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Evaluation of Vortex Flow in Left Ventricle by Echo-dynamography and Phase Contrast Magnetic Resonance Angiography

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Abstract— **Echo-dynamography (EDG) is a method for visualizing left ventricular (LV) blood flow based on cardiac Doppler measurement in which blood flow component perpendicular to the ultrasonic beam is deduced by applying fluid dynamics theories to two-dimensional (2D) distribution of blood flow component along the ultrasonic beam. EDG has been validated by numerical simulation and particle image velocimetry of model circulation. However, these validations were too simple to reproduce unstable and asymmetrical flow in a beating heart. In the present study, EDG is compared with three-directional (3D) blood flow distribution on the same plane obtained with phase contrast magnetic resonance angiography (PCMRA) for clinical validation. Moreover, the location and vorticity of the vortex flow in LV are measured quantitatively and the relation to echocardiographic parameters of systolic and diastolic functions is discussed.**

3D components of blood flow on a plane were obtained with triple scans of the same plane with ECG trigger and breath holding; 1) phase encode (x-axis), 2) read out (y-axis) and 3) slice selection (z-axis). After the acquisition of MRA dataset, color Doppler dataset of the same plane was acquired and 2D velocity distribution was obtained with EDG in MATLAB programs.

EDG and PCMRA showed similar velocity vector distribution and formation of LV vortex flow. The vortex at mid diastolic phase was strongly affected by early diastolic filling while the vortex at isometric contraction was affected by atrial filling. EDG gained a new insight on systolic-diastolic coupling from the view point of LV blood flow such as LV vortex formation.

I. Introduction

According to the Frank-Starling law, the stroke volume of the heart increases in response to an increase in the volume of blood filling the heart (the end diastolic volume). Thus, cardiac pump function is determined how long the myocardium stretches in end-diastole. Left ventricular (LV) diastolic function apparently affects LV systolic function. In clinical settings, diastolic function is often measured as well as systolic pump function such as LV ejection fraction (EF). Recently, the concept of "diastolic heart failure [1]" or "heart failure with preserved EF" has been proposed and diastolic function is believed to deteriorate prior to the deterioration of systolic function.

Myocardial tissue Doppler imaging can measure longitudinal myocardial velocities of the mitral annulus; (1) s', systolic myocardial velocity above the baseline as the annulus descends toward the apex; (2) e', early diastolic myocardial relaxation velocity below the baseline as the annulus ascends away from the apex; and (3) a', myocardial velocity associated with atrial contraction. The strong correlation between s' and e' may indicate systolic-diastolic coupling in short term relationship from a view of physiology of cardiac myocytes. On the other hand, evaluation of cardiac function has been performed by intracardiac blood flow measurement. For example, diastolic function was assessed by early diastolic filling (E) over /atrial filling (A) ratio and most suitable parameters of CRT (cardiac resynchronization therapy) is set to maximize velocity-time integral of left ventricular outflow.

The blood flow structure in whole LV has been assessed by echo-dynamography (EDG) [2-5]. EDG is a method for visualizing left ventricular (LV) blood flow based on cardiac Doppler measurement in which blood flow component perpendicular to the ultrasonic beam is deduced by applying fluid dynamics theories to two-dimensional (2D) distribution of blood flow component along the ultrasonic beam. EDG has been validated by numerical simulation [6] and particle image velocimetry of model circulation. However, these validations were too simple to reproduce unstable and asymmetrical flow in a beating heart.

In the present study, EDG is compared with three-directional (3D) blood flow distribution on the same plane obtained with phase contrast magnetic resonance angiography (PCMRA) for clinical validation. Moreover, the location and vorticity of the vortex flow in LV are measured quantitatively and the relation to echocardiographic parameters of systolic and diastolic functions is discussed.

II. Methods

A. Echo-dynamography

A Color Doppler movie of the apical three-chamber view containing LV apex, center of mitral leaflets, and center of

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aortic valve was recorded in a commercially available ultrasound machine (SSD-6500SV, Aloka, Tokyo, Japan) in the left lateral recumbent position. The central frequency was 2.5 MHz and the frame rate was 10 fps.

Fig. 1 shows the concept of EDG. Blood flow is separated into two kinds of flow; vortex on a 2D plane and basic flow in the 3D space.

