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FUNDAMENTAL STUDY OF MR-MEASUREMENT-INTEGRATED SIMULATION OF HEART-AORTA-SYSTEM: BLOOD FLOW OF ASCENDING AORTA

Yuki Hori[1], Suguru Miyauchi[2], Toshiyuki Hayase[2], Alain Lalande[3], and Jean-Joseph Christophe[4]
[1] Graduate School of Engineering, Tohoku University,
6-6-C05 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi, 980-8579, Japan,
hori@reynolds.ifs.tohoku.ac.jp
[2] Institute of Fluid Science, Tohoku University,
2-1-1 Katahira, Aoba-ku, Sendai, Miyagi, 980-8577, Japan,
miyauchi@reynolds.ifs.tohoku.ac.jp, hayase@ifs.tohoku.ac.jp
[3] ImViA laboratory, University of Burgundy-Franche-Comté,
7, Bld Jeanne d'Arc, BP 87900, 21000, Dijon, France,
Alain.Lalande@u-bourgogne.fr
[4] R&D manager, CASIS-CArdiac Simulation & Imaging Software,
64A Rue de Sully, 21000 Dijon, France,
jjchristophe@casis.fr

SUMMARY

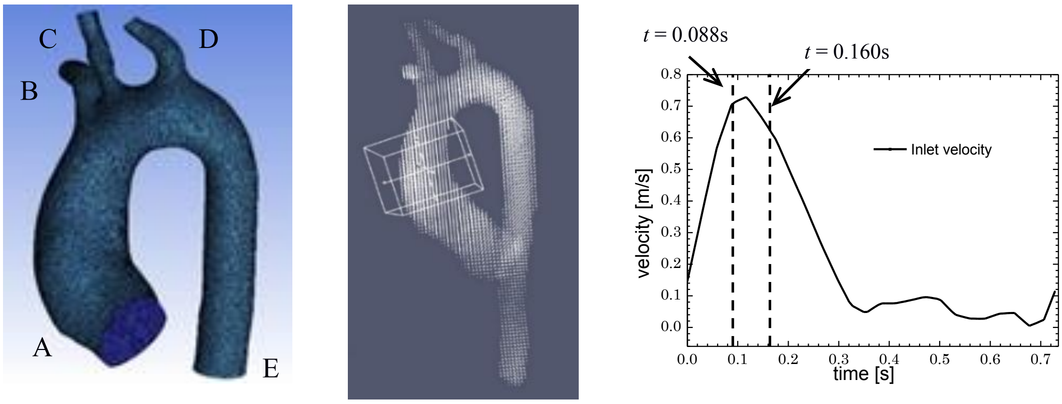
The purpose of this paper was to clarify accurate blood flow dynamics and hemodynamic parameters in the ascending aorta obtained by MR-measurement-integrated (MR-MI) simulation. In this study, flow field and hemodynamic parameters in the ascending aorta were compared between those obtained from MR measurement data, ordinary simulation and MR-MI simulation using modified inflow rate to minimize the mean axial velocity error in the ascending aorta. In the numerical results, MR-MI simulation properly reproduced the velocity profiles of the MR data.

Key words: *Computational fluid dynamics, 4D flow MRI, Measurement-integrated simulation, ascending aorta*

1 INTRODUCTION

It is important to obtain accurate hemodynamic parameters because initiation and progress of cardiovascular diseases are closely related to the flow condition. Magnetic resonance imaging (MRI) and computational fluid dynamics (CFD) are typical ways to obtain information of the blood flow field. However, MRI has relatively low temporal-spatial resolution although it noninvasively obtains the actual data in vivo. On the other hand, giving exact initial and boundary conditions is difficult in the CFD in general. Moreover, a patient-specific modeling of the blood flow has not been established yet. To reproduce the accurate blood flow field in aorta, MR-measurement-integrated (MR-MI) simulation was developed [1,2]. MR-MI simulation reproduces actual blood flow fields by adding the virtual feedback force, which is proportional to velocity difference between the measurement and computation, to the Navier-Stokes equation. In the analysis in a specific region of interest (ROI) in the ascending aorta, it was shown that the velocity error in this ROI was substantially reduced by inflow rate modification in ordinary simulation [1]. The error was further reduced by the feedback in MR-MI simulation. In the MR-MI simulation for the ascending aorta, the error little decreased by inflow rate modification in ordinary simulation but substantially decreased by feedback in MR-MI simulation [2].

The purpose of this paper is to clarify accurate blood flow dynamics and hemodynamic parameters in the ascending aorta by MR-MI simulation. In this study, flow field and hemodynamic parameters



(a) Geometry and computational mesh (b) Region of interest (ROI) (c) Inlet velocity extracted from MR data

Fig.1 Geometry and computational condition

in the ascending aorta are compared between those obtained from MR measurement data, ordinary simulation and MR-MI simulation using modified inflow rate to minimize the mean axial velocity error in the ROI.

