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Numerical Estimation of the Intraventricular Pressure Gradients Based on Echo-Dynamography and Bernoulli's Principle

Echo-Dynamography 法とベルヌーイ定理に基づく心室内圧力勾配の推定法

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1. Introduction

Intraventricular pressure gradients (IVPG) are how much pressure changes between the apex and the base of the left ventricle (LV), and is related to cardiac function[1)]. The diastolic IVPG was reported to reflect the efficiency of blood filling, while the ejection IVPG was suggested to be related to myocardial contractility[2,3)]. Such IVPG assessments, however, could only be obtained by measuring pressure at multiple points in the LV with invasive catheterization of pressure sensors.

Recently, color Doppler M-mode echocardiography has been proposed as a new method for noninvasively estimating IVPG[1)]. This method assumed that the Doppler M-mode cursor approximates the streamlines, but the straight lines and streamlines unlikely match throughout the cardiac cycle. In addition, the IVPG value was estimated with limited information as the color M-Doppler method could only measure the velocity component parallel to the ultrasound beam. As a solution, an ultrasound vector flow imaging method that can visualize two-dimensional velocity field in the LV, so called Echo-Dynamography (EDG) method[4)], may be used to estimate streamlines of blood flow in the LV more accurately.

In this study, we hypothesized that consistent estimation of the IVPG is possible by combing the EDG method and a pressure gradient estimation method using streamlines[5)]. The feasibility of the IVPG estimation using those methods was evaluated using a custom-made volume-driven LV phantom.

2. Method

In this study, we first obtained time-resolved flow vector fields in the LV using the EDG method. From the obtained blood flow vectors, a streamline was generated, and the pressure difference along the streamline was estimated by substituting the velocity gradient along the streamline into the Bernoulli equation. The EDG and the pressure gradient estimation methods are respectively described in Sections 2.1 and 2.2.

2.1 Echo-Dynamography (EDG) method

EDG method[4)] can estimate the velocity component that is perpendicular to the radial component obtained by color Doppler and hence, it can visualize flow vector filed in the LV. First, the flow is divided into two streams with different properties. Next, the direction perpendicular to the ultrasonic beam is obtained by applying various hydrodynamic laws to each of the two flows. Finally, the two-dimensional velocity vector is obtained by summing the velocity along beam direction and perpendicular velocity.

2.2 Pressure estimation using the blood velocity gradient

3D flow is governed by the Navier-Stokes equations for incompressible fluids. Rewriting the Navier-Stokes equations into a scalar equation following a streamline, omitting the terms of the gravity and viscosity, yields the following:

$$dp_s = -\rho\left[\frac{\partial v_s}{\partial t}ds + v_s\frac{\partial v_s}{\partial s}ds\right] \qquad (1)$$

where dp_s is the individual pressure gradient, and ρ is the density of blood, and ds is an element of distance along the streamline that runs in the direction s, and v_s is the scalar product of a fluid's velocity field $\vec{v}(\vec{r},t) = (v_x(t), v_y(t), v_z(t))$ and the vector that lies tangent to the streamline ds. Integrating the individual pressure gradient dp_s along a streamline, from the l_1 to l_2, yields the unsteady Bernoulli equation:

$$\Delta P(t) = -\rho\left[\frac{v_{s,l2}^2 - v_{s,l1}^2}{2} + \int_{l1}^{l2}\frac{\partial v_s}{\partial t}ds\right] \qquad (2)$$

In this study, we used the EDG method that provides a two-dimensional vector velocity field $\vec{v}(\vec{r},t) = (v_x(t), v_y(t))$. Thus, we assumed that $v_z(t) = 0$ in this proposed method.