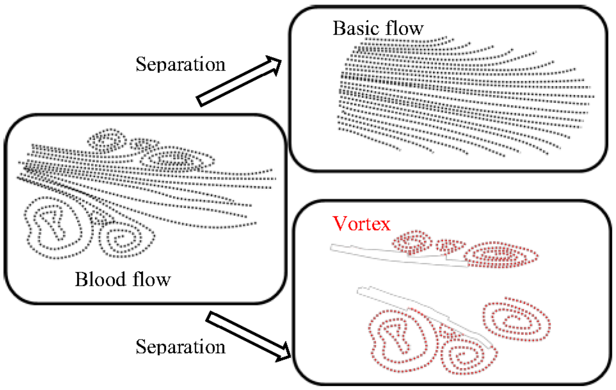

Fig. 1 Principle of echo-dynamography. Vortex components on a 2D plane and basic flow components in the 3D space are separated.

The processing algorithm of EDG consists of four steps.

Step1: The color Doppler data are decomposed into basic and vortex flow components such that the velocity profile of each vortex flow component is bilaterally symmetric.

Step2: In the vortex flow component, tangential velocities are found using stream function on an assumption that the velocity components perpendicular to the scan plane are zero.

Step3: In the basic flow component, the directions of flow vectors are found using flow function [2]. Tangential velocities can be found from the directions of flow vectors and the basic flow component of the color.

Step4: The velocity vector field is generated by composing the vectors from the two components.

EDG was obtained by these steps on MATLAB.

B. *Phase Contrast Magnetic Resonance Angiography*

All PCMRA data acquisitions were performed using a 1.5-Tesla MRI scanner (EXCELART Vantage MRT200-PP5; Toshiba Medical, Japan).

MR flow data were obtained from apical three chamber images. 2D PCMRA data was acquired with the following parameters: repetition time 24 msec, echo time 10 msec, flip angle 20 degree and 8-mm slice thickness. The velocity-encoding gradient value was 100cm/s, and three-directional (3D) components of blood flow were obtained with quadraple scans of the same plane with ECG trigger and breath holding; T_2-weighted image, phase encode (x-axis), read out (y-axis), and slice selection (z-axis).

III. Results

A. *Echo-dynamography*

Three normal volunteers were examined by EDG and PC-MRA. Fig. 2a shows the conventional color Doppler echocardiography and Fig. 2b shows the 2D distribution of blood flow vector in LV at isovolumic contraction (IC) phase. The direction of the vector is indicated by arrow and the magnitude of the vector is indicated by the color scale.

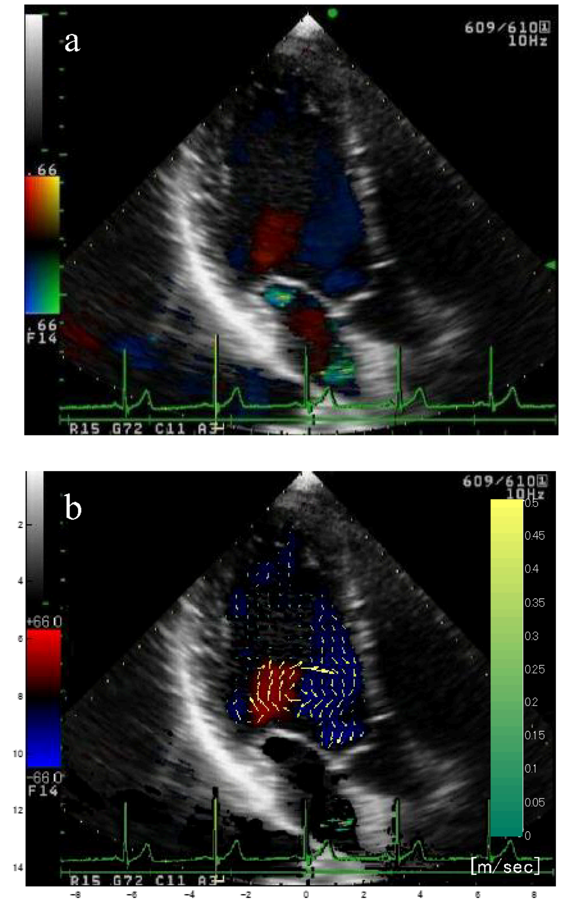

Fig. 2 a: conventional color Doppler, b: 2D distribution of blood flow vector obtained by echo-dynamography

