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Validation of Echo-Dynamography by Virtual Color Doppler Echocardiography Generated from Phase Contrast Magnetic Resonance Angiography Datasets

Takanori Kojima, Aiko Omori, Hiroyuki Nakajima, Takafumi Kurokawa, Takeyoshi Kameyama and Yoshifumi Saijo, *Member, IEEE*

***Abstract*— Echo-Dynamography (EDG) is a smart visualization technique in echocardiography in which two-dimensional distribution of blood flow vectors in cardiovascular system is deduced by applying fluid dynamics theories into Doppler velocity datasets. Previous validation studies such as numerical simulation of free jet model or model circulation were too simple to reproduce unstable and asymmetrical flow in left ventricle. In the present study, virtual color Doppler echocardiography is generated from PC-MRA (phase contrast magnetic resonance angiography) datasets. EDG is applied on virtual Doppler data and the blood flow vectors are compared with those of the original PC-MRA data. EDG-derived blood flow vectors showed similar pattern as the original PC-MRA data when blood flow velocity had high value. The errors were caused from underestimating the magnitude of vortex flow component in the flow field near the boundary of the left ventricular wall. The results also indicated that apical long axis view had small error compared with parasternal long axis view. Despite EDG method causes small errors, it provides important information on blood flow dynamics in most parts.**

I. Introduction

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 left ventricle (LV) has been assessed by echo-dynamography (EDG) [1-4]. EDG is a smart visualization technique in echocardiography in which two-dimensional distribution of blood flow vectors in cardiovascular system is deduced by applying fluid dynamics theories into Doppler velocity datasets. EDG has been validated by numerical simulation and particle image velocimetry of model circulation [5]. However, these validations were too simple to reproduce unstable and asymmetrical flow in a beating heart. Clinical validation of EDG was performed; EDG was applied on color Doppler echocardiography and the blood flow vectors were compared those obtained with PC-MRA (phase contrast magnetic resonance angiography). The distribution pattern roughly matched each other; however, quantitative analysis was difficult because the observation plane was not completely matched between echocardiography and PC-MRA [6].

In the present study, virtual color Doppler echocardiography is generated from PC-MRA datasets. EDG algorithm is validated by comparing blood flow vectors obtained by EDG applied on virtual Doppler data and those of the original PC-MRA data.

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T. Kojima is with the Graduate School of Biomedical Engineering, Tohoku University, Sendai, Japan (e-mail: takanori.kojima@bme.tohoku.ac.jp).

A. Omori is with the Graduate School of Biomedical Engineering, Tohoku University, Sendai, Japan (e-mail: a.omori@ecei.tohoku.ac.jp).

H. Nakajima is with Tohoku Welfare Pension Hospital, Sendai, Japan (e-mail: hiro1029@sea.plala.or.jp).

T. Kurokawa is with Tohoku Welfare Pension Hospital, Sendai, Japan (e-mail: nenkin_kurokawa@yahoo.co.jp).

T. Kameyama is with the Department of Cardiology, Miyagi Social Insurance Hospital, Sendai, Japan (e-mail: takeyosh@wa2.so-net.ne.jp).

Y. Saijo is with the Graduate School of Biomedical Engineering, Tohoku University, Sendai, Japan (phone: +81-22-717-8514; fax: +81-22-795-7149; e-mail: saijo@ idac.tohoku.ac.jp).

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 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.

The processing algorithm of EDG is the following.

First, the LV blood flow is considered as incompressible and three-dimensional (3D) flow. Thus, equation of continuity in the 3D space can be applied.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \cdots (1)$$

The rest of the components v on the x-y plane can be estimated by integrating continuity equation for incompressible flow along the y-axis as follows:

$$v(x,y)=-\frac{\partial}{\partial x}\int_{y_0^-(x)}^{y} u(x,y')\,\partial y' - \frac{\partial}{\partial z}\int_{y_0^-(x)}^{y} w(x,y')\,\partial y' + v\left(x,y_0^-(x)\right) \cdots (2)$$

In conventional color Doppler echocardiography, the velocity component w in the z direction cannot be measured. In some previous methods, the second term of the equation (2) was ignored assuming w=0. This flow condition is considered

as 2D flow. Thus, classical statement of stream function can be applied as equation (3).

$$v(x,y) = -\frac{\partial}{\partial x}\int_{y_0^-(x)}^{y} u(x,y')\,\partial y' \cdots (3)$$

However, LV flow should be considered as 3D flow and classical stream function cannot be applied. In EDG method, the second term of the equation (2) is modeled as equation (4).

$$v(x,y) = -\frac{\partial}{\partial x}\int_{y_0^-(x)}^{y} u(x,y')\partial y' + \frac{\partial}{\partial x}\int_{y_0^-(x)}^{y} (1-k(x,y'))u(x,y')\,\partial y' + (1-k(x,y))u(x,y)\tan\kappa \cdots (4)$$

Figure 1 shows an example of EDG representing blood flow velocity vectors.

