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Analysis of Plasma Skimming within a Hydrodynamic Bearing Gap for Designing Spiral Groove Bearings in Rotary Blood Pumps*

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Abstract—**The blood damage problem inside the narrow hydrodynamic bearing is potentially considered to be solved by applying plasma skimming. However, the consideration of improving plasma skimming has not been included in the design of hydrodynamic bearings. The absence of experimental investigation on revealing the relationship between blood flow and plasma skimming in the bearing gap impedes the design of groove shape for plasma skimming. Thus, the present study was undertaken to evaluate how the blood flow direction and the groove shape affect plasma skimming in the bearing gap. To this end, blood tests using porcine blood were repeated three times with a hematocrit of 0.8%. The bearing gap during the tests was adjusted to 25 µm and the rotational speed was adjusted from 50 rpm to 2500 rpm. The blood flow and plasma skimming effect was evaluated based on image analysis utilizing a high-speed microscope. Results of three tests indicated that the flow direction of RBCs was dominated by the rotating surface in the bearing gap when the rotational speed increased over 1200 rpm. The best plasma skimming effect was observed when the angle between the flow direction of RBCs and the tangent line of the groove was within -10 degrees to 10 degrees. The future study will be conducted with including the consideration of plasma skimming in the bearing shape design. The findings in this study aid the future design and development of hydrodynamic bearing for use in rotary blood pumps.**

Clinical Relevance—**This study suggested a design proposal of hydrodynamic bearing shape aiming for the improvement of the plasma skimming effect, which is expected to be applied to the development of hydrodynamically levitated centrifugal blood pumps.**

I. INTRODUCTION

Rotary blood pumps are extensively employed for assisting blood circulation in open-heart surgery and long-term therapy for heart failure patients. Since the contacting area of the rotating impeller and the supporting bearing causes mechanical wearing and thrombus problem inside the pumps, the third generation of rotary blood pumps with noncontact bearing has been developed to have outstanding durability and better blood compatibility using magnetic bearing [1-3] and hydrodynamic bearing [4-5]. Especially, the hydrodynamic bearings are further considered to have greater potentials in pump miniaturization because they don't need sensors and the control system for levitating the impeller inside the rotary blood pumps. The current concern about hydrodynamic bearings in miniaturization development is the theoretical risk of hemolysis that the damage of red blood cells (RBCs) with the release of hemoglobin, due to the high shear force caused by the extremely small gap size [6]. Therefore, how to avoid hemolysis inside a narrow hydrodynamic bearing gap is considered a challenge for the future development of rotary blood pumps.

In recent years, studies of plasma skimming within spiral groove bearings (SGBs) have addressed a potential solution for solving this hemolysis problem in the hydrodynamic bearing gap [7-8]. Plasma skimming [9] in the bearing gap refers to the hematocrit decline of blood at the specific narrow openings with a secondary flow, compared to the original hematocrit of the main flow in the pump. Fig. 1 shows a schematic of SGB inside a hydrodynamically levitated centrifugal blood pump [10]. The local pressure generated by the alternating ridges and grooves inside the bearing provides the levitation force to lift the impeller. The opening formed by the impeller bottom surface with the ridge surface is defined as the ridge opening where the shear force is higher than the force in the openings formed with the groove surface. Plasma skimming in SGB is expected to relieve hemolysis risk with a hematocrit decline in the ridge opening by excluding RBCs from the ridge opening and guiding them to the groove opening which provides environment of a lower shear force for RBCs.

Although plasma skimming has been observed and verified in SGB, suggestions on how to improve plasma skimming in the ridge opening have not been reported. Considering the advantage of simplicity for hydrodynamic bearing, we consider it promising to improve plasma skimming through the groove shape design of SGB. Kink and Reul first employed the SGB shape within a rotary blood pump and testified enough load-carrying capacity of SGB for levitating the impeller [11]. Then more studies have been devoted to improving the load carrying-capacity, washout effect of secondary flow, and hemocompatibility performance in SGB by optimizing the design of groove shape [6, 12-14]. Until now, the shape design proposal of SGB to improve plasma skimming has not been proposed due to the lack of basic experimental study on the relationship between plasma skimming and RBCs flow inside the bearing gap.