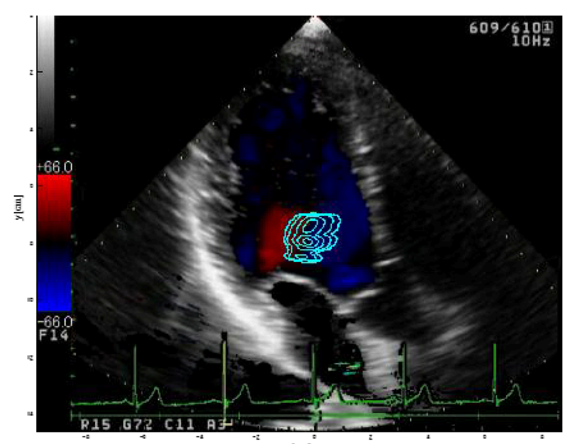

Fig. 3 Vortex flow presentation in echo-dynamography

Vortex component of the flow is represented in Fig. 3. The interval of the stream line shows the blood flow volume of 10 cm/s. The flow volume at the center of vortex was defined as vortex flow volume. At IC phase, a vortex is observed in the basal portion.

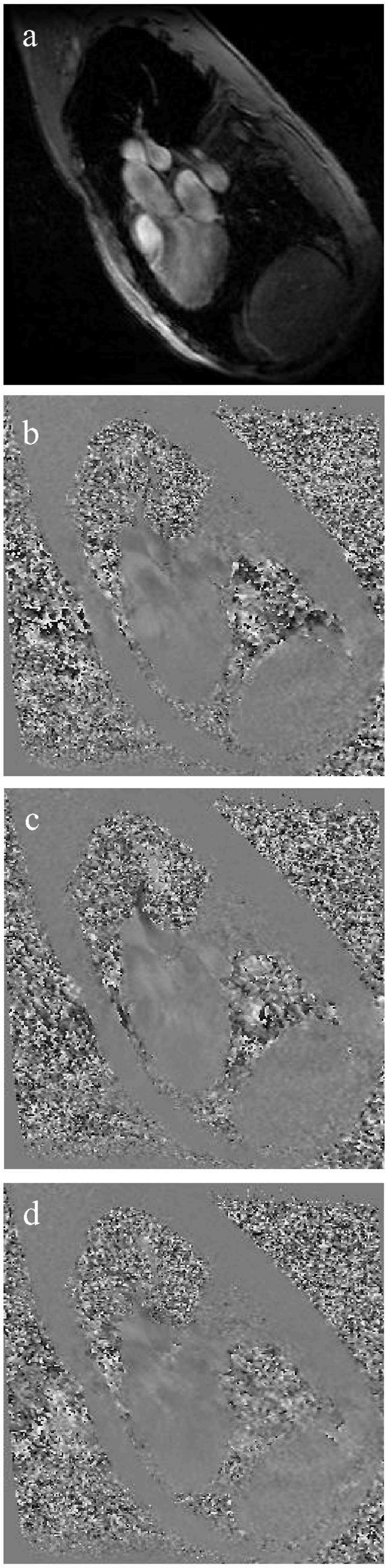

Fig. 4 PCMRA images of normal heart.
a: T_2-weighted image, b: PCMRA encoded in slice select (SS),
c: PCMRA encoded in read out (RO),
d: PCMRA encoded in phase encode (PE)

B. Phase Contrast Magnetic Resonance Angiography

Fig. 4 shows the original Three-chamber view images acquired by PCMRA. Fig. 4a shows T_2-weighted image and phase contrast image obtained simultaneously; Fig. 4b is encoded in slice select (SS) direction, Fig. 4c is encoded in read out (RO) direction, and Fig. 4d is encoded in phase encode (PE) direction respectively. These three phase contrast images were combined to figure out the vector flow map, and superimposed on the T_2-weighted image.

