V_2 - V_0$ and $s\geq 0,\ t\geq 0$ and $s + t\leq 1$. Given a point $X(s,t)$ in the triangle, the height field h of the ellipsoid measured in the normal direction can be determined using the setting

$$Y = X + h\times \vec{N} \qquad (4)$$

where $\vec{N}$ is the normal unit. To obtain the quadratic in h, replacing the ellipsoid equation in (2), the height field can be acquired using

$$(N^T D N)h^2 + (2N^T D X)h + X^T D X = 1 \qquad (5)$$

From the geometry of the situation, there should be a positive and negative root for h except at those vertices where $h=0$. The positive root is the solution of the function $h=h(s,t)$ and the height field of the ellipsoid.

(2) Surface area measurement

In fluid dynamics, the equation of continuity is that the product, called the flow rate, of the cross sectional area and the fluid speed at all points along a pipe is a constant.

This study considered the flow rate equation as.

$$Q = V_a\times S = \sum_{i=1}^{n} V_a\times s_i = \sum_{i=1}^{n} V_i' \times s_i' \qquad (6)$$

where V_a is the aliasing velocity, S is the total surface area, n is the number of total surface patch, V_i' is the aliasing velocity in the small surface patch of the measure flow model, s_i is the small surface patch in the reference flow model, and s_i' is related to the measure flow model, as shown in Fig. 1.

In equation (6), V_i' can be expressed as equation (7).

$$\sum_{i=1}^{n} V_a \times s_i = \sum_{i=1}^{n} H(P_1, P_2)\, V_a \times s_i' \qquad (7)$$

$$H(P_1, P_2) = \frac{A(p_1)}{A(p_2)}$$

Where $H(P_1, P_2)$ is the proportional ratio related to the surface area, $A(P_1), A(P_2)$ is the surface area including the points P_1 and P_2 in the reference flow model. Points P_1, P_2 are included with s_i and s_i', respectively. The surface eccentricity generated by points P_1 and P_2 is the same as in the reference flow model.

Equation (7) means that the aliasing velocity in the measure flow model is induced from the reference flow model which is then used to calculate the surface area of the measure flow model. In equation (7), S_i is calculated using the subdivision principle.

(3) Comparison between flow models

To compare the surface area of the three flow models, the estimated hemispherical surface area of an oblate ellipsoid, which has a major axis, a_1, and minor axis, a_2, is shown in table 1. To calculate the analytic surface area, the technique developed by Dunkl *et al.*[12] technique was used. In table 1, model 1 is hemispherical model, model 2, the non-hemispherical model, and model 3, the surface subdivision flow model.

표 1. 편타원체의 표면적

Table 1. Surface area of oblate ellipsoid.

Axis length		Surface area of flow model			Analytic surface area
a1	*a2*	Model 1	Model 2	Model 3	
1.0	0.5	1.57	4.82	4.34	4.34
1.0	0.6	2.26	5.13	4.69	4.69
1.0	0.7	3.08	5.43	5.06	5.07
1.0	0.8	4.02	5.72	5.45	5.46
1.0	0.9	5.08	6.00	5.86	5.87
1.0	1.0	6.28	6.28	6.27	6.28

Model 1 tended to underestimate the surface area, whereas model 2 was usually larger than the analytic surface area and the overestimation ratio was basically proportional to the eccentricity. For example, when the eccentricity was 1.6, then the overestimation was 9 %.

In model 3, the initial vertices, generated by Rourke techniques[13], were 100 points, after the 4-th subdivision, the error rate between the analytic and the estimated area was below 0.1%.

Ⅲ. Experimental results

To model the PISA isotach, color Doppler pulsatile images were acquired from Mcleod's research at Queen's University. He designed an in-vitro flow simulator that consist of chamber, flow driving system and image acquisition system. And the PISA images were acquired by image acquisition system using ultrasound transducer. To gain a pulsatile image, the pulsatile flow was produced by a solenoid valve. The flow rate was varied from 30 to 60 cm^3/sec. The period was 6 seconds and total number of frames was 180.

1. PISA region estimation

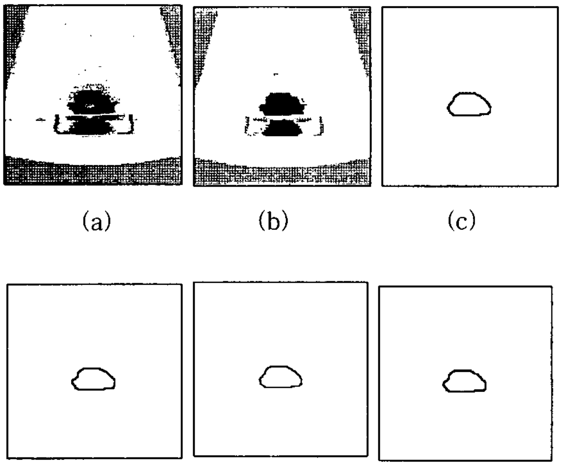
During the MSP, the number of the candidate regions was set to four including the PISA, blue, the region inside transducer, and the region outwith the scope of the transducer.

The Doppler image of the 1st frame from the total 180 frames is shown in Fig. 2(a). And the extracted 4 regions are shown in Fig. 2(b). In the candidate regions, the PISA feature space was extracted from the largest red color in RGB space.

