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3D Blood Flow Vectors Obtained with Multi-Slice Flow Velocity Mapping

多断面の血流マッピングによる 3 次元血流ベクトル

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1. Introduction

Cardiovascular disease is the first leading cause of death in the world. Information on blood flow is important for diagnosis of cardiovascular disease. Several imaging modalities such as MRI, CT and angiography are used for blood flow visualization. Color Doppler ultrasound is well accepted in clinical medicine to assess blood flow because real-time information is obtained non-invasively. However, color Doppler method only measures the velocity component along the ultrasonic beam. 3D blood flow imaging provides more information of hemodynamics in the complex structure in the heart.

We have developed a method to obtain the 2D velocity vector by transmitting plane waves from two different angles[1, 2)]. In this study, we propose a novel method to obtain 3D velocity by applying the equation of continuity to the data on multi-slice 2D flow velocity map. Numerical simulation and flow phantom study are performed for validation of the method.

2. Methods

2.1 2D velocity estimation

Plane waves of two different angles were irradiated from a single probe. A set of one-dimensional velocity components on the plane of each angle was acquired in very short interval with the PRF of 14 kHz. A polynomial regression filter[3)] was used as a clutter filter to calculate one dimensional velocity. It is possible to calculate the blood flow velocity vector based on a geometric relationship (**Fig. 1**).

2.2 3D velocity estimation

Assuming the blood flow is incompressible, the mass flow into and out of the micro-volume is conserved. This relation can be expressed with the length around the micro-volume x, y, z and the blood flow velocity v_x, v_y, v_z.

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0$$

Because from the previous section, the 2D flow velocity v_x and v_y in each plane are known, the 3D velocity vector can be obtained by solving this equation of continuity about v_z (**Fig. 2**).

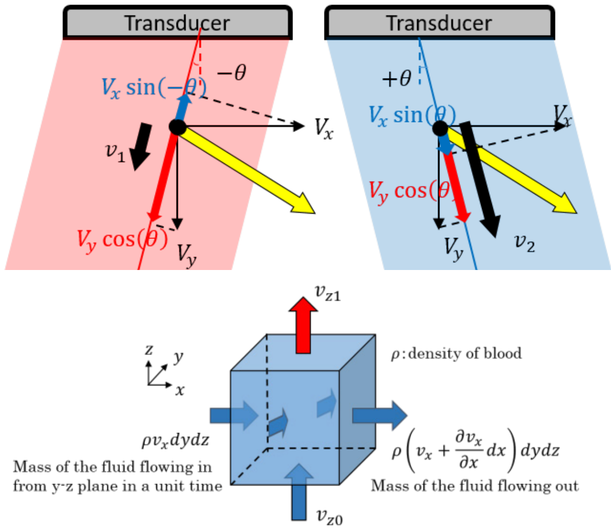

Fig. 2 3D velocity estimation using the equation of continuity

3. Experiments

First, the simulation was performed to verify whether or not the 3D blood flow velocity could be estimated by the proposed method. The equation of continuity was applied to the x and y direction components of data on the three dimensional jet flow to calculate the velocity vector along the z direction.

Next, we conducted an experiment of two dimensional velocity estimation using the phantom. The data were acquired by employing a linear probe from the flow in the carotid artery phantom made with Polyvinyl Alcohol (PVA)[4)]. **Table. 1** shows experiment parameters. In order to investigate the validity of the proposed method, Particle Image Velocimetry (PIV) measurement was also performed at the same time.

Table. 1 2D velocity estimation experiment parameters

Parameters	Values	
Center frequency [MHz]	7.8125	
Elements [ch]	128	
	Setting of Imaging	
	B-mode	Doppler
Number of packerts	7	16×2
Wave transmit angles [deg]	-3.0 → 3.0	±10
Δ angle of transmit waves [deg]	1.0	20
Pulse cycles	1.0	3.0
PRF [kHz]	14	14 / 2

4. Results and Discussion

Fig. 3 shows the 3D velocity vector obtained by applying the equation of continuity to the turbulent flow data. As a result, it was confirmed that the flow was well visualized as a whole compared with the true value. However, it was seen that the error of the velocity at the boundary between the wall and flow was too large to be ignored. This might be due to that forward difference of the equation of continuity could not take into account the difference of the area where the flow existed between each plane. In this case, solving the equation of continuity by combining backward difference and forward and backward differences on the upper and lower planes in addition to forward difference was effective for reducing the error.

In order to calculate the 3D velocity vector, v_z was necessary as an initial condition besides v_x and v_y, and the true value of jet flow data were used as v_z of the first plane in the simulation in this study. In the phantom and *in vivo* experiments in the future studies, v_z is considered to be zero or equivalent to the wall motion velocity because the first plane as the initial condition is the vessel wall.

The 2D velocity vector was obtained by the phantom experiment as shown in **Fig. 4**. A correlation between the proposed method and the PIV was confirmed both in direction and magnitude of the vector, and it was confirmed that the 2D velocity vector can be calculated with high accuracy by the proposed method.

5. Conclusion

In the simulation study of the 3D velocity vector estimation, it was shown that the outline of flow can be visualized by the proposed method. In the phantom experiment, it was shown that 2D velocity vector can be estimated by the proposed method. In the future, we aim to work on phantom and *in vivo* experiments to estimate the 3D velocity vector and to consider the difference method for improvement of the estimation accuracy.

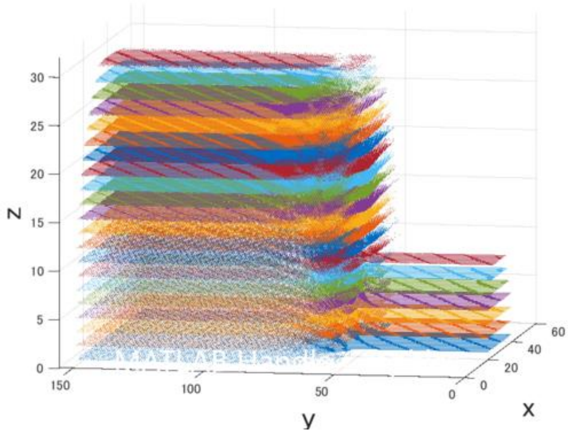

Fig. 3 3D velocity estimation simulation with jet flow data

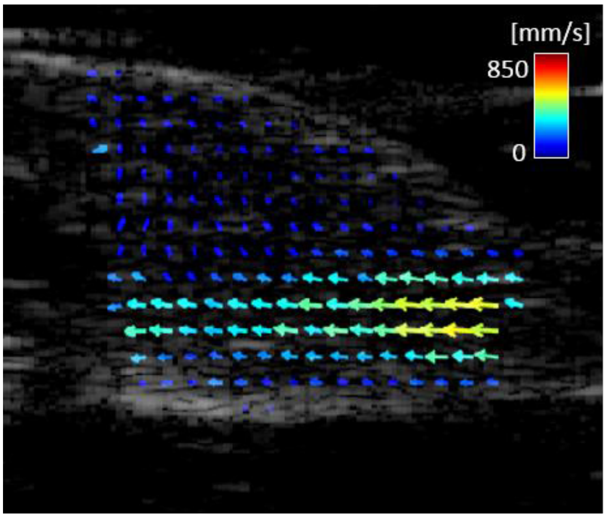

Fig. 4 2D Flow velocity mapping obtained from phantom experiment

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