

Articles

Computational fluid dynamics analysis of venous air trap chamber geometry for reduction of blood coagulation

SHIMAZAKI Naoya*, SHIN'E Yoshimasa¹, OKU Tomoko²,
YAMAUCHI Shinobu², MOTOHASHI Yuka², and SATO Toshio³

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Abstract (Introduction)

In blood purification therapy, contact between foreign particles and the blood can activate blood coagulation factors or platelets. Coagulation in the blood circuit has been reported even with the administration of anticoagulants¹⁾. Sites in the blood circuit noted as coagulation hotspots are the pillow, dialyzer, and arterial or venous air trap chamber. Coagulation in the blood circuit causes hematocrit levels in the patient's remaining blood to decrease, whereas coagulation in the dialyzer reduces dialysis efficiency by shrinking the effective membrane area. Loss of blood when replacing the circuit may cause blood pressure to decrease further and reduce the quality of life of the patient²⁾.

The venous air trap chamber that is the focus of the present study traps air and clots in the blood and keeps them from entering the patient. Most blood circuits are custom made for each institution, and there are various types of chambers in

clinical use with different design parameters, such as the blood inflow design, filter, and total length. Standardized criteria for hemodialysis circuits specify a chamber length of 110 to 150 mm and inner diameter of 16 to 20 mm and a design that does not trigger backflow of blood to the pressure monitor line during pressure fluctuations. Filters can be a mesh or cone type, and no studies have yet examined how this difference affects coagulation or clot trapping performance^{3, 4)}. We considered that improving the filter and blood inflow design to control eddy formation and pooling and reduce the duration of blood pooling could potentially reduce coagulation in the chamber. In the present study, a theoretical investigation of the effects of chamber design parameters on coagulation was performed using computational fluid dynamics (CFD), and the appropriateness of CFD analysis was evaluated through visualization of the flow using particle image velocimetry (PIV).

* SHIMAZAKI Naoya: Research Associate, Faculty of Health Science, Gunma Paz University. 1-7-1, Tonyamachi, Takasaki-shi, Gunma, 370-0006, Japan

¹ SHIN'E Yoshimasa: Graduate School of Engineering, Toin University of Yokohama

² OKU Tomoko, YAMAUCHI Shinobu and MOTOHASHI Yuka: Department of Clinical Engineering, Faculty of Biomedical Engineering, Toin University of Yokohama

³ SATO Toshio: Professor, Graduate School of Engineering, Faculty of Biomedical Engineering, Toin University of Yokohama

I. Experimental methods

1. CFD analysis of venous air trap chambers

CFD analysis software (ANSYS CFX Ver.19.2, Cybernet Systems Co., Ltd.) was used to analyze four types of chambers created by combining horizontal inflow or vertical inflow and the presence or absence of a cone-shaped filter. First, for the hemodialysis circuit chamber shown in **Figure 1(a)** (NV-Y030PK, NIKKISO CO., LTD., horizontal inflow, with a cone-shaped filter), we created the model for analysis shown in **Figure 1(b)**. Based on actual chamber measurements, the base of the model had an inner diameter of 19.4 mm and length of 118 mm, and the blood inlet had an inner diameter of 4 mm and length of 40 mm. The length of the transition part from the base to the blood outlet was set to 8 mm, and the blood outlet had an inner diameter of 4 mm and length of 40 mm. As the filter, we created a model that faithfully simulated ones in clinical use that was 25 mm long, with an inner diameter of 10 mm at the top and 19.4 mm at the bottom. **Figure 1(c)** shows a model with the filter in the **Figure 1(b)** model removed. Next, for the hemodialysis circuit chamber shown in **Figure 2(a)** (NK-D030P, NIKKISO CO., LTD., vertical inflow, with a cone-shaped filter), we created the model shown in **Figure 2(b)**. The base had an inner diameter of 19.4 mm and length of 104 mm, the blood inlet had an inner diameter of 4 mm and length of 44 mm, and the blood inflow tube was inserted close to the center of the chamber. The remaining dimensions for the transition part, blood outlet, filter, and other parts were the same as in the **Figure 1(b)** model. **Figure 2(c)** shows a model with the filter in the **Figure 2(b)** model removed. The type of analysis was steady-state analysis, and the inflow condition was water with a density $\rho=997 \text{ kg/m}^3$ and viscosity $\mu=0.89 \text{ mPa}\cdot\text{s}$ flowing from the blood inlet at 200 mL/min. For the blood outlet, a mean static