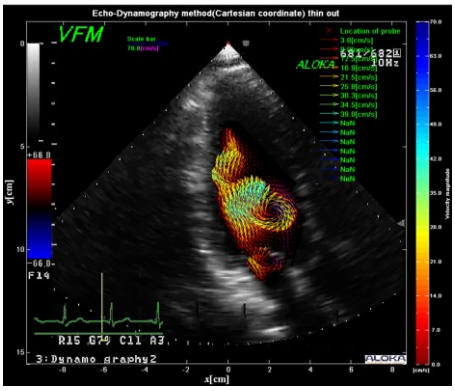

Figure 1. Example of EDG (blood flow velocity vector)

Figure 2 shows an example of EDG representing stream lines.

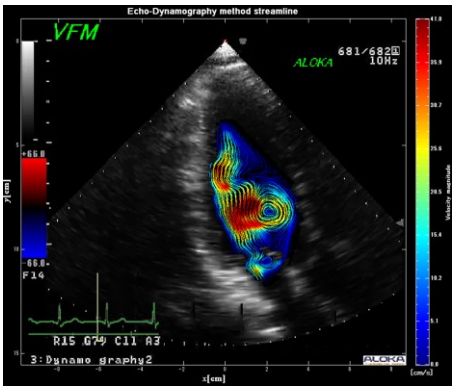

Figure 2. Example of EDG (streamline)

B. PC-MRA

ECG-triggered and breath-hold PC-MRA sequences were obtained from one healthy volunteer. A commercially available 1.5T MRI apparatus (EXCELART Vantage MRT200-PP5, Toshiba Medical, Japan) was equipped for the MRA data acquisition. 2D PC-MRA method with velocity flow encoding of 100cm/s, TR of 24 msec, TE of 10 msec, flip angle of 20 degree, slice thickness of 8 mm, matrix size of 128 (Read out direction) × 256 (Phase encoding direction) and resolution of 2.73 mm × 1.37 mm was used. The cardiac phases such as ejection (E), late systole (LS), early rapid filling (ERF), late rapid filling (LRF), and atrial contraction (AC) phase, were analyzed.

Virtual Doppler velocity is defined as the blood flow components on the radial direction in a polar coordinate system, simply directed to or away from virtual sector probe. Virtual Doppler velocity fields were acquired from various probe positions on the body surface in T2 weighted image (T2WI) (Figure 3).

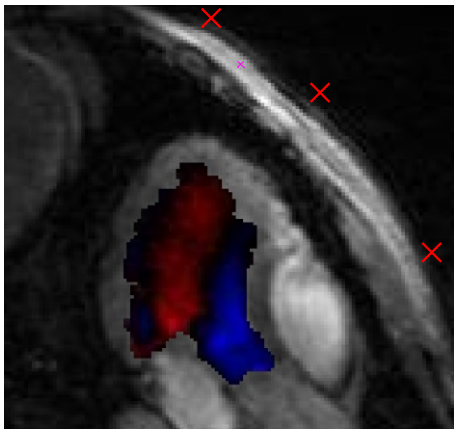

Figure 3. Virtual color Doppler image generated from PC-MRA datasets. ×: Virtual probe location

C. Definition of the Error

In this study, overall relative errors were calculated according to the following equations [7]:

$$E_{tot} = \frac{\int_{\Omega} \varepsilon(x,y)\,dS}{\int_{\Omega} \|\mathbf{V}_{\mathrm{MRI}}\|\,dS} \cdots (5)$$

$$\varepsilon(x,y) = \|\mathbf{V}_{\mathrm{MRI}} - \mathbf{V}_{\mathrm{EDG}}\| \cdots (6)$$

where ε shows the point wise error expressed as a function of the Cartesian coordinates (x, y), which was defined as the difference of the absolute values between $\mathbf{V}_{\mathrm{MRI}}$ (original velocity vectors measured by PC-MRA) and $\mathbf{V}_{\mathrm{EDG}}$ (reconstructed velocity vectors obtained with EDG applied on virtual color Doppler echocardiography). Ω is the area of interest. In particular, note that analytical area was limited to LV and left atrium during filling phases when aortic valve is closed, and LV and ascending aorta during ejection phases when mitral valve is closed.

