

Featured Articles

Intracardiac VFM Technique Using Diagnostic Ultrasound System

Tomohiko Tanaka, Ph.D.
 Rei Asami
 Kenichi Kawabata, Dr. Eng.
 Keiichi Itatani, M.D., Ph.D.
 Tokuhisa Uejima, M.D., Ph.D.
 Tomohide Nishiyama
 Takashi Okada

OVERVIEW: VFM, a technique for imaging blood flow velocity vectors, has been developed to enable the diagnosis of heart disease by using ultrasound to visualize the pattern of blood flow in the heart. VFM is recognized as a non-invasive technique with the potential to provide highly accurate heart disease diagnosis by measuring the velocity vectors, streamline distribution, and vorticity distribution of blood flow inside the heart. The development of the technique included verifying its accuracy to demonstrate its reliability. This accuracy verification consisted of building a heartbeat phantom and comparing the velocities obtained by VFM with those obtained by PIV, a well-established form of laser velocimetry. This demonstrated that VFM is a highly accurate vector imaging technique that is suitable for clinical applications. This article describes clinical applications for valve replacement and dilated cardiomyopathy.

INTRODUCTION

ALONG with magnetic resonance imaging (MRI) and computed tomography (CT), diagnostic ultrasound systems have become a vital diagnostic imaging tool in the healthcare field. The ability to image the interior of the body non-invasively and in realtime using a small and portable instrument has led to a variety of uses for these systems in a diverse range of fields. In cardiovascular medicine in particular, where there is a need to observe the behavior of the fast-moving parts of the heart in realtime, diagnostic ultrasound systems have become an essential diagnostic imaging modality.

The diagnosis of cardiovascular disease requires a way of assessing heart function. The heart can be treated as a pump that undergoes repeated cycles of expansion and contraction to force blood to flow throughout the body, and this pumping function can be assessed by looking at how blood flows through the heart. A variety of methods that use ultrasound and the Doppler effect to measure blood flow behavior have already become vital tools for clinical practice, including color Doppler imaging, continuous wave Doppler imaging, and pulsed wave Doppler imaging.

Fig. 1 shows an echocardiographic image taken using the conventional color Doppler method. Fig. 1 (a) shows the heart being imaged from the ultrasound probe and the relative positions in the echocardiograph, with

the image taken such that the left ventricle is on top. The ultrasound beam is emitted from the ultrasound probe in a radial pattern, as shown in Fig. 1 (b), and the velocity of blood flow measured using the ultrasound Doppler effect. By convention, flow toward the probe is shown in red and flow away from probe is shown in blue.

However, the Doppler effect can only be used to determine the component of blood flow velocity in the direction of the beam. It cannot be used to investigate

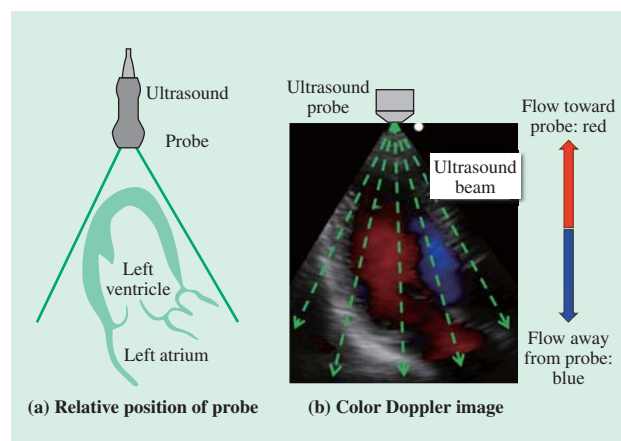


Fig. 1—Echocardiography Images Obtained Using Color Doppler Imaging.

(a) This shows the location of the ultrasound probe relative to heart during cardiography. (b) This shows an example of conventional color Doppler imaging of a heart.

conditions like the direction of flow or presence of vortices. This means there is strong demand from physicians for the imaging of blood flow velocity vectors to provide a more comprehensive picture of blood flow that can be used for detailed diagnosis of heart function.

VFM

To meet this demand, Hitachi has developed the technique of vector flow mapping (VFM), commercializing it in 2013. Fig. 2 (a) shows an example. This technique can provide more intuitive and quantitative imaging of vortex formation, something that is not clearly visible in the color Doppler image in Fig. 1 (b).