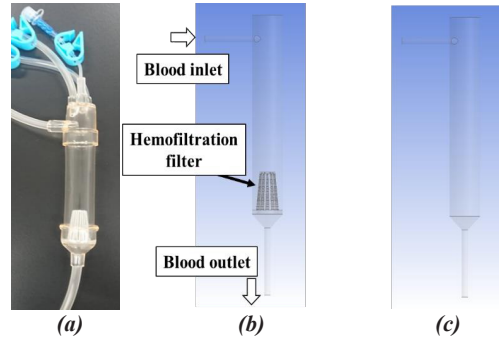


Fig.1 Actual and analytical models of horizontal inflow venous air trap chamber

(a) Actual model

(b) Analytical model with a cone-shaped filter

(c) Analytical model without a cone-shaped filter

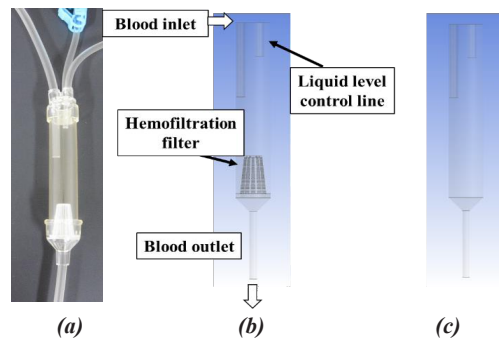


Fig.2 Actual and analytical models of vertical inflow venous air trap chamber

(a) Actual model

(b) Analytical model with a cone-shaped filter

(c) Analytical model without a cone-shaped filter

pressure of 0 Pa was set as the outflow condition. To simplify analysis and prioritize establishing a basic analytical method, water was used in the chamber, and parts such as a pressure monitor line or liquid level control line that do not directly affect flow in the chamber were not used.

2. Visualization of the flow in the chamber with particle image velocimetry

Visualization chambers were created with the same shapes as the models for analysis described above, and PIV was used to visualize the flow in the chamber. The chamber construction process is shown in **Figure 3**. First, as shown in **Figure 3(a)**, a longitudinal slit about 1/3 the length of

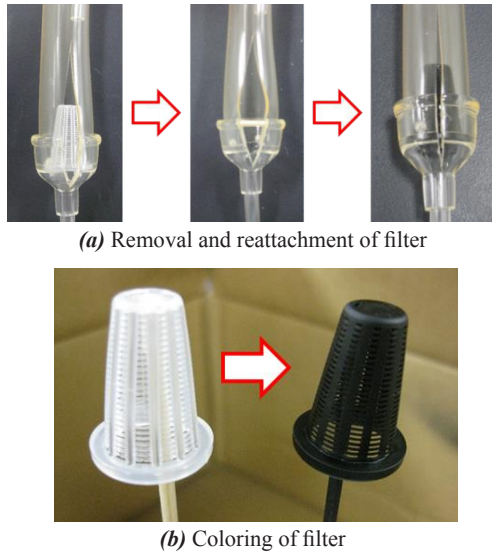
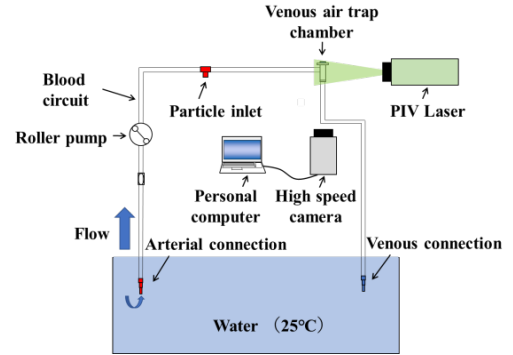


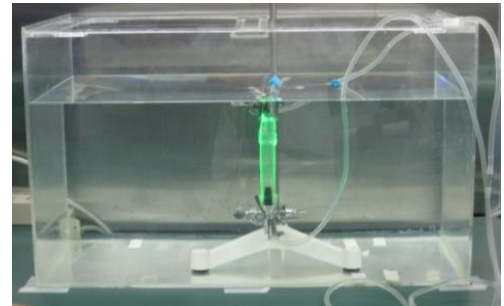
Fig.3 Methods of removal and reattachment of cone-shaped filter

the vertical inflow chamber with a filter was cut in the filter side, and the filter was removed. The cone-shaped filter was a milky white color that reflected a bright light when irradiated with a laser for visualization, making it difficult to clearly see the behavior of tracer particles around the filter. As shown in **Figure 3(b)**, to minimize the effects of the reflected light, the filter was painted black. The black filter was then returned to the chamber and the slit glued shut to create a with a filter vertical inflow visualization chamber. Using the same steps, the filter was removed and the slit glued shut to create a chamber without a filter. For the horizontal inflow chamber, the tops of a horizontal inflow chamber and a vertical inflow chamber with a filter were cut off and swapped to create horizontal inflow chambers with a filter and without a filter.