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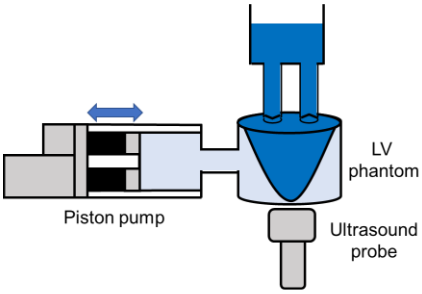

Fig. 1 The experimental system

2.3 Experimental setup and data acquisition

To confirm the feasibility of the proposed method, an experiment was carried out using a custom-made volume-driven LV phantom. The LV chamber (shown as the deep blue triangle in Fig.1) made of conical silicon rubber was assembled in the outer chamber, which was filled with water and connected to a piston pump. As the piston moved, the volume of the water in the outer chamber changed and the LV chamber was deformed accordingly. The piston pump was set to resemble a heart rate of 60 bpm and a stroke volume of about 60 ml. As the blood mimicking liquid, inside of LV chamber was filled with an aqueous solution of 10 wt% glycerin and 0.1 wt% ultrasound scatterer (Godd Ball, Suzukiyushi Industrial Corp.).

A color Doppler movie was recorded in a commercial Ultrasound scanner (Xario100, Canon Medical Systems, Tochigi, Japan). The central frequency was 3.0 MHz, and the frame rate was 14 fps. The acquired color Doppler images were processed offline using MATLAB.

3. Result and Discussions

Diastolic and systolic color Doppler images were acquired to estimate the pressure difference along the streamline using the LV phantom.

Fig. 2 (a) shows the diastolic vector velocity by the EDG method and streamline. The yellow arrows represent velocity vectors, and the green line represents streamline. **Fig. 2 (b)** shows pressure changes in a streamline in the diastolic and the starting point of the streamline, which is set to 0 mmHg, is the LV inflow area. The pressure difference between the apex and the inlet (IVPG) was approximately -0.38 mmHg.

Fig. 3 (a) shows the systole vector velocity by the EDG method and streamline. The yellow arrows represent velocity vectors, and the green line represents streamline. **Fig. 3** (b) shows pressure changes in a streamline in the systole and the starting point of the streamline, which is set to 0 mmHg, is the apex in the LV. The pressure difference between the outlet and the apex (IVPG) was approximately -3.0 mmHg.

Using the LV phantom, the pressure change in a streamline could be evaluated from the velocity vector obtained by the EDG method. It is necessary to verify the accuracy of the proposed method by comparing it with other blood pressure measurements.

4. Conclusion

In this study, we evaluated the feasibility of the EDG and streamline pressure estimation methods using the LV phantom. The experiment indicated that the proposed method would estimate pressure changes accurately and be useful for deriving IVPG indexes noninvasively.

References

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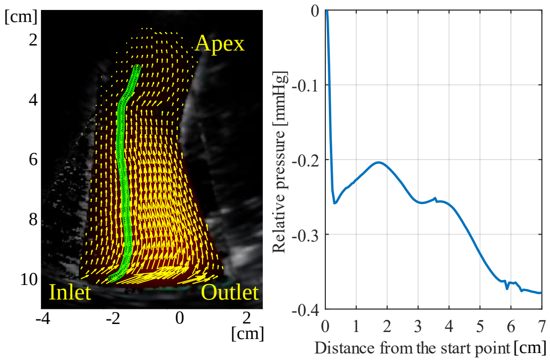
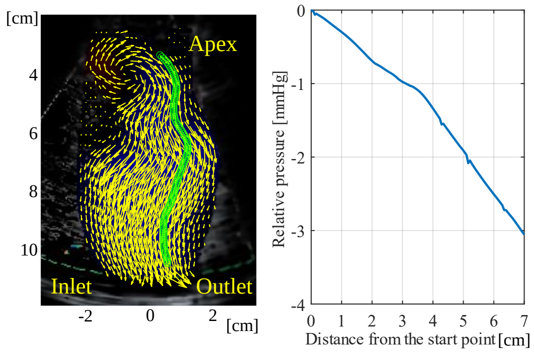


(a) (b)

Fig. 2 (a) Diastolic vector velocity and streamline (b) Pressure changes in a streamline in the diastolic



(a) (b)

Fig. 3 (a) Systole vector velocity and streamline (b) Pressure changes in a streamline in the systole