As examples of the new functions made possible by VFM, Fig. 2 shows velocity vector, streamline distribution, and vorticity distribution images. The streamline distribution uses lines to indicate the direction of flow and can indicate the trajectory of vortices. The vorticity image uses color to display localized rotational flow and can be used to assess the strength of vortices. Counter-clockwise rotation is defined as positive (red), clockwise rotation as negative (blue), and the color intensity represents the amount of rotation. To develop new heart function diagnostic techniques that use these indices, Hitachi is augmenting its clinical experience with VFM through collaborative research with medical institutions around the world.

VFM TECHNIQUES

Principle of VFM

This section provides a simple explanation of the principle of VFM, which is an improved version⁽¹⁾ of a

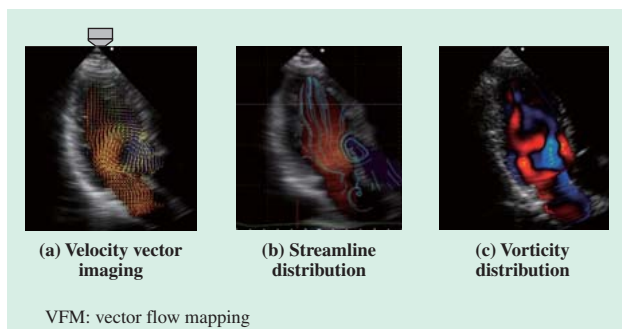


Fig. 2—Functional Overview of VFM. Three examples of new functions made possible by VFM are: (a) velocity vector imaging, (b) streamline distribution, and (c) vorticity distribution.

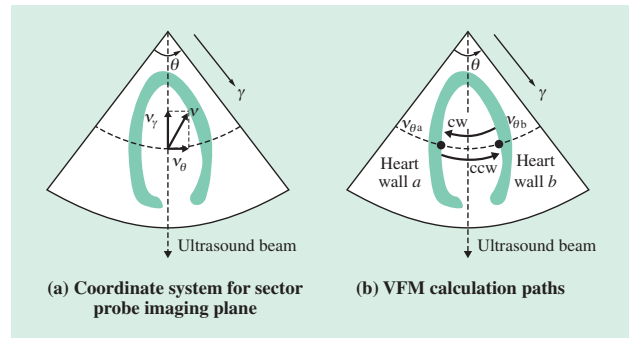


Fig. 3—Overview of VFM Calculation. The VFM calculation typically uses polar coordinates (a). It is possible to choose either of the two heart walls (a or b) to use as the wall velocity (b).

method proposed by Garcia et al⁽²⁾. Fig. 3 (a) shows the coordinate system used in VFM calculations. Because echocardiography involves scanning the ultrasound beam emitted by the probe in a radial pattern, as shown in Fig. 1 (b), it is typically considered in terms of polar coordinates. Using the *r* coordinate to represent the depth direction and the *θ* coordinate the angle of the scanned beam, the velocity component in the *r* direction is *v_r*, and in the *θ* direction is *v_θ*.

While the Doppler effect can only measure the *v_r* component of the three-dimensional blood flow velocity (the component in the direction of the ultrasound beam), VFM uses the conservation of mass to also estimate the velocity perpendicular to the beam direction. Equation (1) expresses the conservation of mass in terms of this polar coordinate system. Here, *z* is the direction perpendicular to the plane of the image being captured, and *v_z* is the component of velocity in that direction.

$$\frac{v_r}{r} + \frac{\partial v_r}{\partial r} + \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z} = 0 \tag{1}$$

Assuming two-dimensional flow (ignoring the influence of the *z* component), *v_θ* can be calculated by integrating equation (1).

$$v_\theta = v_{\theta w} + \int \left(-v_r - r \frac{\partial v_r}{\partial r} \right) d\theta \tag{2}$$

Here, *v_{θw}* is the velocity component in the beam direction at the heart wall (boundary between blood flow and wall). It can be calculated by tracking the movement of the wall. As shown in Fig. 3 (b), either of the two heart walls (wall *a* or wall *b*) can be chosen for the wall velocity. Using the wall velocity for wall *a*, equation (2) can be rewritten as follows by integrating in the counter-clockwise (ccw) direction.

$$v_{\theta}^{ccw} = v_{\theta a}^T + \int_a^{\theta} \left(-v_r - r \frac{\partial v_r}{\partial r}\right) d\theta \quad (3)$$