The visualization system is shown in **Figure 4(a)**. As shown in **Figure 4(b)**, the chamber was fixed in position inside a tank filled with water, and a roller pump of a hemodialysis device (DCS-73, NIKKISO CO., LTD.) was used to circulate water mixed with tracer particles (Fillite 200-7 the average particle size $<150\ \mu\text{m}$, Japan Fillite Co., Ltd.) through the circuit at a blood removal flow



(a) Experimental system



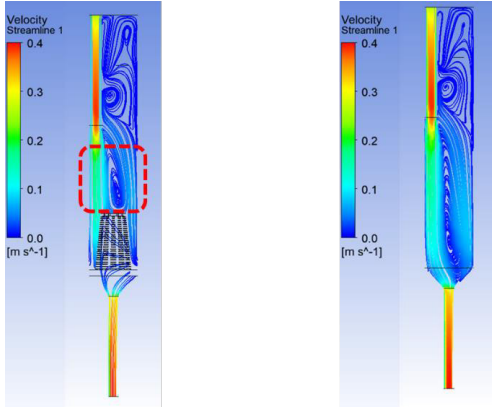
(b) Experiment image

Fig.4 Flow visualization system by PIV

rate of 200 mL/min, recreating the flow within a chamber. The chamber was irradiated with laser sheet light (PIV Laser G5000, Wavelength=532 nm, KATOKOKEN CO., LTD), and the behavior of the tracer particles in cross sections cut from the laser sheet was recorded with a high-speed camera (K-5, KATOKOKEN CO., LTD.). The video parameters were set to a frame rate of 1000 fps and shutter speed of 1/2000 s. Then, flow line graphs were created for the obtained image using fluid analysis software (Flow Expert 2D, KATOKOKEN CO., LTD.), and the flow velocity was obtained from the flow line graphs.

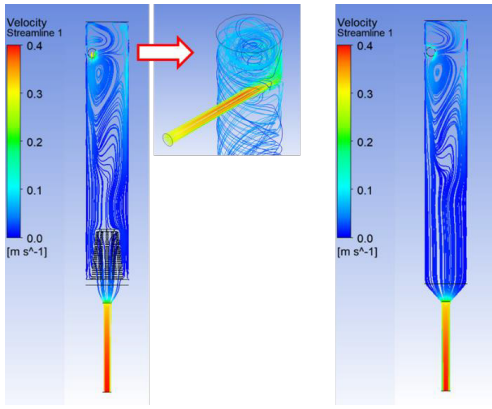
II. Experimental and analytical results

Figure 5 shows diagrams of streamline obtained from CFD analysis of the four types of models combining blood inflow design and the presence or absence of a filter. **Figure 6** shows



(a) Vertical-inflow chamber with a filter

(b) Vertical-inflow chamber without a filter

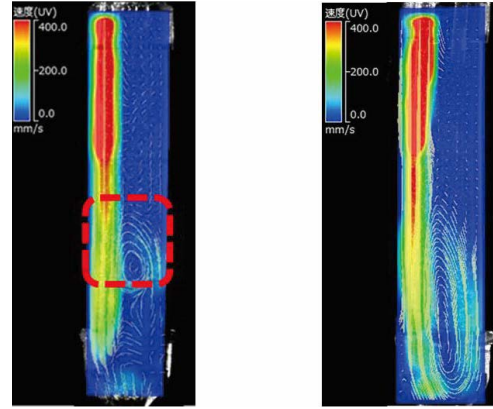


(c) Horizontal-inflow chamber with a filter

(d) Horizontal-inflow chamber without a filter

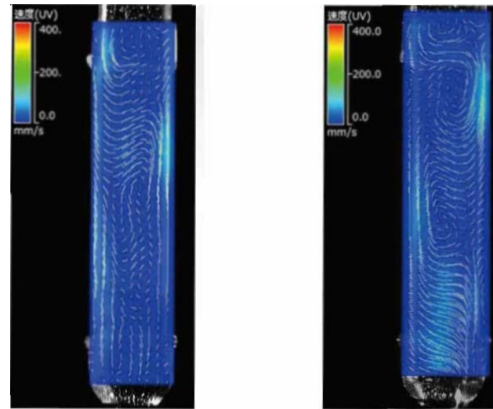
Fig.5 Results of CFD analysis

the flow line graphs obtained from visualization of the flow in chambers with the same shape as the CFD analysis models. In the vertical inflow chamber in **Figures 5(a)** and **6(a)**, high-velocity flow moves vertically from the blood inlet to the bottom of the chamber. The flow spreads out in the middle of the chamber where the flow channel widens suddenly and contacts the area from the top of the filter to the top center of the chamber. Only a tiny portion of the flow that contacts the top of the chamber passes through the filter and continues downstream, while a large portion flows back, creating eddies along the longitudinal axis. In the vertical inflow chamber without a filter in