The result of the cross sectional isovelocity of the PISA, shown in Fig. 2(c)~2(f), was processed with RD smoothing.

In Fig. 2(c), the RD gaussian was 2.0 and the diffusion parameter, β_1 was 2.0, in Fig. 2(d), the RD gaussian was 2.0 and β_1, 1.0, in Fig. 2(e), the RD gaussian was 1.0 and β_1, 2.0.

In Fig. 2(f), the RD gaussian was 1.0 and β_1, 1.0. After smoothing, trimming and EFD estimation was used. The trimming method was based on a contour curvature for concave detection.



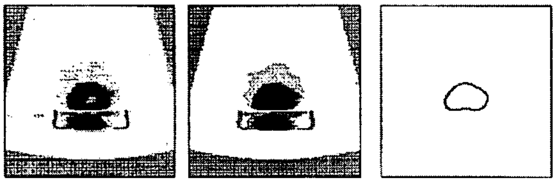
(a) (b) (c)

(d) (e) (f)

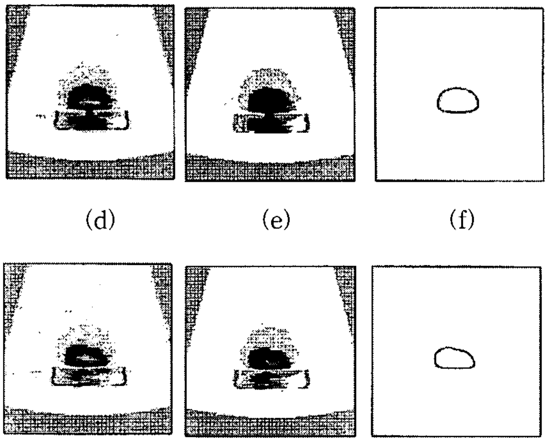
그림 2. PISA 영역 추정 : (a) 원 영상 ; (b) 분할된 영상 ; (c)~(f) : RD 평탄화 영상

Fig. 2. PISA region estimation : (a) Original image ; (b) segmented image ; (c)~(f) RD smoothing image.

Fig. (3) shows the result processed by the region-based scheme. The source images, Fig. 3(a), 3(d), and 3(g) were the 10th, 100th and 150th frame images out of the total 180 images, respectively.



(a) (b) (c)



(d) (e) (f)

(g) (h) (i)

그림 3. PISA 등속도 추출 : (a), (b) 및 (g) 원영상 ; (b), (e) 및 (h) 분할된 영상 ; (c), (f) 및 (i) 추출된 등속도 영상

Fig. 3. PISA isovelocity estimated : (a), (b) and (g), Original image ; (b), (e) and (h) estimated image ; (c), (f) and (i) estimated isovelocity image.

2. Flow rate estimation

The calculated flow rate using the proposed models for the in-vitro experiment was found to be in agreement with the measured flow rates and similar to that of the non-hemispherical flow model.

In Fig. 4(a), the mean value of the flow rate in

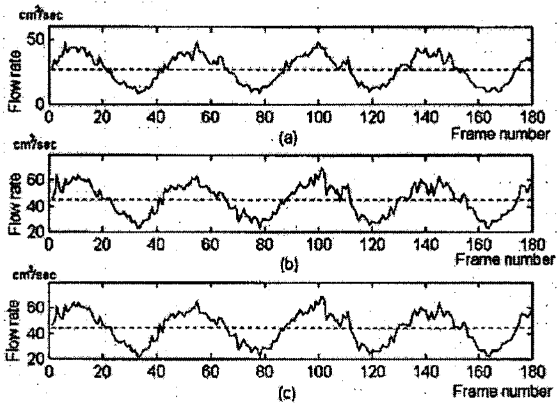


그림 4. (a) 반구, (b) 비반구, (c) 표면 분할 모델에 의해 추정된 유량

Fig. 4. Flow rate estimated by (a) hemispherical, (b) non-hemispherical, surface subdivision flow models.

the hemispherical flow model was 29. This model underestimated by 35% compared with the measured flow rate. In Fig. 4(b) and 4(c), the non-hemispherical flow model and proposed flow model had a mean value of 45. The small difference of waveform between the non-hemispherical and proposed flow model is insignificant as the flow rate error is mainly concerned the width and height of the PISA isotach.

Ⅳ. Conclusions and discussion

This paper presented an automated extraction of the PISA iostach and geometric flow isotach modelling for quantifying valvular regurgitation. The novel aspect of this method is the use of a region-based scheme to extract the PISA isotach from color Doppler images combined with a subdivision surface flow model for physically modelling the PISA isotach.

This proposed method is a direct method rather than a approximately calculated one that is numerically modelled, In an in-vitro evaluation test; the proposed method produced a similar result to the non-hemispherical flow model, which was modelled using the height and half-width of the isotach. In contrast, the hemispherical flow model underestimated by 35% compared with the measured flow rate.

Accordingly, given an asymmetric isovelocity, a more exact flow rate needs to be estimated. Furthermore, this method can also be physically applied to any 3D shape velocity profile and directly estimate the flow rate.

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저자소개

陳 景 贊(正會員) 第 36卷 S卷 第 8號 參照
현재 경북대학교 센서기술연구소 연구원

曺 辰 鎬(正會員) 第 36卷 S卷 第 8號 參照
현재 경북대학교 전자공학과 교수