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The Flow Velocity Distribution from the Doppler Information on a Plane in Three-Dimensional Flow

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Abstract : In order to observe and estimate the flow of fluid in three-dimensional space, the pulsed Doppler method has been used widely. However, the velocity information acquired is only the velocity component in the beam direction of the wave even if an observation plane is formed by beam scanning. Accordingly, it is difficult to know the velocity distribution in the observation plane in tree-dimensional flow. In this paper, the new idea for processing the velocity distribution in the beam direction on an observation plane for transposing to flux distribution (flow function method) has been introduced. Further, the flow in an observation domain is divided into two kinds of flows, viz., the base flow which indicates the directivity of the flow in the observation domain and the vortex which is considered a two-dimensional flow. By applying the theory of a stream function to the two-dimensional flow, and by using the physical feature of a streamline to the base flow, the velocity component v which intersects perpendicularly to the beam direction is estimated. The flow velocity distribution in a scanning plane (observation plane) can be known from these two components of velocity, viz., beam direction component u and perpendicular component to the beam direction v. The principle was explained by an example of the blood flow measurement in normal and abnormal heart chamber, by the ultrasonic Doppler method.

Keywords : Pulsed Doppler technique, Ultrasonic Doppler method, Flow function, C-mode flow, Flow velocity distribution, Stream function, Streamline.

1. Introduction

When observing the flow of fluid existing in three-dimensional free space, two or more observation planes are established, and if the velocity distribution on each plane can be observed, quantitative analysis of a three-dimensional flow is attained.

For this purpose, the ultrasonic color Doppler equipment developed for medicine by the ultrasonic pulsed Doppler method (Tanaka, et al., 1977; Namekawa, et al., 1983) and the Doppler radar equipment developed for weather observation and prediction by the electromagnetic wave pulsed Doppler method (Tatehira, 1987; Sasaki, 1998) can be put into practical use. The Doppler velocity distribution obtained by carrying out a beam scan on an observation plane can be displayed on the screens of these instruments in real time. Since the velocity information acquired now is based on the Doppler effect, it is only the Doppler velocity which is the velocity component in the beam direction of the wave. If the velocity component in the orthogonal direction to the beam in the observation plane is calculated, distribution of the velocity in an observation plane will be obtained from this velocity distribution. Then, we studied the method in order to obtain the velocity distribution on the section plane of the fluid (Ohtsuki et al., 1986; Ohtsuki et al., 1987; Ohtsuki et al.,1989; Ohtsuki et al.,1989; Tanaka et al., 1977; Tanaka et al., 1989).

In this paper, we show how to estimate the velocity component, which intersects perpendicularly with the beam in an observation plane, in consideration of the in-flow and out-flow from the outside of a plane, based on the distribution of the velocity component in the direction of the beam in the scanning plane. Furthermore, the method for deducing the velocity distribution of the flow in the observation plane is proposed.

2. The Method of Estimating the Velocity Component in the Direction which Intersects Perpendicularly with a Beam in the Scanning Plane

The principle of the estimating method is shown here by an example. The example is the blood flow measurement in a normal heart chamber by the ultrasonic pulsed Doppler method.

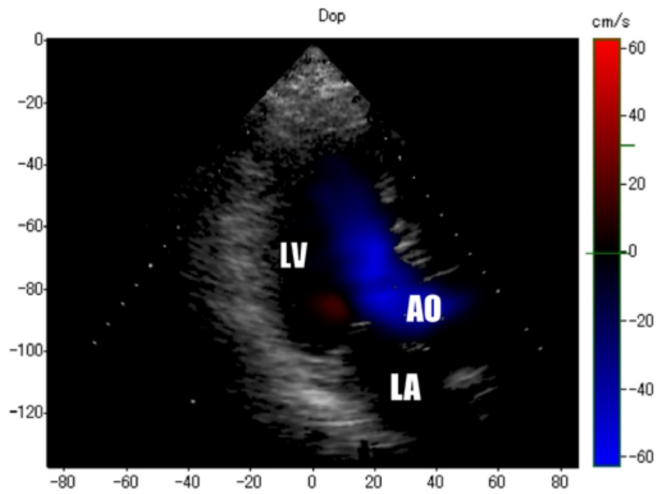

Fig. 1. Color Doppler image of blood flow in the left ventricle on the longitudinal cross section of the heart (LV: left ventricle, LA: left atrium, AO: Aorta).

Figure 1 shows the Doppler velocity distribution of the blood flow (velocity component in the beam direction) in the left ventricle obtained when the heart is scanned with an ultrasonic beam along the long axis of the heart and passing through the central part of the left atrium, the left ventricle, and the basal portion of the aorta. This figure is obtained by a sector scan on the chest surface during the systolic phase. The monochrome image shows a section of heart structure and the blood flow is expressed as the color image. A red component shows the blood flow approaching the ultrasonic probe and a blue component shows the blood flowing away from the probe according to the shade corresponding to the color bar on the right side of the figure. In this example, the velocity distribution along the beam direction by the sector scan is shown in Cartesian coordinates, in order to simplify the expression of the description of the principle.