We made a hypothesis that the angle between the flow direction of RBCs and groove shape has an impact on the plasma skimming effect because the RBCs are expected to flow along the groove rather than moving across the ridge opening inside the bearing gap. Hence, it is necessary to uncover the impact of blood flow on plasma skimming in the

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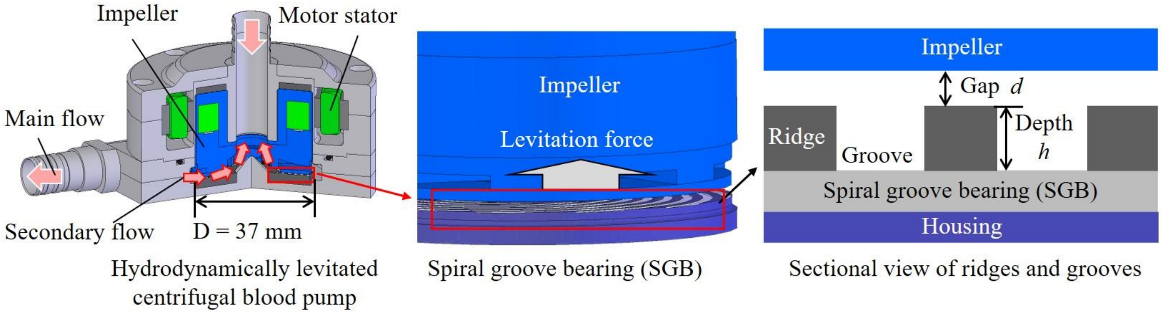

Figure 1. Schematic of spiral groove bearing (SGB) inside a hydrodynamically levitated centrifugal blood pump.

ridge opening first and suggest the proposal of designing SGB groove shape for improving plasma skimming.

Therefore, the purpose of this study is to investigate if the flow direction of RBCs has an impact on plasma skimming in ridge opening and propose suggestions for the future optimization of SGB groove shape aiming for enhancing plasma skimming within the hydrodynamic bearing gap. An experimental device, together with an RBCs visualization system, was designed for evaluating the flow direction of RBCs and plasma skimming.

II. METHODS

A. Experimental setting and in vitro blood tests

The flow direction of RBCs in the ridge opening is mainly influenced by the gap size of the ridge opening, the rotational speed of the impeller surface, and the flow rate of the secondary flow. In this study, we designed an experimental device that enabled the independent adjustment of rotational speed and gap size of the ridge opening. The secondary flow in the bearing gap was imitated with the aid of a centrifugal pump. Fig. 2 illustrates the experimental setting for investigating the influence of rotational speed on the flow direction of RBCs and plasma skimming with *in vitro* blood tests. The blood circuit consists of the designed experimental device, a high-speed microscope (VW-9000; Keyence Corp., Osaka, Japan) for photographing RBCs in the bearing gap, a centrifugal pump (MD-10K-N; IWAKI CO., LTD., Tokyo, Japan), two pressure gauges (GP-M001) and a flowmeter (FD-XA1; Keyence Corp., Osaka, Japan). The total priming volume of the circuit was 400 ml. Fresh porcine blood was collected from a local slaughterhouse and anticoagulated with trisodium citrate. For photographing clear vision of RBCs in the bearing gap, the blood diluted with phosphate-buffered saline (PBS) solution (FUJIFILM, Wako Pure Chemical Corp., Osaka, Japan) to a hematocrit of 0.8% was used as the test fluid based on our previous photographing tests.

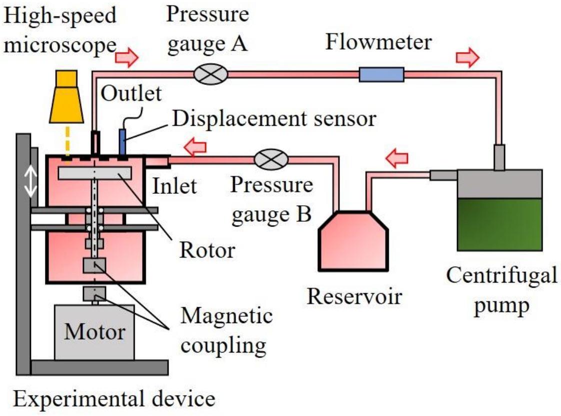

Figure 2. Experimental setting and blood circuit for blood tests.

