Geometric Optimization for Non-Thrombogenicity of a Centrifugal Blood Pump through Flow Visualization

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A monopivot centrifugal blood pump, whose impeller is supported with a pivot bearing and a passive magnetic bearing, is under development for implantable artificial heart. The hemolysis level is less than that of commercial centrifugal pumps and the pump size is as small as 160 mL in volume. To solve a problem of thrombus caused by fluid dynamics, flow visualization experiments and animal experiments have been undertaken. For flow visualization a three-fold scale-up model, high-speed video system, and particle tracking velocimetry software were used. To verify non-thrombogenicity one-week animal experiments were conducted with sheep. The initially observed thrombus around the pivot was removed through unifying the separate washout holes to a small centered hole to induce high shear around the pivot. It was found that the thrombus contours corresponded to the shear rate of 300 s⁻¹ for red thrombus and 1300 – 1700 s⁻¹ for white thrombus, respectively. Thus flow visualization technique was found to be a useful tool to predict thrombus location.

Key Words: Flow Visualization, Turbo Machinery, Medical Engineering, Medical Equipment, Biomechanics

1. Introduction

A monopivot centrifugal blood pump, whose impeller is supported with a pivot bearing and a passive magnetic bearing, is under development for implantable artificial heart*. Since the total volume of 160 mL, the overall efficiency of 13%, and the endurance over 3 months have been attained and the hemolysis level is now lower than that of commercial centrifugal pumps for open heart surgery, the remaining objective is the prevention of thrombus formation. Thrombus is generally classified into white thrombus and red thrombus, namely platelet deposition and fibrin gel entraining blood cells, respectively. Though there are many kinds of causes for thrombus such as immunological factors, the object of the present study is restricted to causes governed by fluid dynamics.

Regarding the study of thrombus formation, many researchers have investigated biological mechanisms and biochemical reactions between blood and artificial surfaces. On the other hand, a quantitative study for thrombus formation caused by flow stagnation was performed by Hashimoto et al. They conducted in vitro thrombus experiments with fresh
canine blood and with a cone-cone rheometer generating a uniform shear field. The experiment clarified the relation between the shear rate and the thrombus formation index, or the sudden torque rise due to thrombus formation. As a result, the reduction of shear rate causes the increase of thrombus formation index. Affeld et al. conducted in vitro platelet deposition experiments in a stagnation region and demonstrated that platelet deposition occurs mainly in low shear regions, except for extremely low shear rates less than 10 s⁻¹. Ahmed et al. found that the platelet deposition, observed on the impeller surface of a centrifugal blood pump in the animal experiment, corresponded to the area with low relative velocity in flow visualization experiments.

Typical technologies against thrombus formation are as follows: Schina et al. provided secondary vanes on the casing bottom to introduce radial wash behind the impeller. Naito et al. provided a purge circuit around the shaft seal of a centrifugal pump for open-heart surgery and demonstrated two-week non-thrombogenicity.

In the early stage of animal experiment for the developed centrifugal blood pumps, thrombus remained around the pivot though other thrombi were easily removed by simple design changes. Therefore, so-called washout holes were provided around the center of the impeller to introduce recirculation around the pivot. The present study concerns the geometric optimization for the pivot and the washout holes through flow visualization experiments with partial pump models and animal experiments with sheep. Though coagulation characteristics of blood have been studied by many researchers, actual conditions for thrombus formation in the blood pumps have not been investigated in quantitative manner. A correlation study was conducted here between flow visualization and animal experiments, and this study clarified the actual fluid dynamic conditions for thrombus formation.

2. Experimental Method

2.1 Flow visualization experiment

The driving unit of the model was located in front of the impeller not to obstruct the image of the pivot region (Fig.1). Based on Reynolds similarity law, a three-fold scale-up model allows the rotational speed to be reduced to 1/9. To shorten the production period of the visualization model, simple partial acrylic models for the impeller rear part were made.

When the rear surface of the impeller is visualized, light refraction can be neglected. 5 wt% NaCl solution (specific gravity: 1.065) and fluorescent poly-styrene beads of 0.30 mm in diameter (specific gravity: 1.9) were used as working fluid and particles. When the side view of the pivot is visualized, image deformation due to refraction must be compensated. In this case, 64 wt% NaI solution (specific gravity: 1.9) and SiO₂ sphere beads of 0.15 mm in diameter (specific gravity: 1.9) were used as working fluid and tracer particles. A continuous Ar-ion laser light sheet (Lalex 90-7) was used as illumination with the output power of 4 W. The image of the tracer particles was taken with a high-speed video system (Photon Ultima UV) with a recording rate of 2250 frame/s (Fig.2). Obtained images were analyzed with 4-frame particle tracking software (Kanomax Current) and were expressed in terms of relative positions and relative velocities.