2 METHOD

MR data used in this study is the same as that of the former study for the descending aorta and ascending aorta [1, 2]. It was extracted from a 38-year-old female patient with a dilatation at the level of Valsalva sinuses and of the aortic root. The data was treated based on the ethical guidelines of the University Hospital of Dijon (France). Three-dimensional shape of the aorta was extracted from the MR data using medical image analysis software (Flova2.9, R'Tech, JPN). 3D data tool software (Paraview5.4.0, SNL, LANL, Kitware Inc., USA) was used to smooth the extracted blood vessel shape. A computational grid generation software (ICEM CFD16.2, ANSYS, USA) was used to create a computation mesh for blood flow analysis (Fig. 1(a)). Tetrahedral and prism meshes were used for the calculation, and three-layer prism meshes were arranged near the wall surface. The numbers of grid points and cells are respectively 223317 and 794497. The ROI in this paper, the same as that of the former report [2] was set in the ascending aorta using 3D data tool software (Paraview5.4.0) (Fig.1(b)). Unsteady fluid flow analysis was performed by the commercial thermal fluid analysis software (FLUENT16.2, ANSYS, USA). The density and the viscosity of the fluid were set $\rho = 1000$ kg/m^3 and $\mu = 0.004$ Pa・s, respectively, with reference to the physical property of the blood. The feedback gain was set to 40 based on former report [2]. Flow rates for the outlet E and branches B, C, D are 80 %, 10 %, 6 % and 4 %, respectively. Figure 1(c) shows the inlet flow rate obtained from MR data. The cross-sectional velocity distribution at the inlet was uniform in all cases. Data points were interpolated from 25 points to 100 points using linear interpolation in the time direction. Figure 2 shows the simulation procedure performed in this study. Ordinary simulation was performed using the inflow rate estimated from the mean axial velocity error in the ROI.

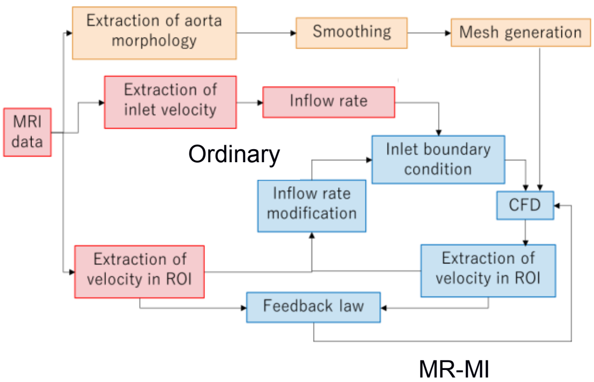
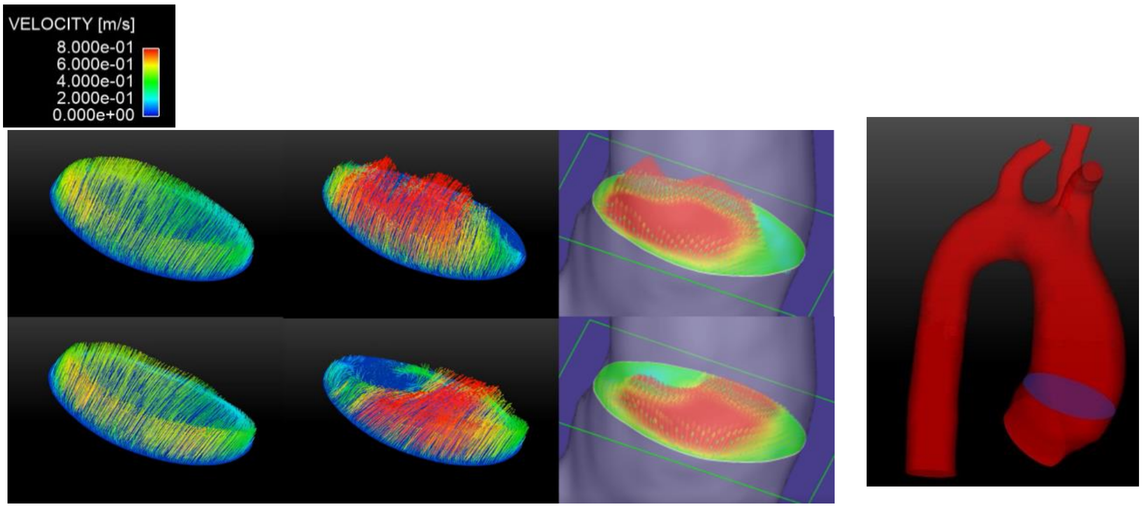


Fig. 2 Block diagram of MR-MI simulation and Ordinary simulation



(a) Ordinary (b) MR-MI (c) MRI measurement (d) Plane A

Fig. 3 Velocity profiles on Plane A colored by purple in (d). Upper and lower figures of the velocity profiles are at t = 0.088s and t = 0.160s, respectively. The same color bar for velocity magnitute is used for (a), (b), (c). The difference of the colors of the Plane A in (a), (b) and (c) is due to different visualization softwares for the numerical simulation and MR data.

MR-MI simulation was also performed using the modified inflow rate. In MR- MI simulation, the feedback force was added to all computational points in ROI using MRI data closest to each point. The number of calculation points in the ROI was 174423, and those of MRI measurement points was 3815.

3 RESULTS AND DISCUSSION

Figure 3(a), (b) and (c) show the velocity vectors of the ordinary simulation, MR-MI simulation and MRI data on the plane A, which is a surface of ROI near the inlet, at t = 0.088s and t = 0.160s (see Fig 1(c)) in the systolic phase. In Fig. 3(a) showing the results of the ordinary simulation without feedback force, the velocity profiles are rather flat. On the other hand, in Fig. 3(b) showing the results of MR-MI simulation with the feedback force, the velocity profiles are deflected to inside and outside for the curvature of the aorta for the two cardiac phases, and they are similar to those of MR data (Fig. 3(c)). The velocity profiles of MR-MI simulation and MR data are also in good agreement on other cross sectional planes, which are consistent with former report [2] in which the error of the MR-MI simulation largely decreased compared with that of the ordinary simulation.

4 CONCLUSIONS

The purpose of this paper was to clarify accurate blood flow dynamics and hemodynamic parameters in the ascending aorta obtained by MR-MI simulation. In this study, flow field and hemodynamic parameters in the ascending aorta were compared between those obtained from MR measurement data, ordinary simulation and MR-MI simulation using modified inflow rate to minimize the mean axial velocity error in the ascending aorta. In the numerical results, MR-MI simulation properly reproduced the velocity profiles of the MR data.

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