2.1 The Flow in an Observation Plane and an Observation Domain

We consider the plane in which the velocity is observed. A pulse is emitted in this plane and the velocity component in the direction of the beam of the pulse is obtained. The linear scan of the beam is carried out. The x axis is set as the direction of the beam, and the y axis is set as the beam scanning

direction. They are orthogonal. This is shown in Fig. 2. The observed velocity is described as $u(x, y)$. Let the domain where measurement data is obtained be an observation domain (green area) within this observation plane. Out side of this observation domain, the velocity $u(x, y)$ is taken to be zero. A portion of the fluid flows through the plane which contacts an observation domain. Even on the basis of these two assumptions, generality of the expression of flow will not be lost.
In this case, we estimate the velocity component $v(x, y)$ in the direction of the y axis which intersects perpendicularly with the direction of the beam.

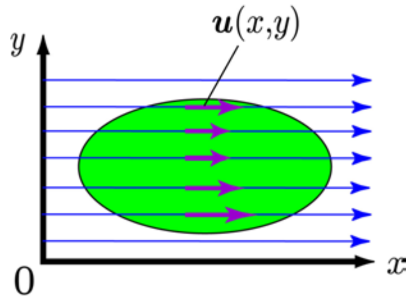

Fig. 2. An observation plane and an observation domain.

In the vortex, the velocity component in the beam direction is closely connected with the velocity component in the direction which intersects perpendicularly. The flow in an observation domain is then separated into a vortex flow and a base flow.

The velocity component $u(x, y)$ in the direction of the beam is expressed by the vortex component $u_s(x, y)$ and base-flow component $u_b(x, y)$ as

$$u(x, y) = u_s(x, y) + u_b(x, y) \tag{1}$$

The velocity component $v(x, y)$ of the direction intersecting perpendicularly with the beam is also expressed corresponding to each component by the vortex component $v_s(x, y)$ and base-flow component $v_b(x, y)$ as

$$v(x, y) = v_s(x, y) + v_b(x, y) \tag{2}$$

The task is to calculate $v_s(x, y)$ and $v_b(x, y)$ as velocity components which intersect perpendicularly with the beam, after separating the vortex component $v_s(x, y)$ from the velocity component $u(x, y)$ in the beam direction.

2.2 The Vortex and Its Stream Function in an Observation Domain

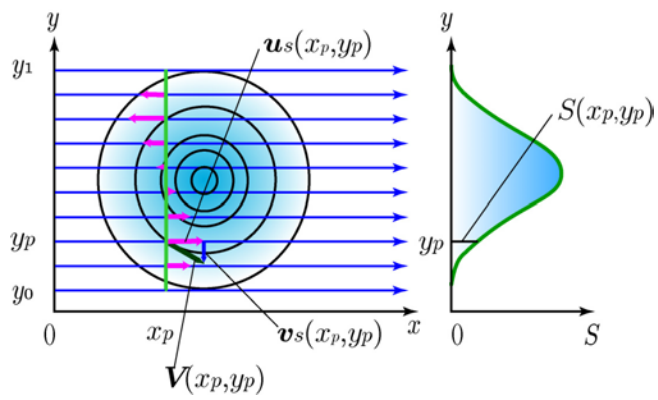

Fig. 3. The vortex component of velocity in the direction of the beam $u_s(x, y)$, and its stream function $S(x, y)$.

Note that the vortex in the observation domain, without supply of external fluid, is a two-dimensional flow, and the state of the flow can be expressed by the stream function which is the foundation of hydrodynamics.

If this stream function $S(x, y)$ expresses the flux of two-dimensional flow and it differentiates over distance, the velocity components u_s and v_s will be obtained as

$$u_s = \frac{\partial S}{\partial y} \tag{3}$$

$$v_s = -\frac{\partial S}{\partial x} \tag{4}$$

Here, a stream function is called for by the following expression, as shown in Fig. 3,

$$S = \int u_s dy \tag{5}$$

Since the vortex in an observation domain, as shown in Fig. 3, is a two-dimensional flow, and moreover does not contain the flow which passes through the boundary of a domain, the total flow through the integration line which crosses a domain serves as zero. This shows the feature of the vortex, namely, the flux calculated by the positive and negative component parts of u_s which intersect perpendicularly with the integration line negate each other.

2.3 The Flow Function and the Flow Distance-Function

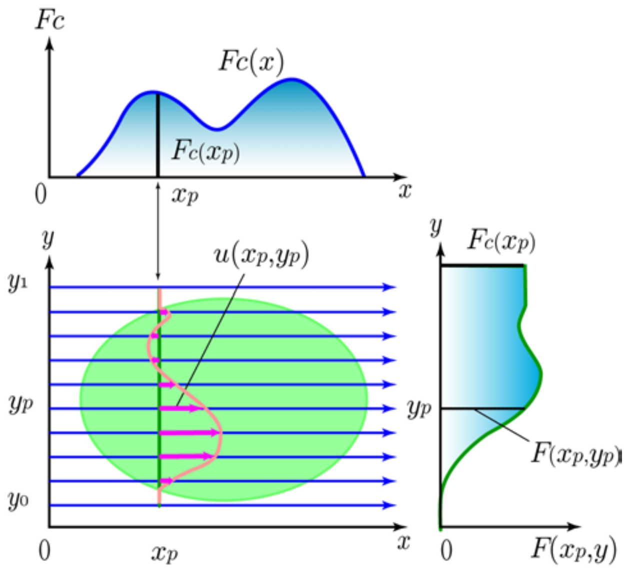

Fig. 4. Relation between the flow function $F(x, y)$ and the C-mode flow $F_c(x)$.