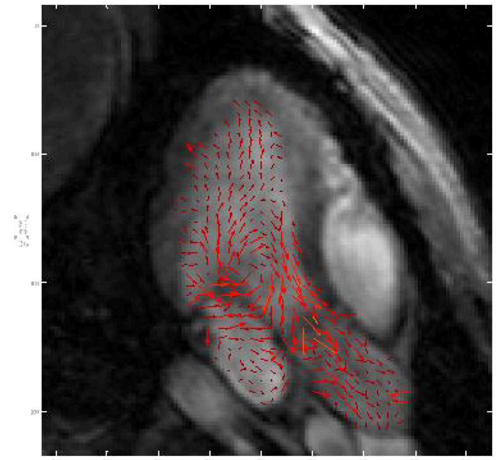

Fig. 5 2D distribution of blood flow vector obtained by PCMRA

Fig. 5 shows the blood flow vector component on the scan plane at IC showing similar patterns with Fig. 2b. Originally, the velocity information acquired by conventional color Doppler method is only the velocity component along the ultrasonic beam. When deducing 2D distribution of blood flow vector from one-dimensional information, the vortex flow components tangential to the ultrasonic beam are found using stream function on the assumption that the velocity components perpendicular to the scan plane are zero. This is the fateful limitation of EDG in estimating vortex flow component from the view point of fluid dynamics. However, the result showed no contradiction with the fluid dynamics.

C. Vortex Flow in LV

The flow volume at the center of vortex was defined as vortex flow volume. The maximum value of the vortex flow from the closure of mitral valve to the opening of aortic valve was defined as isovolumic contraction (IC) vortex flow. These values were compared with LV inflow in normal (n=10) and DCM (n=13). IC vortex flow showed a strong correlation with maximum amplitude of A wave (R^2=0.6097, Fig. 6). The results indicate that LV inflow strongly affects LV vortex formation.

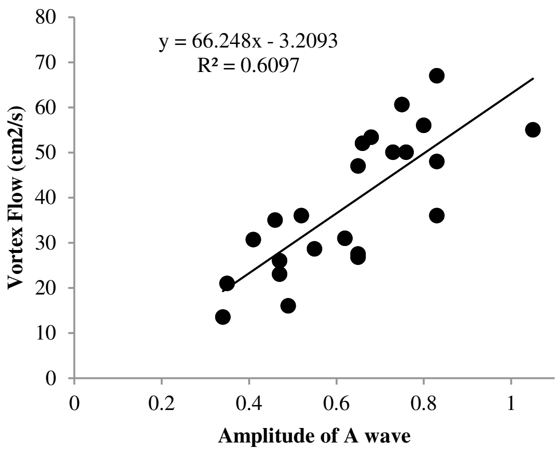

Fig. 6 Relation between atrial filling velocity and vortex flow

IV. DISCUSSION

EDG is superior in the spatial resolution in regards to the slice thickness. The slice thickness of the PCMRA data was 8-mm in order to gain the signal-to-noise-ratio. Because the color Doppler contains the instantaneous velocity information, EDG is superior in temporal resolution, too. On the other hand, concerning reproducibility and a degree of freedom of dimensions, PC-MRA is superior to EDG.

The intraventricular vortex had close relationship with the maximum velocity of the A wave. The inertial force of the LV inflow continuing after mitral valve closure should be the origin of the LV vortex formation.

Our previous study [5] has shown that the size of the vortex became larger in failure heart compared with normal heart. The phenomenon was discussed with LV contraction and geometry. The results of the present study clearly showed that LV inflow also influence the size and location of LV vortex. When the heart rate is increased, LV inflow velocity is increased because of fusion of E and A waves. In such cases, large vortex at IC was observed. In cases of atrial fibrillation, LV vortex was not affected by A wave but the influence of E wave remained until IC.

Conventionally, diastole is occurred by releasing elastic energy stored by the preceding systolic deformation. This concept of systolic-diastolic coupling was discussed based on the physiology of contraction of the myocytes. In the present study, systolic-diastolic coupling was discussed based on LV blood flow such as vortex formation. Watanabe et al. found that the physiological flow path did not have an energy-saving effect by their multiscale, multiphysics heart simulator [7]. However, the vortex at early systole was affected by diastolic blood flow. Steen and Steen reported that the flow propagation velocity was originated by the movement of LV vortex [8]. The "vortex" in their report should be the "separation vortex" while our measurements included both "separation and rotating vortexes". The difference should be discussed later.

V. CONCLUSIONS

In the present study, 3D blood flow vector using the PCMRA was obtained and its 2D velocity components on the observed plane were compared with the 2D distribution of blood flow vector obtained by EDG method. In many cases, the vector components showed similar patterns in both methods.

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