III. Results

Figure 4 shows 2D blood velocity fields measured by PC-MRA and the reconstructed velocity fields with EDG method in ejection, early rapid filling and atrial contraction phases. Virtual probe position located at the apex of LV is expressed as cross (×) on the T2WI image shown in Figure 4.

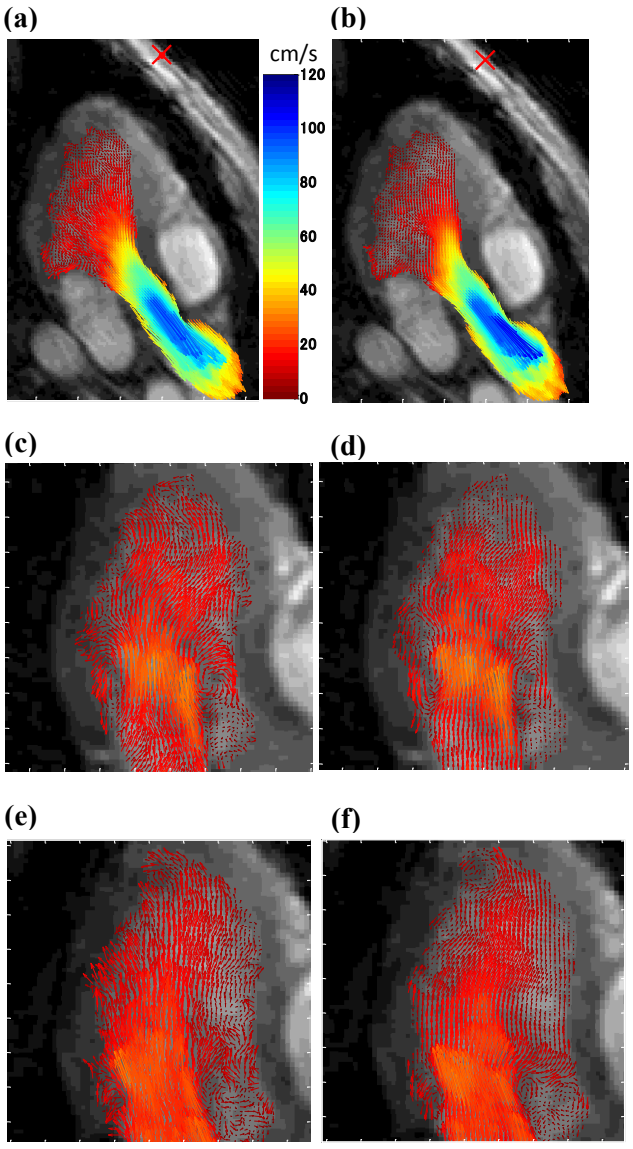

Figure 4. Blood velocity mapping in normal LV comparing the velocity field of the original PC-MRA measurements (PC-MRA) and the velocity field of EDG applied on virtual color Doppler echocardiography (EDG). (a) PC-MRA, (b) EDG at ejection phase, (c) PC-MRA, (d) EDG at early rapid filling, (e) PC-MRA, (f) EDG at atrial contraction. The vectors indicate the direction and magnitude of the velocity as coded in the color bars (cm/s). The cross (×) located at the apex of LV on T2WI represents the virtual probe position.

Velocity distribution pattern showed no significant difference by qualitative visual observations.

Table.1 represents the overall error parameter E_{tot} at five cardiac phases in the same probe position in Figure 4.

Phase	E	LS	ERF	LRF	AC
E_{tot} [%]	18.0	27.7	28.4	24.0	30.0

Table.1 Error parameters at five cardiac phases (E: ejection, LS: late systole, ERF: early rapid filling, LRF: late rapid filling, AC: atrial contraction)