Although there is generally leaving and coming flow between the observation domain and the domain which contacts in the observation domain in three-dimensional flow, as shown in Fig. 4, when the velocity component u in the beam direction in the observation domain is integrated along the course in the direction which intersects perpendicularly with the beam, as the stream function in two-dimensional flow, flux is calculated. This is called the flow function $F(x, y)$, in distinction to stream function $S(x, y)$, as

$$F(x, y) = \int_{y_0}^{y} u(x, y)dy \tag{6}$$

Here, distance integration of the velocity component u in the beam direction is carried out over distance x in the direction of y, which intersects perpendicularly with the beam over range $[y_0, y_1]$ of a beam scan, and the flux is calculated. Considering C-mode image in medical ultrasonic system, this is named C-mode flow.

Consequently, the C-mode flow $Fc(x)$ is calculable, as

$$Fc(x) = \int_{y_0}^{y_1} u(x, y)dy \tag{7}$$

This is the total flux over the interval y_0 to y_1.

In case of polar coordinate,

$$F(r,\theta) = \int_{\theta_0}^{\theta} u(r,\theta)rd\theta \tag{8}$$

$$Fc(r) = \int_{\theta_0}^{\theta_1} u(r,\theta)rd\theta \tag{9}$$

Figure 5 shows an example of the flow function $F(r,\theta)$ and the C-mode $F_c(r)$.

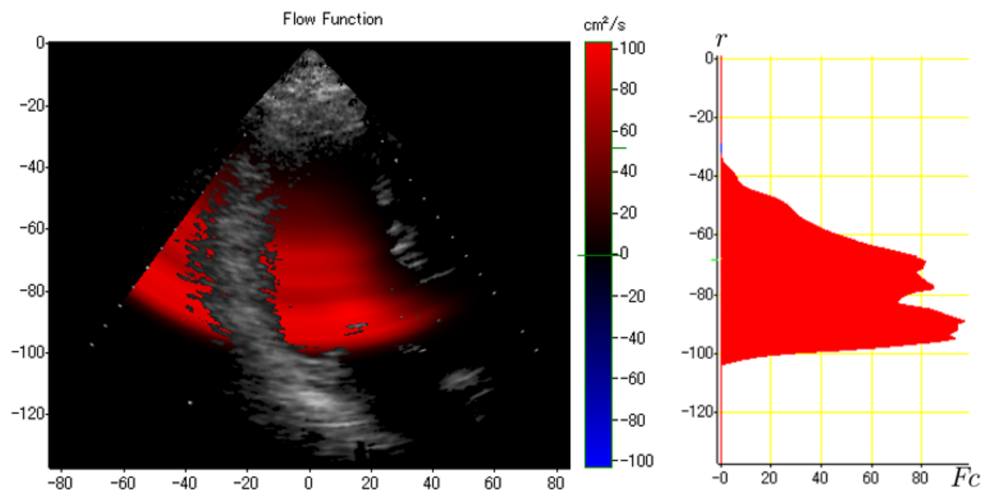

Fig. 5. The flow-function $F(r,\theta)$ displayed on the cross section picture of the heart (red area in left picture) and the C-mode flow $F_c(r)$ (graph in right picture).

2.4 Separation of a Vortex Component and a Base Flow Component

The relation among the velocity component u in the beam direction, flow function $F(x, y)$ and C-mode flow $Fc(x)$ at the distance x is shown in Fig. 6.

When calculating this flow distance-function, flux of only the positive portion of u is included in F_{c+}, and flux of only the negative portion is included in F_{c-}, that is

$$Fc(x) = Fc_+ + Fc_- \tag{10}$$

Here, when calculating the stream function S of a vortex, the flux of only the positive portion of u_s is included in S_+, and the flux of only the negative portion is included in S_-. Generally, if the vortex component in a domain is a maximum, the following relation occurs,

$$S_+ = -S_- = \min(Fc_+, -Fc_-) \tag{11}$$

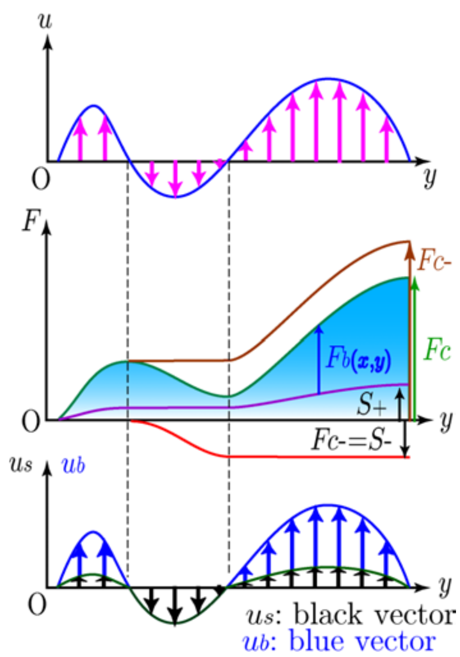

Fig. 6. Schematic representation of the logic for separating the two components of vortex and base-flow.