To satisfy the pressure boundary conditions the model had front vanes with the same discharge angle as the actual pump since the pressure of the impeller tip is governed by the centrifugal force of the front vanes. Corresponding to the actual rotational speed of 1900 rpm for blood (kinematic viscosity: $\nu = 3 \times$
$10^{-4} \text{m}^2/\text{s}$, the similarity law requires a rotational speed of 70 rpm for NaCl solution ($\nu=1 \times 10^{-6} \text{m}^2/\text{s}$) and of 127 rpm for NaI solution ($\nu=1.8 \times 10^{-6} \text{m}^2/\text{s}$).

2.2 Short-term animal experiment

To verify the non-thrombogenicity of the developed pump, one-week animal experiments were performed with sheep at University of Tsukuba. Two new pumps were prepared for an experiment and each pump was tested on sheep for a week. The developed pump was connected externally in a ventricular assist configuration, namely blood was extracted from the left ventricle and was sent to the descending aorta. Consequently the pump was exposed to pulsatile blood flow. The rotational speed was set to be 1 900 rpm, the flow to be around 2 L/min as half of the total flow, and the activated clotting time was kept to be 200 s with heparin.

3. Results and Discussion

3.1 Multiple washout hole models

Figure 3 shows the impellers used in animal experiments. The initial model, DD3, has four holes of 2.5 mm in diameter. Figure 4(a) shows the relative velocity distribution obtained through flow visualization of the impeller rear surface. Blood flow entering the impeller rear gap conserves its angular momentum, increases its tangential velocity beyond the impeller speed, and enters the washout holes as pressure sinks, forming a spiral flow just like a typhoon. However, the velocity increase can be observed only at the rim of the washout holes. There still remain relative stagnant regions between washout holes and around the pivot as well as the inside of the washout holes.

Figure 4(c) shows the thrombus formation ob-

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(a) Separated hole model, DD3  
(b) Separated hole model, DD5  
(c) Centered hole model, DD6  
(d) Centered hole model, DD7  
(e) Centered hole model, DD8 and DD9

Fig. 3 Monopivot centrifugal impellers being investigated

(a) Vector plot of relative velocity  
(b) Visualized shear contour  
(c) Thrombus formation observed around the pivot

Fig. 4 Results of visualization and animal experiment for DD3
observed just after the one-week animal experiment. Red thrombus was observed around the pivot and in the washout holes and white thrombus was observed on the surface between the pivot and the washout holes. One of the washout holes was plugged with red thrombus, which might be initiated by the separation in the washout holes and be combined with the thrombus started from the pivot.

Thrombus was observed in the relative stagnation region found in the flow visualization. The contour of thrombus corresponded to the iso-velocity contour of 0.3 m/s. To estimate the shear rate the following model was assumed. The measured relative velocity corresponded to the average velocity in the illuminated volume by the laser and can be correlated with the wall shear rate by considering the velocity distribution as follows. The radial position of 6 mm from the pivot center and the relative velocity of 0.3 m/s correspond to the radius Reynolds number of 1,800. We assumed a laminar velocity distribution without interference of the boundary layers on the both sides. Since the laser light sheet illuminates 50 - 70% of the impeller/casing gap from the impeller surface and the data cannot be obtained within a distance equal to the particle radius, the mean velocity of 0.3 m/s can be regarded to represent the velocity at 0.175 - 0.235 mm from the casing surface. Subsequently the thrombus contour for DD3 is estimated to correspond to a shear rate of 1,300 - 1,700 s\(^{-1}\) (Fig. 4(2)).

The next model, DD5, was designed to have washout holes with a larger diameter, 5 mm, and with closer position to the pivot. Figure 5(a) shows the relative velocity obtained through flow visualization. Though the enlargement of the holes brought high velocity near the pivot, there still remains stagnation around the pivot. Therefore, it was estimated that the thrombus around the washout holes would disappear but that the thrombus around the pivot would not be predictable.