For observing the RBCs flow direction inside the bearing gap, an SGB designed in our previous study [15], which is shown in Fig. 3 (a), was employed. The groove depth h was 100 μm. Fig. 3 (b) shows the experimental view of photographing RBCs with the manufactured SGB plate. The SGB plate was made of transparent resin for photographing the RBCs flow inside the bearing gap. The illuminated area shows the observation point, which was kept consistent for all the tests. During the blood tests, the ridge gap size d was adjusted to 25 μm and monitored with three displacement sensors embedded on the half-circle of the plate. The actual gap size d on the observation point was calculated based on the three displacement sensors which were located evenly at a radius of 13 mm, assuming that the surface of the ridge is an ideal plane. The rotational speed was adjusted from 50 rpm to 2500 rpm. The RBCs flowing in the bearing gap were photographed at each rotational speed condition with 150× magnification for evaluating plasma skimming effect and 100× magnification for analyzing flow direction of RBCs, respectively. The shutter speed of the high-speed microscope was set to 1/900000 s and the frame rate was set to 4000 frames/s. The data collected by the sensors and the high-speed microscope during the experiment were recorded synchronously. *In vitro* blood tests were repeated three times with the same controlled conditions.

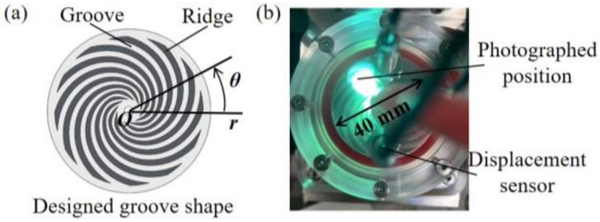

Figure 3. View of the SGB during the experiment. (a) The employed SGB shape for blood tests with a groove depth of 100 μm. (b) The observation position over the SGB during the blood tests. The diameter of the SGB grooves was 40 mm. Three displacement sensors were embedded on the right half-circle of the plate for calculating the actual ridge gap size d on the observation point in the bearing gap.

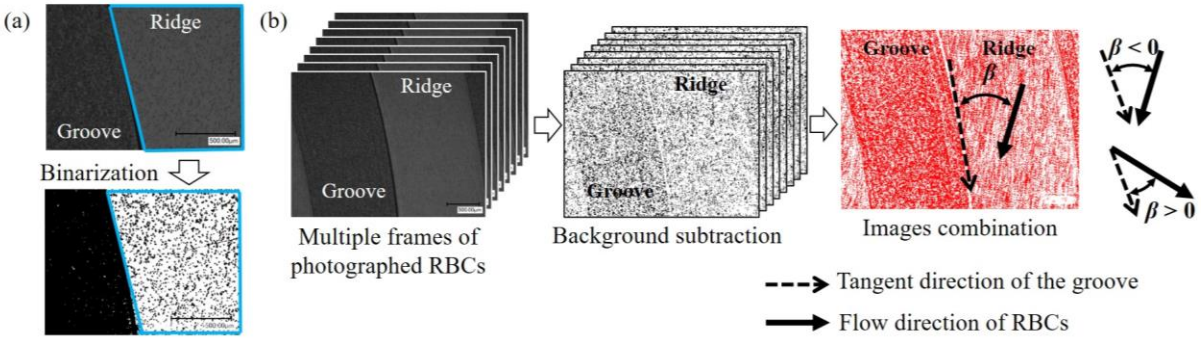

Figure 4. Evaluation methods of the RBCs flow in the ridge opening in the bearing gap. (a) Binarized image of photographed RBCs for evaluating plasma skimming effect based on the occupancy ratio of RBCs in the blue frame. (b) The method for analyzing RBCs flow inside the ridge gap. The photographed RBCs video was first divided into multiple continuous frames of photographed RBCs. After the background was subtracted from each image, the multiple images were combined to analyze the flow direction of RBCs in the ridge area.

