11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20 - 25, 2014, Barcelona, Spain

# COMPUTER SIMULATION OF THROMBUS FORMATION IN SINGLE VENTRICLE USING PARTICLE METHOD

**Ken-ichi Tsubota[1], Kazuki Okauchi[1], Koichi Sughimoto[2] and Hao Liu[1]**

[1] Dept. Mech. Eng., Chiba University, 1-33 Yayoi, Inage, Chiba 263-8522, Japan,
tsubota@faculty.chiba-u.jp, http://www.em.eng.chiba-u.jp/~lab8/
[2] Dept. Cardiac Surg., The Royal Children's Hospital, Melbourne, 50 Flemington Rd, Parkville, VIC 3052, Australia

**Key Words:** *Computational Biomechanics, Blood Flow, Thrombus, Particle Method*

In a patient with a functionally univentricular heart, blood flow dynamics from the inferior and superior vena cava to the pulmonary artery is improved by a surgical operation to reconstruct the blood flow channel. Despite of several modifications in the surgical procedure, an intracardiac thrombus has been a major concern leading to considerable late mortality and morbidity [1]. In this study, we perform a computer simulation of thrombus formation in single ventricle under the influence of an abnormal blood flow using a particle method.

Two types of blood components, normal blood and thrombus, are modelled by computed particles (Fig. 1). Assuming incompressible viscous flow, motions of particles are calculated by the moving particle semi-implicit (MPS) method [2] based on equation of continuity and Navier-Stokes (NS) equations. To express thrombus formation by blood coagulation, spring force,

$$\mathbf{f}_{ij}^{C} = -k(|\mathbf{r}_{ij}| - r_0)\frac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|} = -\mathbf{f}_{ji}^{C} \qquad (|\mathbf{r}_{ij}| < r_{cutoff}), \tag{1}$$

is applied between two thrombus particles $i$ and $j$, where $\mathbf{r}_{ij} = \mathbf{r}_j - \mathbf{r}_i$, $\mathbf{r}_i$ and $\mathbf{r}_j$ are postion vectors of particles $i$ and $j$, respectively, $r_0$ is natural length of the spring, $k$ is spring costant, and $r_{cutoff}$ is cutoff length of the spring. Spring force $\mathbf{f}^{C}_{ij}$ is substituted into NS equations as the external force to couple blood coagulation and blood flow [3].

To investigate effects of a geometry of blood flow channel on thrombus formation, blood flow models are constructed for atrio-pulmonary connection (APC) and total cavo-pulmonary connection (TCPC) (Fig. 2). The models have two inlets which correspond to superior and