(a) Vertical-inflow chamber with a filter

(b) Vertical inflow chamber without a filter



(c) Horizontal-inflow chamber with a filter

(d) Horizontal-inflow chamber without a filter

Fig.6 Results of flow visualization by PIV

Figures 5(b) and **6(b)**, the lack of a filter means the incoming vertical inflow contacts the chamber bottom directly. Compared to the chamber horizontal inflow chambers, larger eddies form on the longitudinal axis, creating pools. The flow line graphs in **Figures 5(c)** and **(d)** and **Figures 6(c)** and **(d)** for the horizontal inflow type blood inlet show that a fast inward flow from the inlet in the minor axis direction passes along the inner walls of the chamber, forming swirls. In the horizontal inflow chamber, new inflows and swirls of water hit each other near the inlet with or without the filter, forming relatively small, localized eddies. However, the pools and eddies that formed were

only localized, and the flow throughout the chamber was relatively good.

III. Discussion

Standardized criteria for hemodialysis circuits specify that the blood inflow design of air trap chambers must include a mechanism for reliably trapping air bubbles, regardless of whether the design is vertical or horizontal. Although coagulation is thought to be significantly affected by hemodynamics³⁾, almost no studies have tested the relative merits of different blood inflow designs from the perspective of suppressing coagulation. Moreover, whereas a filter to trap microaggregates is a requirement for venous air trap chambers, very little evidence has been obtained on the effects of filter shape on coagulation or the benefits of filters in trapping blood clots and foreign particles. Accordingly, users are left to decide for themselves what shape of filter to use.

In the present study, theoretical analysis by CFD and flow visualization by PIV were combined to determine the hydrodynamic behavior of the flow inside the chamber and examine possible improvements to identify the optimal chamber shape for controlling coagulation. In our investigations, horizontal inflow chambers formed fewer pools and eddies, and chamber-wide pooling did not occur, suggesting that this type may cause less coagulation than the vertical type. This finding supports the results of a study by Hori *et al.* in which microbubbles were used to visualize the flow in arterial and venous chambers⁵⁾. Normally, venous air trap chambers are placed downstream of the dialyzer and are therefore mostly unaffected by pulses from the roller pump. Also, as the chamber capacity increases, more blood accumulates, and pooling occurs more readily, accelerating coagulation. In contrast, in horizontal inflow chambers, swirls form continuously along the

inner walls of the chamber, stirring the blood as it passes through the chamber. This results in less accumulation of blood in horizontal inflow chambers and a higher capacity to suppress coagulation than vertical inflow chambers.

The blood clot formation process varies greatly with conditions such as velocity, flow channel length, and blood viscosity. As we were able to introduce CFD analysis to alter the design parameters that affect the flow field within the analytical software, we obtained flow visualization results and could combine them with theoretical results from CFD for a complex assessment, allowing us to clarify the flow behavior by identifying the velocity, vorticity distribution, stress distribution, and pooling areas. If we can use the methods we describe to quantitatively and individually assess the effects of each parameter on blood coagulation, we can apply these methods to optimize not only chambers, but also various blood circuits used in extracorporeal circulation.

In recent years, airless circuits have been introduced to the market that aim to reduce blood coagulation with low priming volume that achieve approximately 95% less contact between blood and air compared to regular blood circuits for dialysis, potentially reducing the coagulant dosage needed⁶⁾. Although this circuit has a cylindrical filter to trap microaggregates, as already pointed out, no studies have examined the effects of filter shape on coagulation or capacity to trap blood clots. In addition to chambers with cone-shaped filters, we are also currently working on assessing chambers with mesh filters using the same methods. With either type, the filter is a resistance component with respect to blood flow and can cause drifting, pooling, and eddies. The creation of a filter with less resistance to blood flow could potentially reduce instances of drifting, pooling, and eddy formation considerably and, as a result, increase the capacity to suppress coagulation. Kitamoto *et al.* also point out that bubbles in blood act to boost

coagulation⁷⁾. In the present study, the blood flow inlet was placed at the top of the chamber in all of the chamber variations. If we added the effects to reduce pooling shown by Yokomitsu *et al.*, such as placing the blood flow inlet under the liquid level⁸⁾ or adding another inlet in the middle of the chamber where blood pools, we may be able to propose a chamber shape that can reduce coagulation further.

IV. Conclusion

Theoretical analysis by CFD and visualization results from PIV can be used to clarify the differences in blood flow behavior with different designs of venous air trap chambers in a hemodialysis circuit and make improvements to create the optimal chamber shape to suppress coagulation. In the present study, a basic method for CFD analysis of chambers was established that could be used to perform theoretical analysis of models with different settings for design parameters such as blood inflow design and filter shape. This method can reduce costs and labor and make it possible to determine and experimentally test the optimal shape from a hydrodynamic perspective, enabling the development of a new chamber shape that can reduce coagulation.

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