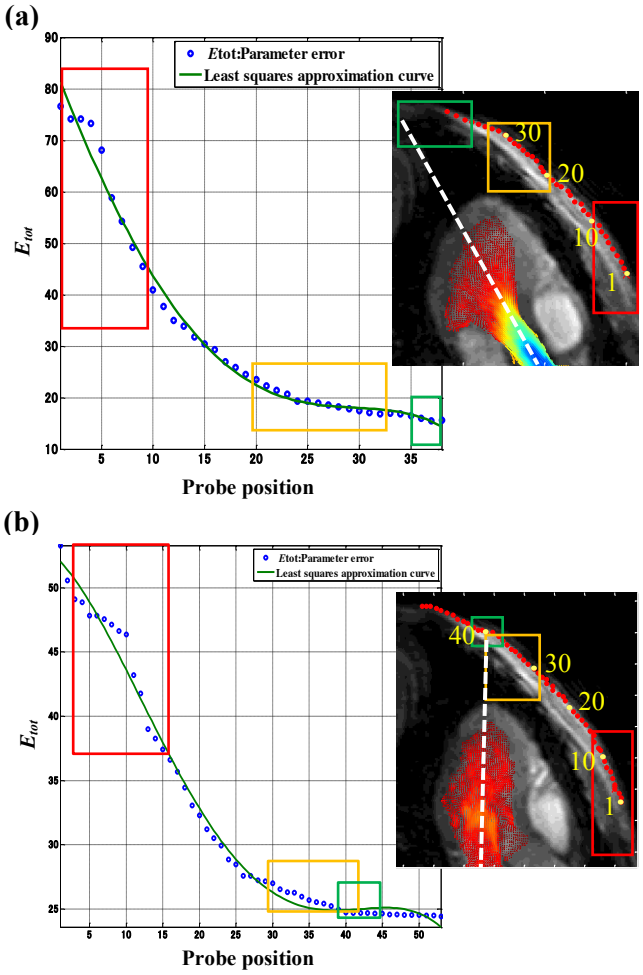

Figure 5. Relation between the error parameter E_{tot} and the virtual probe position at ejection phase (a) and early rapid filling phase (b). Blue circle shows values of E_{tot} at each probe position. Right figures show the original velocity fields measured with PC-MRA and the virtual probe position.

Graphs in Figure 5 show the relation between error parameter E_{tot} and the virtual probe position at the ejection phase and early rapid filling phase. Blue circles show values of E_{tot} at each probe position. The green curves are quadratic least square fits to the data.

The probe positions were numbered from the parasternal portion to the LV apical portion. Virtual probe position is expressed as the red circle in the right figures showing original velocity fields measured with PC-MRA. Yellow circles show the virtual probe position numbered as 1, 10, 20, 30, and 40. Apical three chamber view is obtained when the virtual probe is located in the orange-colored boxes. Left parasternal long axis view is obtained when the virtual probe is located in the red-colored boxes.

Error parameter depended on the virtual probe position at both ejection phase and early rapid filling phase. White dashed lines indicate the main flow axis at each phase. E_{tot} was minimized when the virtual probe is located in the blue-colored boxes where main flow axis aligns parallel to the virtual ultrasonic beam.

IV. Discussion

In comparison with original blood flow vectors obtained with PC-MRA, the error of EDG was smallest in the ejection phase among five cardiac phases. In the ejection phase, LV outflow showed the fastest flow and the flow was nearly parallel to the ultrasonic beam. In the early rapid filling phase, the error was relatively small and a large vortex was observed in the center of LV. In EDG algorithm, vortex flow and basic flow is separated in the first step. In these cardiac phases, vortex flow and basic flow might be clearly separated.

In our previous studies [2-4], apical three-chamber view showed clear and smooth blood flow distribution compared to other views such as apical four-chamber view or parasternal long axis view. In the present study, the error was minimized when the virtual probe point was located at the "real" LV apex. It is assumed that small errors result from when a visible vortex and a main flow have no contradiction in flow fields observed from the LV apex. On the other hand, errors were caused from underestimating the magnitude of vortex flow component in the flow field near the LV boundary. The error parameter was max at the atrial contraction phase. However, the absolute value of blood flow velocity was low in atrial contraction phase. Thus, the flow pattern was not significantly different from original PC-MRA in the visual observation.

The clinical significance of EDG, especially quantitative analysis of LV vortex was already shown in our previous study [6]. 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 relationship between systole and diastole from the view point of LV blood flow dynamics. The pump function has been mainly discussed with myocardial contractility based on the measurement of classical ejection fraction, myocardial strain obtained with tissue Doppler or speckle tracking. Discrepancies between myocardial contractility and LV blood flow obtained with EDG may clarify the nature of heart failure.

V. Conclusion

Virtual color Doppler echocardiography was generated from PC-MRA datasets. EDG algorithm was validated by comparing blood flow vectors derived by applying EDG on virtual Doppler data and original PC-MRA data. EDG-derived blood flow vectors showed similar pattern as the original PC-MRA data when blood flow velocity had high value. The errors were caused from underestimating the magnitude of vortex flow component in the flow field near the LV boundary. The results also indicated that apical long axis view had small error compared with parasternal long axis view.

As echocardiography is a real-time, non-invasive and repeatable medical imaging technique, EDG may provide important information on blood flow dynamics in clinical settings.

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