2E5-3

Proceedings of Symposium on Ultrasonic Electronics, Vol. 33 (2012) pp. 145-146
13-15 November, 2012

Intraventricular Flow Velocity Vector Visualization Based on the Continuity Equation and Measurements of Vorticity and Wall Shear Stress

連続の式に基づく心室血流ベクトル可視化法の開発および渦度と壁せん断応力の計測

Keiichi Itatani[1†5,6], Takashi Okada[2], Tokuhisa Uejima[3], Tomohiko Tanaka[4], Minoru Ono[5], Kagami Miyaji[6], Katsu Takenaka[7]. ([1]Department of Hemodynamic Analysis, Kitasato University School of Medicine; [2]Hitachi-Aloka Medical Co. Ltd.;[3] The Cardiovascular Institute; [4] Hitachi Ltd., Central Research Laboratory; [5]Deparment of Cardiac Surgery, the University of Tokyo; [6]Department of Cardiovascular Surgery, Kitasato University School of Medicine;[7] Department of Laboratory Medicine, The University of Tokyo)

板谷慶一 [1†,5,6], 岡田 孝 [2], 上嶋徳久 [3], 田中智彦 [4], 小野 稔 [5], 宮地 鑑 [6], 竹中 克 [7] ([1] 北里大学血流解析学講座; [2] 日立アロカメディカル株式会社; [3] 心臓血管研究所; [4] 日立製作所中央研究所, [5] 東京大学心臓外科; [6] 北里大学心臓血管外科 ; [7] 東京大学検査部)

1. Introduction

Blood flow patterns inside the ventricle chamber or large vessels are closely linked to the morphology and function of the cardiovascular system such as valve or ventricular wall motion. Therefore, blood flow visualization with spatial and temporal velocity distribution would provide diagnostic and prognostic information of cardiovascular diseases. Because echocardiography is noninvasive and portable, flow visualization method has been expected for clinical applications and several systems has been developed [1-4].

Garcia D et al.[3] constructed 2D intraventricular velocity vector based on the continuity equation combining the unidirectional color Doppler velocities with ventricular wall tracking. We also have developed a flow visualization system called vector flow mapping (VFM) by modifying Garcia's method. In order to derive clinically useful parameters, which reflect ventricular performances, characterizing and quantifying the vortex flow and flow-wall interaction would be essential; thus, we examined the following two points: color Doppler data smoothing method especially standard deviation (SD) of the Gaussian filter to provide robust and reasonable vorticity; and weight function on two solution from two obtained boundaries to provide accurate not only inner rotational flow but also near wall flow velocity distribution.

2. Methods

2.1 VFM system

Blood flow visualization with vector was based on the 2D continuity equation on the measurement plane expressed with polar coordinate system (r, θ) centered at the sector probe.

$$\partial_\theta V_\theta = -r\partial_r V_r - V_r \qquad (1)$$

V_θ and V_r are azimuthal and radial velocity vector components. V_r was given by the smoothed color Doppler data, and the boundary condition was given by the speckle tracking data of the ventricular wall. The method was illustrated in Figure 1.

2.2 Color Doppler data smoothing method

Because raw color Doppler data is too rough to solve the differential equation (1), sufficient data smoothing is necessary to stabilize differential term. After the median filtering within 3 neighborhood points toward the radial direction, color Doppler data were smoothed out with the Gaussian averaging filtering. Influences of the SD on the vorticity during one cardiac cycle were examined.

2.3 Weight functions on the bilateral boundaries

Because the continuity equation is the first order differential equation and because speckle tracking data gives two wall boundary conditions derived from the anteroseptal and posterior wall, two flow velocity fields are acquired ($V_{\theta+}$ and $V_{\theta-}$, respectively). V_θ was calculated by mixing the two fields according to a weight function (w), which denoted a normalized length from the left boundary.

$$V_\theta = w V_{\theta-} + (1-w) V_{\theta+} \qquad (2)$$

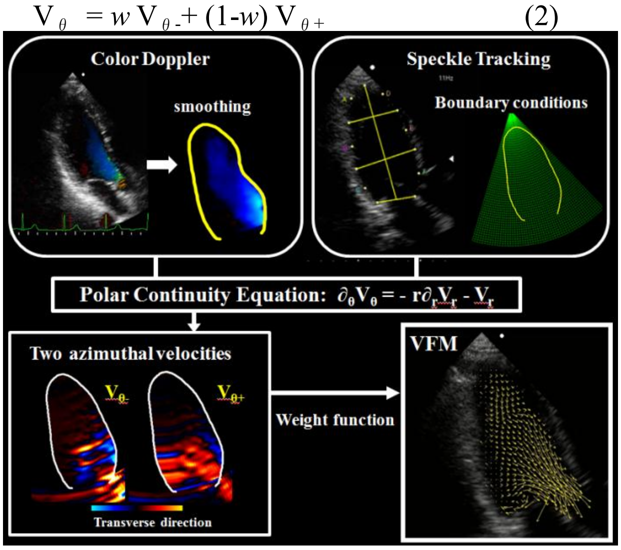

Figure 1: VFM system based on the continuity equation

Corresponding to Keiichi Itatani keiichiitatani@gmail.com

2.4 Data Acquisition and Algorism Validation

Color Doppler and B-mode speckle tracking data of a healthy volunteer left ventricle were acquired using ProSound α 10 (Hitachi-Aloka medical CO., Ltd.). Nyquist limit was set to be 53 cm/s. Vorticity was calculated from the constructed velocity.