In the case of Fig. 6, since $Fc(x)$ of expression (8) is positive, the magnitude of F_{c+} is larger than that of F_{c-}. Therefore, it follows that

$$S_{-} = F_{c-} \tag{12}$$

$$S_{+} = -F_{c-} \tag{13}$$

Then, the ratio k is defined as

$$k = \frac{S_{+}}{F_{c+}} \tag{14}$$

In this case, k represents the ratio of the positive flux of the vortex to the positive portion of the total flux passing through the integration boundary.

Accordingly, when inflow and outflow in the observation domain occur uniformly, and the velocity component u is positive, the velocity component u_s of the vortex is expressed as

$$u_s = ku \quad (u > 0) \tag{15}$$

Also, the velocity component u_b of the base flow is

$$\begin{aligned} u_b &= (1-k)u \quad (u > 0) \\ &= 0 \qquad\qquad (u \le 0) \end{aligned} \tag{16}$$

From u_s thus obtained, the stream function $S(x, y)$ is calculated by using the equation (5), and the velocity component v_s which is the rectangular component corresponding to u_s is obtained by equation (4). Actual examples of the stream function $S(x, y)$ and the velocity component u_b of the base flow are shown in Fig. 7.

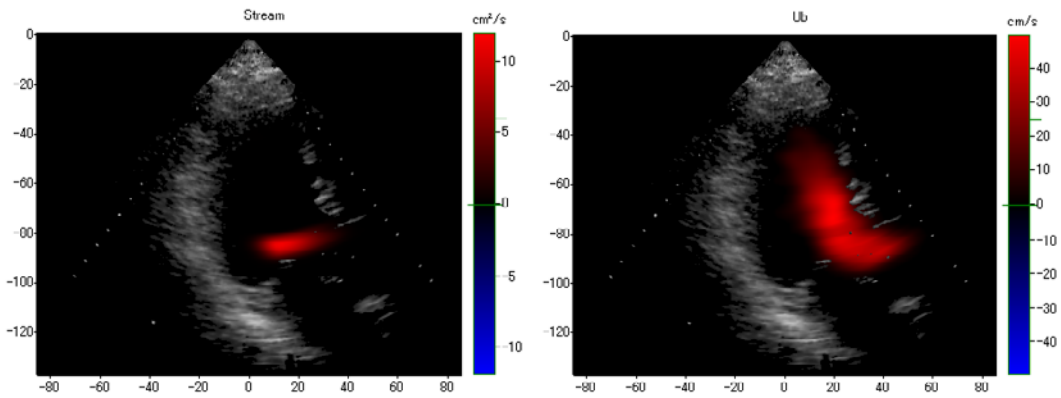

Fig. 7. The stream function $S(r, \theta)$ in the left figure, and the two-dimensional distribution of the velocity component of the base flow u_b in the right figure.

2.5 Estimation of the Orthogonal Velocity Component v_b to the Velocity in the Beam Direction of the Base Flow by the Use of the Base Flow Streamline

The base flow function $F_b(x, y)$ is defined as

$$F_b(x, y) = F(x, y) - S(x, y) \tag{17}$$

The base flow function signifies the integration value of the base flow velocity component $u_b(x, y)$ carried out normal to the beam direction. Further, the integration value of the flow function $F(x, y)$, along the line which intersects the observation domain at distance *x*, is in agreement with the C-mode flow $Fc(x)$ as shown in Fig. 4.

Now, a central streamline is considered in base-flow. Since the flux at every position *x* is the C-mode flow $Fc(x)$, generally the flow distance-function differs at every position *x* because of the amount of flux at the border of the observation domain. Then, as a representative streamline of basic flow, the central line of the flow is regarded as the flow axis and the curve connected with the points where the flux becomes 50% in each position *x* is defined as the central streamline. Next, in order to obtain the central streamline thus defined, the flux is normalized by the C-mode flow $Fc(x)$ at each range *x*. The $F_{bn}(x, y)$ thus obtained is named the normalized base flow function.

$$F_{bn}(x, y) = \frac{F_b(x, y)}{F_c(x)} \tag{18}$$

The contour line of this function becomes a base flow streamline. At each point of the contour line, when the angle between the beam direction and a tangent to the base flow streamline is θ, the velocity component v_b, which is perpendicular to the velocity component u_b in the beam direction of base flow, can be found as follows.

$$v_b = u_b \tan\theta \tag{19}$$

An example of the normalized base flow function $F_{bn}(x, y)$ is shown in Fig. 8.

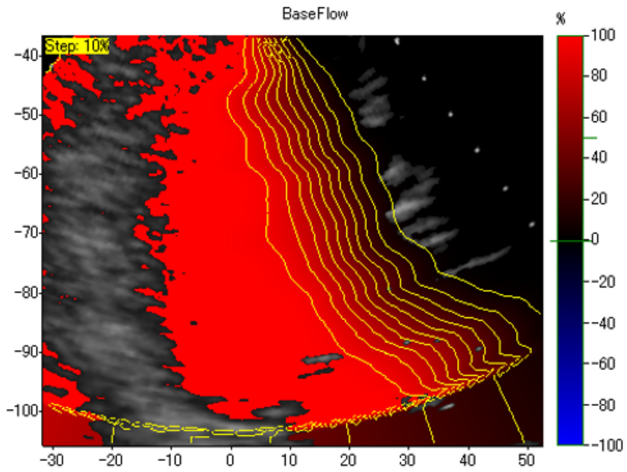

Fig. 8. An example of the normalized base flow function and the distribution of streamlines of the base flow.