Here, $v_{\theta a}^T$ is the velocity component in the θ direction obtained by heart muscle tracking of point a . Similarly, v_{θ}^{cw} can be calculated by integrating in the clockwise (cw) direction from wall b . Because, in practice, the velocity components v_{θ}^{cw} and v_{θ}^{ccw} in the directions perpendicular to the beam will not match, Garcia et al. used a weighting function to correct for this. Similarly, Hitachi used weighting function correction based on the distance from the wall, as indicated below. Here, θ_a and θ_b are the θ coordinates at the wall boundary.

$$v_{\theta}(r, \theta) = Wv_{\theta}^{cw}(r, \theta) + (1-W)v_{\theta}^{ccw}(r, \theta)$$

$$W = \frac{\theta - \theta_a}{\theta_b - \theta_a} \quad (4)$$

In this way, the velocity vectors can be obtained from the velocity component in the beam direction measured using the color Doppler method and the velocity component perpendicular to the beam direction obtained from equation (2).

Verification Testing of VFM

While VFM has the advantage of being a simple way to obtain information about blood flow velocity vectors, because the data obtained are estimates based on an assumption of two-dimensional flow, there is a need to adequately validate its accuracy. Hitachi confirmed its reliability by conducting verification testing of VFM

accuracy using particle image velocimetry (PIV), the most well-established form of laser velocimetry.

Fig. 4 shows the test apparatus used for this work. It consisted of a left ventricle phantom (a “phantom” is a model of a body part used to test an imaging system), a pressure chamber to drive the beating motion of the phantom, a piston to vary the pressure in the pressure chamber, an ultrasound probe to perform measurements on the left ventricle phantom, and a PIV apparatus to measure the flow inside the phantom. The left ventricle phantom was 1.6 times actual size and was made from transparent modeling urethane resin based on left ventricle anatomical data (model No. 2, Virtual Anatomia*) [see Fig. 4 (b)]. The pressure chamber used to drive the beating motion of the left ventricle was designed to expand and contract the ventricle in step with the change in pressure from the piston.

The pressure chamber shown in Fig. 4 was filled with polyethylene glycol 400 (PEG400) (molecular weight: 400, supplied by Wako Pure Chemical Industries, Ltd.). The measured refractive index of PEG400 is 1.47, which is approximately the same as that of the left ventricle phantom. Selecting a liquid with the same refractive index as the phantom ensured transparency in the pressure chamber, as shown in Fig. 4 (c), and made it possible to use optical methods for measuring flow in the three-dimensional structure of the left ventricle phantom.

* Virtual Anatomia is a trademark of SGI Japan, Ltd.

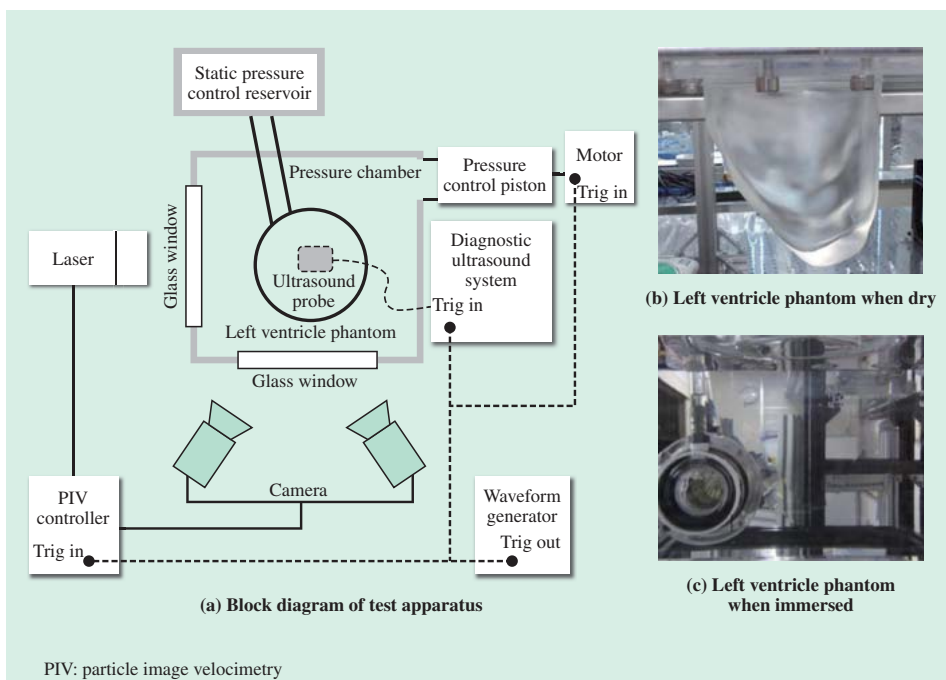


Fig. 4—Overview of Test Apparatus. The test apparatus consisted of a transparent left ventricle phantom to enable PIV measurement, a pressure chamber to drive the beating motion of the phantom, a piston to vary the pressure inside the pressure chamber, an ultrasound probe to perform measurements on the left ventricle phantom, and a PIV apparatus to measure the flow inside the phantom.