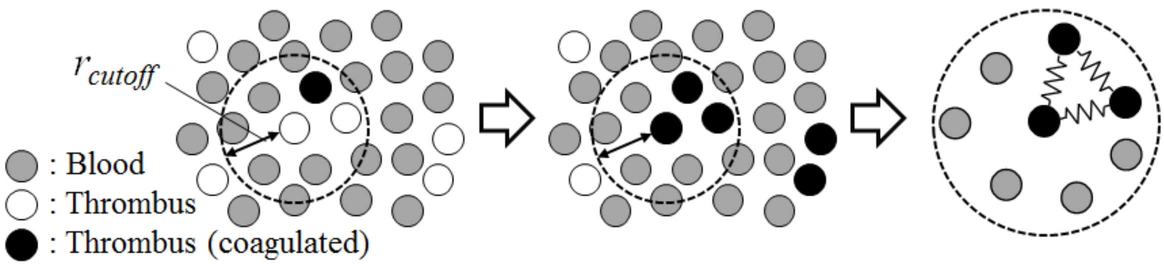
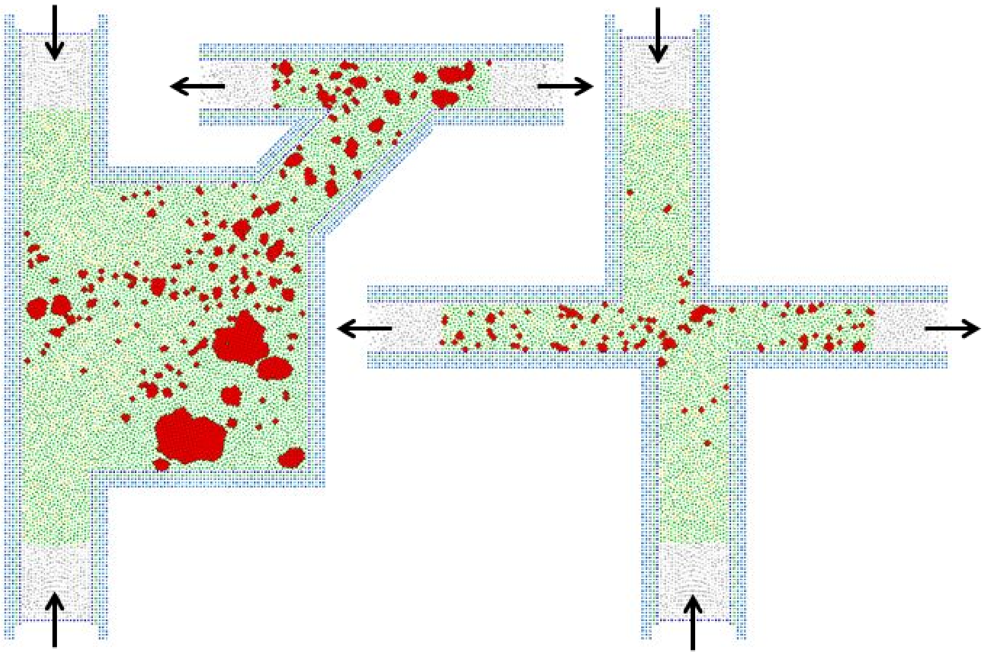



**Fig.1** Model of thrombus formation.



(a) (b)

**Fig.2** Simulated thrombus formation in (a)APC and (b)TCPC models.

inferior vena cava, and two outlets which correspond to pulmonary artery. Mean distance between computed particles is $d_0$ = 1 mm. Uniform and constant velocity $|u_0|$ = 0.092 m/s [4] is set at the inlets. Zero-pressure condition is set at the outlets. For spring force on thrombus particles by Eq. (1), $k = 5\times10^{-2}$ N/m, $r_0 = d_0$ and $r_{cutoff} = 1.75d_0$.

In a simulation of the APC model (Fig. 2(a)), a large thrombus forms in the atrium where recirculating flow occurs in the right-lower region. A thrombus also forms at contact region of flows from the two vena cava. This simulation result is due to a thrombus formation at small fluid force relative to spring force of Eq. (1). A significant thrombus formation does not appear in the TCPC model (Fig. 2(b)), where flow stagnation is absent and fluid force relative to spring force (Eq. (1)) is enough large in the entire model to prevent thrombus formation. Thus, based on our modelling, TCPC is better than APC to avoid thrombus formation and thromboembolic events. In future work, it is necessary to compare simulation results to experimental and clinical ones in details, toward development of prediction and evaluation tools of thrombosis in single ventricle.

## REFERENCES


[1] G. Balling, M. Vogt, H. Kaemmerer, A. Eicken, H. Meisner, and J. Hess, *J. Thorac. Cardiovasc. Surg.*, Vol. **119**, pp. 745–752, 2000.

[2] S. Koshizuka and Y. Oka, *Nucl. Sci. Eng.*, Vol. **123**, pp. 421–434, 1996.

[3] H. Kamada, K. Tsubota, M. Nakamura, S. Wada, T. Ishikawa, and T. Yamaguchi, *Int. J. Numer. Method Biomed. Eng.*, Vol. **26**, pp. 488–500, 2010.

[4] K. Itatani, K. Miyaji, T. Tomoyasu, Y. Nakahata, K. Ohara, S. Takamoto, and M. Ishii, *J. Ann. Thrac. Surg.*, Vol. **88**, pp. 565–573, 2009.