By the process mentioned above, the velocity component *v*, which is normal to the beam direction in the observation plane, can found from expression (2). An example of the velocity component *v* is shown in Fig. 9.

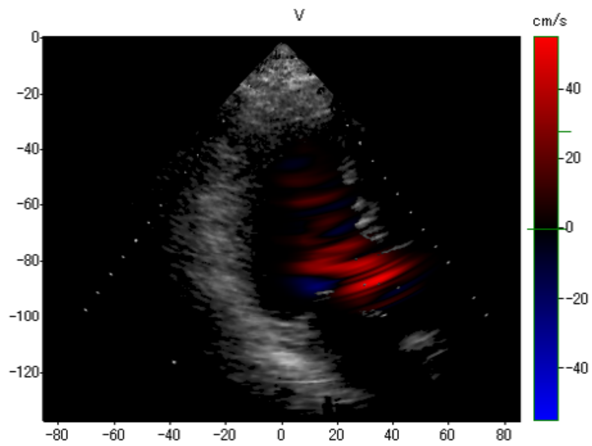

Fig. 9. Two-dimensional distribution of the velocity component v .

2.6 Derivation of the Flow Velocity Distribution on an Observation Plane

As mentioned above, we can ask for the velocity component $v(x,y)$ in the direction perpendicular to the beam from expression (2) based on the distribution information on the velocity component $u(x,y)$ in the direction of the beam in the observation domain. Thus, the flow velocity in the observation domain from both velocity components $v(x,y)$ and $u(x,y)$ is obtained.

In order to confirm reliability of the method proposed in this analysis, simulation of measurement of the velocity distribution of a flow model was carried out using the Rankine vortex. The scale of the Rankine vortex is as follows, radius of the vortex is 50 mm, radius of the forced vortex is 20 mm and the maximum velocity of the vortex is 50 cm/sec. Results of the simulation are demonstrated in Figs. 10 and 11.

Figure 10 shows the two-dimensional distribution of the velocity of the Rankine vortex model. Figure 11 shows the comparative data of the velocity profile of the vortex obtained by this method and by calculation. The velocity profiles are in good agreement with each other.

From these results, it can be said that reliability of the proposed method is very high, as the method for obtaining the velocity distribution in the observation plane established in three-dimensional flow.

Figure 12 shows the flow velocity distribution for the case of Fig. 1 as the example.

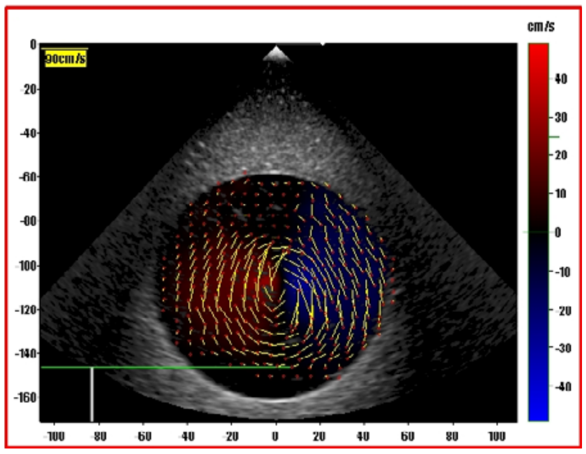

Fig. 10. Two-dimensional velocity distribution of the Rankine vortex obtained by the proposed method.

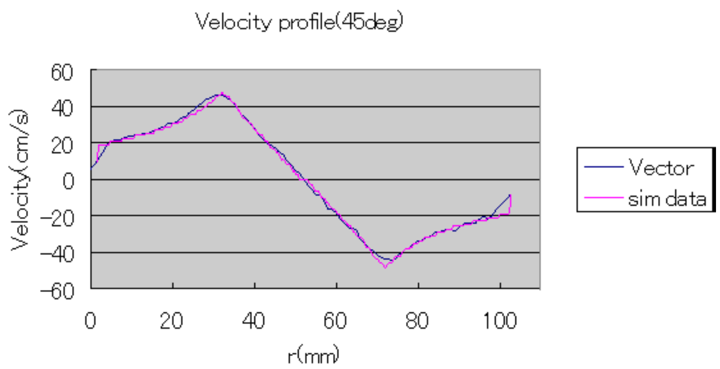

Fig. 11. Comparison between the velocity profile of the Rankine vortex obtained by the proposed method and the theoretical calculation at the center of the vortex.