Mechanical valves equivalent to those used clinically were selected for the mitral valve and aortic valve. The two tubes separated from the top of the phantom by mechanical valves were each connected to a static pressure control reservoir to draw in and expel liquid with the expansion and contraction of the heart.

Fig. 5 shows a comparison of the flows measured by VFM and PIV. Both give the same qualitative results, demonstrating that VFM can represent the actual flow field with good accuracy even when the flow field is three-dimensional. Although VFM is calculated based on an assumption of two-dimensional flow, thanks to the use of error correction [see equation (4)], the flow field it provides is not two-dimensional and is a close approximation of the actual flow field.

A quantitative assessment of VFM and PIV found that the differences between the two methods were approximately 10% of the color Doppler velocity range being measured. Based on this result, work has now proceeded to clinical testing.

CLINICAL USE

Post-operative Artificial Valve Replacement Case

In post-operative artificial valve replacement cases, the pattern of blood flow is sometimes abnormal even if the pumping function of the heart is normal. In a case in which the mitral valve was replaced by a mechanical valve, the flow of blood into the left ventricle in the diastolic (expansion) phase was directed toward the ventricular septum forming a counter-clockwise vortex [see Fig. 6 (a)]. With the passage of time, this vortex shrunk and slowed, while a new vortex formed in the ventricular apex [see Fig. 6 (b)]. The direction of rotation of this vortex can be seen in the vorticity image [see Fig. 6 (c)]. In the vorticity image, red indicates the vortex is rotating counter-clockwise and blue indicates clockwise rotation (data courtesy of Tokuhis Uejima of the Department of Cardiovascular Medicine, The Cardiovascular Institute).

Dilated Cardiomyopathy Case

In a dilated cardiomyopathy case, the left ventricle was dilated compared to a healthy organ, with a large vortex forming from the center of the left ventricle toward the ventricular apex during the diastolic phase, as shown in Fig. 7. It was found that this vortex remained present and prevented blood from flowing efficiently during the systolic phase. This demonstrates the close links between heart disease and how blood

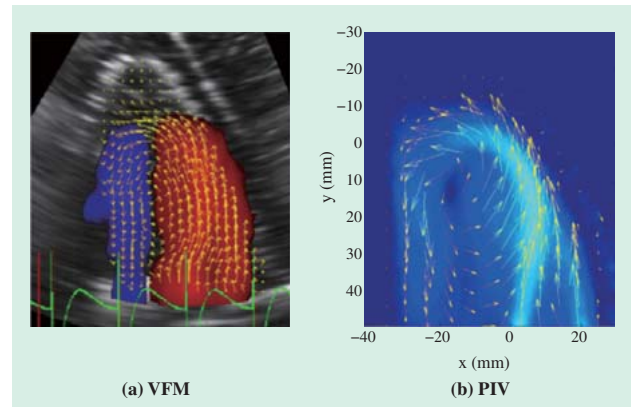


Fig. 5—Comparison of Blood Flow Patterns Obtained Using VFM and PIV.

The flow fields obtained using VFM and PIV are qualitatively the same, demonstrating that VFM can represent the actual flow field with good accuracy even when the flow field is three-dimensional.

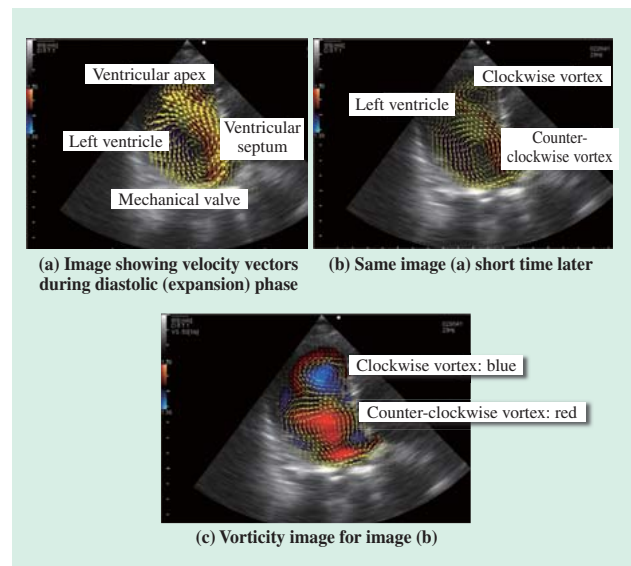


Fig. 6—Blood Flow in Left Ventricle with Artificial Valve. The direction of rotation of vortices could be determined in a post-operative artificial valve replacement case.