In the animal experiment with DD5 though no washout holes were plugged, thrombus was observed in the stagnation region found in the flow visualization. The contour of the thrombus again corresponded to the mean velocity of 0.3 m/s and the shear rate of 1,300 - 1,500 s\(^{-1}\) (Fig. 5(b)). The thrombus for DD3 and DD5 would correspond to the white thrombus, mainly composed of platelets, exposed to high shear rate though the effect of surface roughness cannot be neglected.

3.2 Unified central hole models

To remove impeller surface around the pivot from multiple washout hole models, the washout holes for DD6 were unified to a hole of 16 mm in diameter.

The relative velocity distribution measured in flow visualization is shown in Fig. 6(a). The stagnant regions between washout holes disappeared and fast flow occurred along the rim of the washout hole. The velocity of the flow around the pivot is a little lower than the pivot velocity, it was not predictable whether the wash is sufficient or not.

Figure 6(c) shows the thrombus formation observed in the animal experiment. Though no thrombus was observed around the washout hole, thick red thrombus formed around the pivot. The shape was similar to the result of contour observed in flow visualization. Therefore, it was found that the slower flow around the pivot did not contribute to wash of the pivot and the thrombus was formed in the low velocity region.

To evaluate condition for thrombus formation the shear rate in the rotational plane was evaluated. The in-plane shear rate is defined as follows:

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\tau = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}
\]  

The contour of the thrombus corresponds to the shear rate of 300 s\(^{-1}\) for the flow visualization as Fig. 6(b). Since the blood in this region rotates like a solid, the shear rate was sufficiently low to form thrombus. This case might correspond to red thrombus purely
because the shear rate is low.

To bring the swirl closer to the pivot, DD7 was designed to have a washout hole of 10 mm in diameter. The relative velocity in the back gap is shown in Fig. 7(a). Not only the fast flow is observed at the rim of the washout hole, but also fast wash is reaching to the pivot and the relative stagnant region is diminished. Flow visualization from the side revealed the secondary flow, shown as time average, reaching the pivot through the impeller/casing gap (Fig. 7(b)). It can be seen that the secondary flow goes straight to the pivot and makes a turn to the exit of the washout hole. DD7 was expected to have much better non-thrombogenicity.

Figure 7(c) shows the thrombus observed in the animal experiment. Though a small quantity of thrombus was observed in the gap between the male and female pivots, no other thrombi were observed. Induction of the swirl close to the pivot brought the good result.

3.3 Geometric optimization of the impeller through flow visualization

The above study clarified that the washout hole diameter would be the governing design parameter for non-thrombogenicity. Therefore, impellers with different hole diameters, such as 9, 8, 7, and 6 mm, were made and the relative velocity and the secondary flow were compared through flow visualization to find the optimum geometry.

Flow visualization showed that the secondary flow not only goes toward the pivot but also reaches to the pivot surface for 7 and 6 mm hole models (Fig. 8). The shear rate around the pivot was estimated to be higher than 300 s⁻¹. Consequently, a 7 mm hole was selected for DD8 as the optimum geometry which assures sufficient flow through the washout hole.

During the animal experiment with the DD8 only a thin ring of red thrombus was observed in the gap of the male and female pivots. Therefore, DD9 was designed not to have the pivot gap by designing the radius of the concave-sphere female pivot to be equal to the sphere male pivot. Flow visualization revealed no problem regarding the stagnation or the pivot wash by secondary flow (Fig. 9(b)). In the animal experiment no red thrombus was observed and, at least, red substances on the pivot surfaces were not adhesive (Fig. 9(c)). In the above optimization process flow visualization was a useful tool to establish fluid dynamic optimum geometry for the monopivot centrifugal blood pump.
4. Conclusion

To improve the non-thrombogenicity for the monopivot centrifugal blood pump, flow visualization experiments and one-week animal experiments were undertaken and produced the following results:

(1) By changing the geometry from the multiple washout holes to the unified central hole, and by reducing the washout hole diameter to the optimum size, low shear rate regions were removed. As a result, no thrombus was observed in the corresponding animal experiment.

(2) Correlation studies between the flow visualizations and animal experiments clarified the conditions for thrombus formation. The condition for white thrombus formation between the opposing disks corresponds to a shear rate of 1,300-1,700 s⁻¹. The condition for red thrombus formation, due to stagnation near the pivot, corresponds to a shear rate less than 300 s⁻¹.

(3) Utilizing the flow visualization, we could establish fluid dynamic non-thrombogenicity efficiently for the monopivot centrifugal blood pump. Flow visualization is a useful tool for the prediction of thrombus location and subsequently for the design optimization of blood pumps.

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