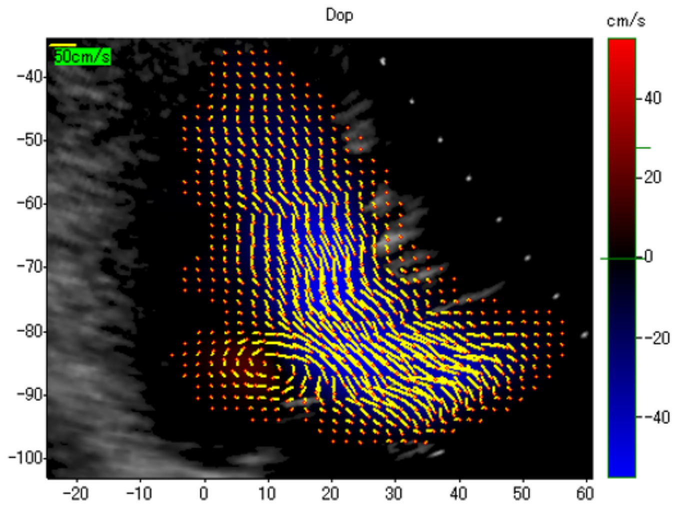

Fig. 12. The velocity distribution image of blood flow in the left ventricle during the ejection phase on the longitudinal cross section of the heart.

3. Practical Application for the Clinical Cardiology

In corroboration of the practical significance of the method proposed here, clinical application of this method was tried to use for analyzing the characteristics of blood flow in the heart chambers. The ultrasonic pulsed Doppler method, frequency used was 2.5 MHz and pulse repetition rate was 4 kHz, was used for obtaining the velocity data of the blood flow. The cross section picture of the heart passing through the long axis of the left ventricle, aorta and left atrium was obtained by sector scanning on the chest surface of an examinee in supine position. Following three cases were examined, that is, normal, aortic stenosis and dilated cardio-myopathy.

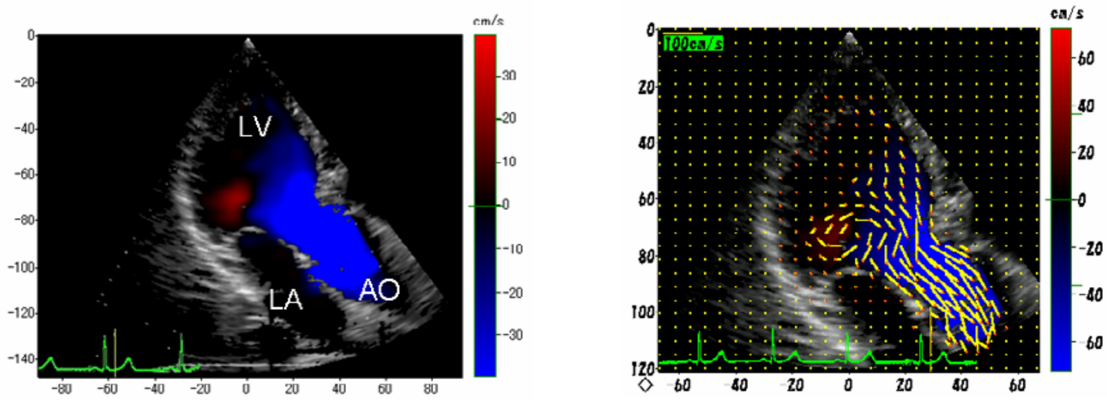

Fig. 13. Two-dimensional distribution of the Doppler velocity (left) and the velocity (right) of the blood flow in the left ventricle in normal adult case. The monochrome image shows a longitudinal cross section of the heart structure and the blood flow is expressed as the color corded image of the velocity signal in the beam direction obtained by the ultrasonic method. A red component shows the flow approaching to the ultrasonic probe and a blue component flowing away from the probe. Magnitude of the velocity represents by the length of the yellow bar and the direction of the vector is shown by a red spot attached to the one end of the yellow bar.

Figure 13 shows an example of a normal adult case obtained in the early systolic phase (ejection phase). The velocity image indicated that only the blood situated at the basal part of the ventricle is ejected in this phase. The magnitude of the vector is gradually increasing from the outflow tract to the aorta. A circular arranged pattern of the vector is observed at the area just below the closed mitral valve (the area between the LA and LV), that is indicated an existence of the eddy.

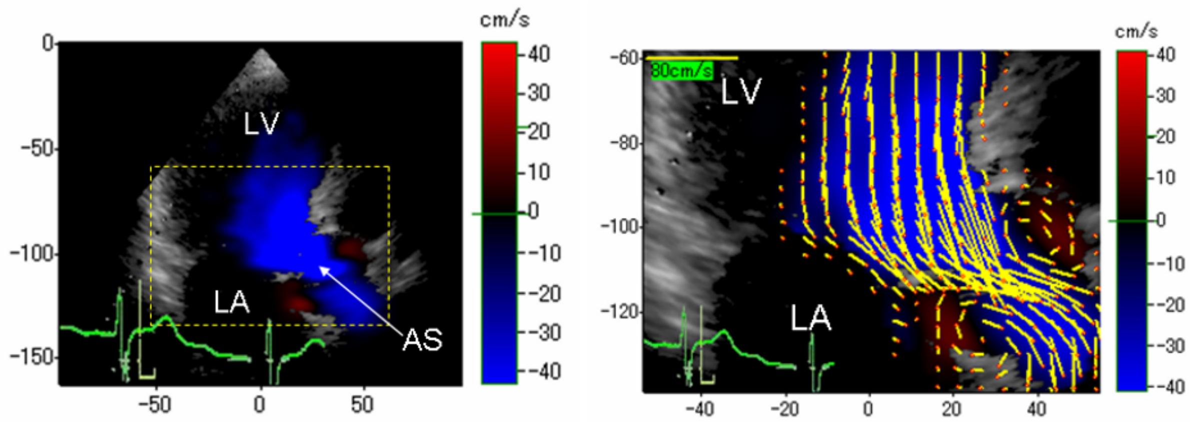

Fig. 14. A case of the aortic valve stenosis. The velocity distribution represented in the right side picture is obtained at the outflow tract area of the left ventricle encircled with a dotted line in the left side picture (AS : isthmus of aortic valve stenosis).