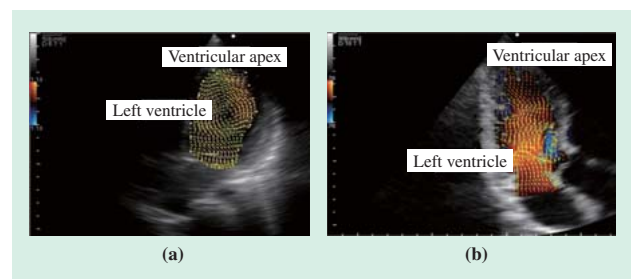


Fig. 7—Dilated Cardiomyopathy Case.

When a case of dilated cardiomyopathy (a) is compared to a healthy organ (b), the left ventricle is dilated and a large vortex forms from the center of the left ventricle toward the ventricular apex during the diastolic phase, and persists at the same location.

flows (data courtesy of Keiichi Itatani, Department of Cardiovascular Surgery, Kyoto Prefectural University of Medicine).

CONCLUSIONS

VFM was developed to enable the detailed study of blood flow in the heart. While it is sometimes difficult in medicine to obtain the actual value of the quantity being measured, resulting in a lack of adequate accuracy verification, the accuracy of VFM was demonstrated using laser measurements.

While this article has presented examples of the utility of VFM for artificial valve replacements and dilated cardiomyopathy, clinical data is also being

collected for other cases. Hitachi hopes to continue contributing to medical progress in the future by demonstrating how VFM offers even greater clinical value.

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ABOUT THE AUTHORS



Tomohiko Tanaka, Ph.D.
Medical Systems Research Department, Center for Technology Innovation – Healthcare, Research & Development Group, Hitachi, Ltd. He is currently engaged in the research and development of diagnostic systems. Dr. Tanaka is a member of the American Heart Association, The Japan Society of Mechanical Engineers, The Japan Society of Fluid Mechanics, and The Japan Society of Ultrasonics in Medicine.



Rei Asami
Medical Systems Research Department, Center for Technology Innovation – Healthcare, Research & Development Group, Hitachi, Ltd. She is currently engaged in the research and development of diagnostic and treatment systems. Ms. Asami is a member of The Japan Society of Ultrasonics in Medicine.



Kenichi Kawabata, Dr. Eng.
Center for Exploratory Research, Research & Development Group, Hitachi, Ltd. He is currently engaged in the research and development of diagnostic and treatment systems. Dr. Kawabata is a member of the IEEE and an engineering fellow of The Japan Society of Ultrasonics in Medicine.



Keiichi Itatani, M.D., Ph.D.
Cardiovascular Surgical Fellow, Department of Cardiovascular Surgery, Kyoto Prefectural University of Medicine. Dr. Itatani is a member of the Japan Surgical Society, The Japanese Society for Cardiovascular Surgery, The Japanese Association for Thoracic Surgery, the Japanese Circulation Society, the Japanese Society of Pediatric Cardiology and Cardiac Surgery, The Japan Society of Ultrasonics in Medicine, and the Japanese Society of Echocardiography.



Tokuhsa Uejima, M.D., Ph.D.
Manager, the Department of Cardiovascular Medicine, The Cardiovascular Institute. Dr. Uejima is a member of the Japanese Circulation Society and the Japanese Society of Echocardiography, and a medical specialist of The Japan Society of Ultrasonics in Medicine.



Tomohide Nishiyama
R&D Section 1, Engineering R&D Department 1, Medical Systems Engineering Division 2, Hitachi Aloka Medical, Ltd. He is currently engaged in the development of VFM.



Takashi Okada
R&D Section 1, Engineering R&D Department 1, Medical Systems Engineering Division 2, Hitachi Aloka Medical, Ltd. He is currently engaged in the development of diagnostic ultrasound systems. Mr. Okada is a member of The Japan Society of Ultrasonics in Medicine and The Japanese Society of Echocardiography.