For the validation of the VFM algorism, CFD (Computational Fluid Dynamics) pipe flow model (Reynolds number: 1560. Convergence criteria: 10^{-6} times the residual) was created with finite volume solver ANSYS-CFX (ANSYS Japan). The velocity vector of the central plane was transformed into polar coordinate system, unidirectional radial velocities were derived and azimuthal velocity was reconstructed. Vector direction and magnitude was validated with CFD solutions, and wall shear stress (WSS) was calculated with the near wall vectors.

3. Results

3.1 Color Doppler data smoothing and vorticity

Figure 2 illustrates vorticity distributions dependent on the SD of the Gaussian filtering during diastolic and isovolumic systolic phase, when characteristic vortex flow is known to appear. Insufficient SD remained unphysiological azimuthal directional stripe shape, whereas too large ones caused radial directional stripe. 8 pixels SD seemed reasonable and minimized the stripe shape noise. Robust vorticity field was obtained with this smoothing method.

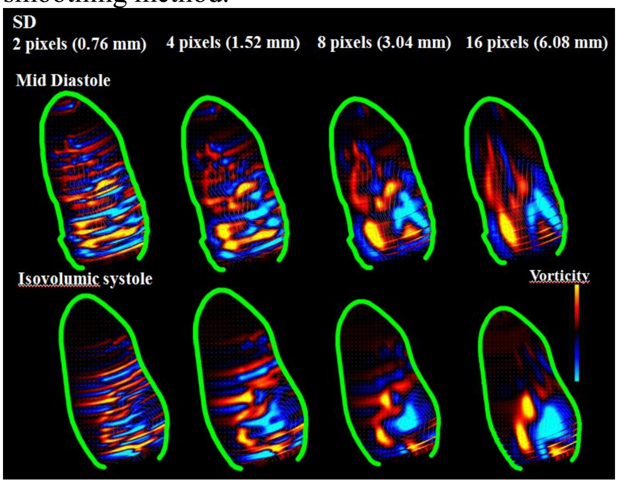

Figure 2: SD of the Gaussian kernel and vorticity

3.2 Weight function and near wall flow

Figure 3 illustrates CFD and VFM vector velocity fields and WSS. Vortex flow with in the larger pipe was realized in VFM with sufficient accuracy. The velocity magnitude error between CFD and VFM vectors was 2.45 ± 4.25 % of the Nyquist limit, and the vector angle error was 0.03 ± 8.41° .

The distributions of the WSS were quite similar in both CFD and VFM, suggesting that the accurate near wall flow was obtained by increasing the weight of the near side wall motion.

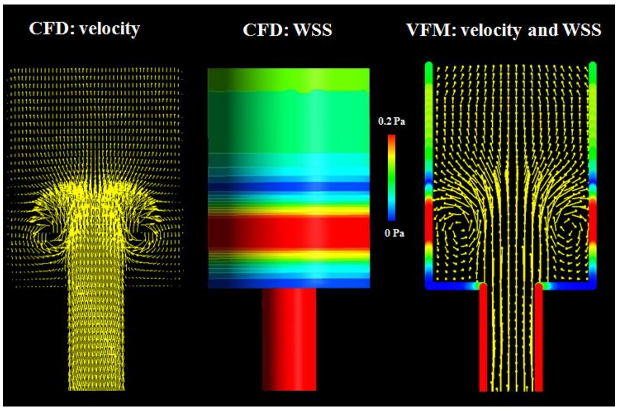

Figure 3: CFD and VFM: velocity vector and WSS

4. Discussions and Conclusions

For the development of the flow visualization system based on the continuity equations, Gaussian filter SD and weight functions on the bilateral boundaries were determined, and physiologically essential parameters vorticity and WSS were measured. Linear weight function (2) not only provided accurate velocity vector in the central region but also had advantages to realize faithfully the influence of wall motion on the near wall flow.

2D flow assumption was one of the most important limitations on vector constructions with echocardiography. Validations with experimental equipments or other flow measurement modalities such as MRI (magnetic resonance imaging) warrant further studies. Future studies include clinical applications such as creating diagnostic indexes from vectors or revealing the pathophysiological mechanisms of the cardiovascular diseases.

Acknowledgment

This work was financially supported by Hitachi-Aloka medical. CO., Ltd.

References

1. Ohtsuki S, Tanaka M. The flow velocity distribution from the Doppler information on a plane in three-dimensional flow. J Visualization. **9** (2006) 69-82
2. Hong GR, Pedrizzetti G, Tonti G, Li P, Wei Z, Kim JK, Liu S, Chung N, Houle H, Narula J, Vannan MA Characterization and quantification of vortex flow in the human left ventricle by contrast echocardiography using vector partile image velocimetry. J Am Coll Cardiol Img **1** (2008) 705-17
3. Garcia D, Del Alamo JC, Tanne D, Yotti R, Cortina C, Bertrand E, Antoranz JC, Perez-David E, Rieu R, Fernandez-Aviles F, Bermejo J. IEEE Trans Med Imaging. **10** (2010) 1701
4. Sengupta PP, Pedrizzetti G, Kilner PJ, Kheradvar A, Ebbers T, Tonti G, Fraser A, Narula J. Emergin trends in CV flow visualization. J Am Coll Cardiol Img **5** (2012) 305-16