Figure 14 shows an example of the convergent flow in a case of the aortic stenosis. As observed in the right side picture, the velocity distribution in the outflow tract area of the ventricle represents convergency to the isthmus of the aortic valve. The two circular distribution of the vector are observed at the area just behind the stenotic valve.

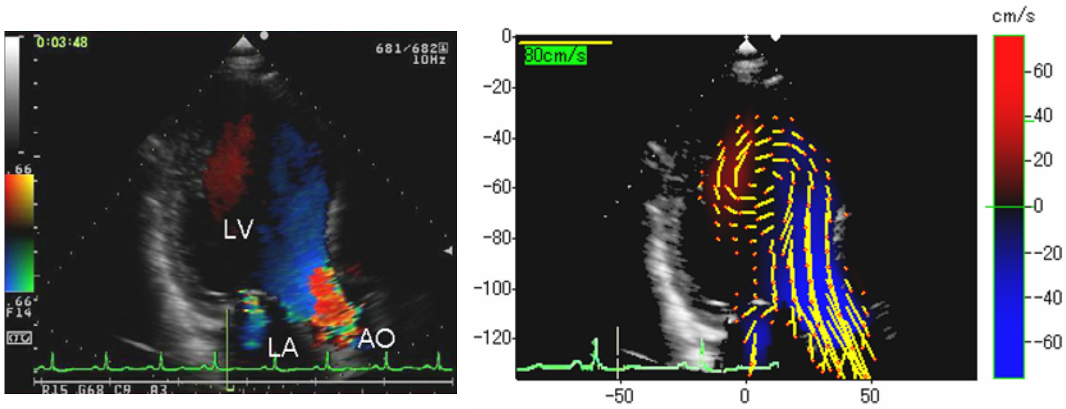

Fig. 15. A case of the dilated cardio-myopathy. The left ventricle is made to enlarge due to myocardial damage of the ventricular wall and decrement of the contractility. A large vortex is easily produced in the ventricle in both systolic and diastolic phase. In the left side figure, a red color area observed at the outflow area near AO indicates the aliasing of the velocity signal caused by the Nyquist limit.

Figure 15 is obtained from a patient with the dilated cardio-myopathy. A circular arrangement of the velocity is demonstrated at the central area of the enlarged ventricle due to failure of the pump function. The circular arrangement indicated that the large vortex appears in the ventricle in early systolic phase.

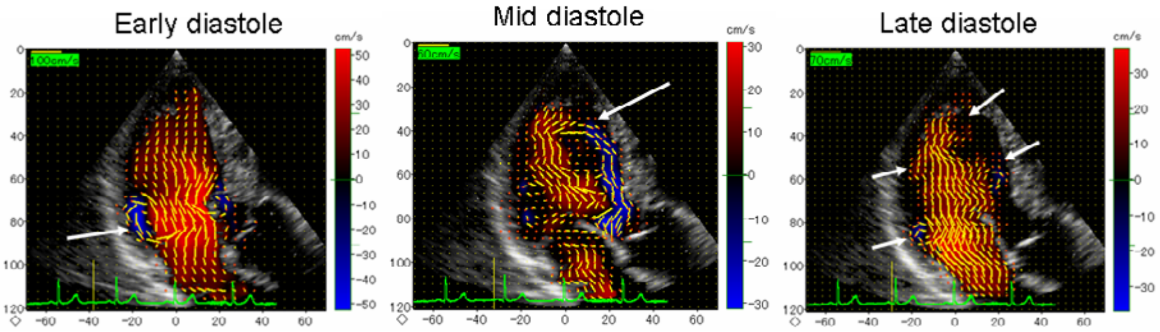

Fig. 16. The circular arrangement of the velocity appeared in three phases of the inflow to the ventricle during diastole in normal case, that is, rapid filling phase, slow filling phase and one shoot filling phase by the atrial contraction.

Figure 16 shows various kinds of circular arrangement of the velocity appeared in the left ventricle during diastole in normal case. The white arrow in the left side picture shows the eddy originated by the separation of the rapid blood flow passing through the orifice of the mitral valve in the early diastolic phase. The white arrow in the middle picture shows a large rotating flow appeared along the internal surface of the left ventricle from posterior wall to anterior one in the slow filling phase in diastole. In the right side picture obtained in the late diastolic phase, many small eddies (white arrows) are observed in the curved area of the meandering flow like as the Karman Vortex street. From the results of clinical experiment, it can be said that the estimation of the flow characteristics by the velocity distribution proposed in this study is very useful for clinical diagnosis and analysis of the flow dynamics in cardiology.

4. Discussion

In order to perform quantitative evaluation of flow in which various flows exist in natural space, it is essential to measure and to analyze quantitatively not only the flux and the pressure, but also the character of the flow (turbulent, laminar or vortex, etc). However, the flow which exists in natural space cannot necessarily be easily measured according to the substance which constitutes the flow, the environment where the flow exists, the scale of flow, etc. There is a methodological limit in the measurement using transducers, such as flow instruments and pressure gauges especially. All flows in natural space are three-dimensional. Furthermore, the following conditions are required of the measurement procedure, to comprehend fully the phenomenon of flow:

1. The instantaneous phenomenon of change must be obtained (real time measurement is required).
2. Information on spatial spread, position, and range must always be confirmed (detection of spatial position information is required).
3. The rate of change is large. The portion which changes at high speed, and the portion which changes at a low speed, must be discriminable. It is required that what has large change width should be obtained simultaneously.

In order to realize such measurements, laser Doppler methods, the radar Doppler methods, or ultrasonic Doppler methods, have applied the Doppler effect to light, to electromagnetic waves, or to ultrasonic waves respectively have been developed. Recently, the method for evaluating the quality of flow, from velocity information acquired with the Doppler method, is used increasingly (Sasaki, 1998; Tanaka et al., 1989; Tatehira, 1987). However, in such measurements, it is necessary to detect velocity for spatial position information simultaneously. Accordingly, a pulse wave must be used, an observation plane is formed by beam scanning and two-dimensional distribution of velocity on the scanning plane must be measured. However, the velocity information thus measured is only the component of velocity in the beam direction. Although the velocity data is displayed like as a two-dimensional distribution, three velocity components are still contained in the flow in the scanning plane. Therefore, when observing three-dimensional flow by a two-dimensional observation plane (beam scanning plane), it is necessary to detect the velocity within the plane, taking each of the two kinds of components of flow, viz., the parallel component and the orthogonal component in the beam direction. However, a method for detecting these two velocity components separately has not yet been established.

The method proposed here is one in which the two kinds of velocity components in an observation plane can be found separately by taking enough of the flow into consideration which crosses an observation plane and flows as a three-dimensional distribution (Ohtsuki, et al., 1986; Ohtsuki, et al., 1987; Ohtsuki, et al., 1989). Thus, the method can expect appreciable application as the processing method of velocity distribution information, if the component of velocity in the beam direction is obtained on the plane scanned with the beam of an electromagnetic wave or of an ultrasonic wave.

This method is applicable in practice under the conditions that the two-dimensional measuring plane is formed in consecutive flow by beam scanning and that the velocity in the beam direction is measured as a two-dimensional distribution. Moreover, in applying this method, it is essential that the flow is the continuous flow without boundaries for separating the flow in three-dimensions. The reasons for this are as follows: Even if the velocity data is in the beam direction when being measured the continuous flow, the velocity component in the other beam direction which exists adjacently has a mutual affect. By using this relevance, in the method proposed here, the velocity component intersecting perpendicular to the beam direction is estimated. Therefore, it is difficult to ask for the velocity component in the direction which intersects perpendicularly by the use of the component of velocity on only one beam axis.

The new idea for processing the velocity distribution in the beam direction on an observation plane for transposing to flux distribution has been introduced in this method. Further, the flow in an observation domain is divided into two kinds of flows, viz., the base flow which indicates the directivity of the flow in the observation domain and the vortex which is considered a two-dimensional flow. By applying the theory of a stream function to the two-dimensional flow, and by using the physical feature of a streamline to the base flow, the velocity component v which intersects perpendicularly to the beam direction is estimated.

If this method is applied to analysis in medicine for blood flow in the human body, which is considered the most complicated flow, particularly blood flow in the heart and great vessels, this method is expected to play a major role in the analysis of the character of flow and the dynamic state measurement of the flow in local regions.

5. Conclusion

The method of performing velocity measurements in arbitrary portions in fluids is proposed by employing the Doppler effect for which the wave motion is used as the method of evaluating quantitatively the flow existing in natural space, without disturbing the flow.

In this paper, the new idea which can estimate velocity distribution of a three-dimensional flow on a two-dimensional observation plane is proposed. Here, the beam of a pulse wave can be scanned, the component of velocity within a plane of the direction of a beam and the direction which intersects perpendicularly can be estimated from distributions of the velocity component in the beam direction on the scanning plane obtained in real time, and the flow velocity distribution in a scanning plane (observation plane) can be known from these two components of velocity. Radar Doppler and ultrasonic Doppler methods are widely applied to measurements of fluids in which direct insertion of a transducer is impossible. The proposed method provides useful information processing as a technique for quantitative measurement of flow.

Herein, the principle was explained as a linear scan. However, the same principle as the sector scan analyzed in cylindrical coordinates is applicable. Measurement of blood flow in the heart illustrated the case for application of the method. Consequently, it is easy to understand from a vector display and the velocity distribution in a scanning plane can be calculated, although it is hard to understand by the color display image of the directional component of velocity of a beam when it is easy to produce, especially a vortex, quantitative measurement of flow is possible.

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