B. *Evaluation of hematocrit in the ridge opening*

In this study, the evaluation method that measures hematocrit in the ridge opening by high-speed microscope was the same as the method adopted in [7]. As shown in Fig. 4 (a), the photographed image of RBCs was binarized to recognize the RBCs as black pixels and the rotor surface as white pixels. Therefore, the occupancy ratio q of RBCs is defined as:

$$q = \frac{p_b}{p_b + p_w} \tag{1}$$

where p_b is the sum of black pixels and p_w is the sum of white pixels in the blue frame. The measured hematocrit HCT_r of blood inside the ridge opening is calculated by:

$$HCT_r = \frac{q \times MCV}{d \times \sigma}. \tag{2}$$

MCV is the mean corpuscular volume of the RBCs, which was measured by the automated hematology analyzer (α MEK-6550; Nihon Kohden Corp.). σ is the cross-section area based on MCV, which is calculated by:

$$\sigma = \pi\left(\frac{3MCV}{1.561\pi}\right)^{\frac{2}{3}}. \tag{3}$$

C. *Analysis of RBCs flow in the ridge opening*

The direction of the RBCs flow path was analyzed by combining multiple images of photographed moving RBCs, which is shown in Fig. 4 (b). For ensuring enough images of RBCs to identify the flow direction and avoid overlapping of RBCs in the images, 8 continuous frames of RBCs images were selected when there is the lowest occupancy ratio of RBCs in one revolution of the rotor. New images of RBCs, where RBCs were binarized as black pixels, were obtained by subtracting image background from the selected 8 images of RBCs. Then the flow direction of RBCs in the ridge opening became easier to recognize by combining the binarized images of RBCs. Computer-Aided Design (CAD) software was used for analyzing the angle β between the tangent line of the groove edge and the flow direction of RBCs. It was defined that when the tangent direction and RBCs flow direction converges, $\beta < 0$; when the tangent direction and RBCs flow direction diverges, $\beta > 0$.

III. RESULT

Table.1 presents the measured mean hematocrit in the circuit, mean MCV, and mean actual gap size d of the ridge opening. Fig. 5 shows the variation of calculated occupancy ratio q of RBCs with (1), and the calculated ridge gap size d in 0.3 s at a condition of 1200 rpm rotational speed as an example. The variation of ridge gap size and the occupancy ratios has the same variation period.

TABLE I. RECORDED AND MEASURED DATA FOR THREE TESTS

	Test 1	***Test 2***	***Test 3***
Mean hematocrit in the circuit	0.80%	0.83%	0.83%
Mean *MCV*	59.3 fL	64.8 fL	61.1 fL
Mean gap size *d*	29.9 µm	26.4 µm	26.9 µm

Fig. 6 shows analyzed angle β between the tangent line of the ridge and the flow direction of RBCs, and the calculated hematocrit of blood in the ridge opening with the high-speed microscope for three tests. The angle β analyzed at each rotational condition was plotted with orange triangles. The orange dotted line represents where the angle equals zero. For three tests, the mean hematocrit calculated from the continuous frames of RBCs within one revolution of the rotor was plotted at different rotational speed conditions with blue circles. The hematocrit varied to reach the lowest as the rotational speed increased from 50 rpm to 1200 rpm, and the variation became stable from 1200 rpm to 2500 rpm. The

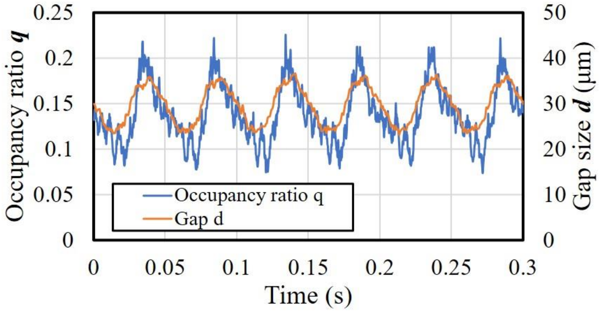

Figure 5. Variation of measured occupancy ratio q and the actual ridge gap size d at a rotational speed of 1200 rpm.

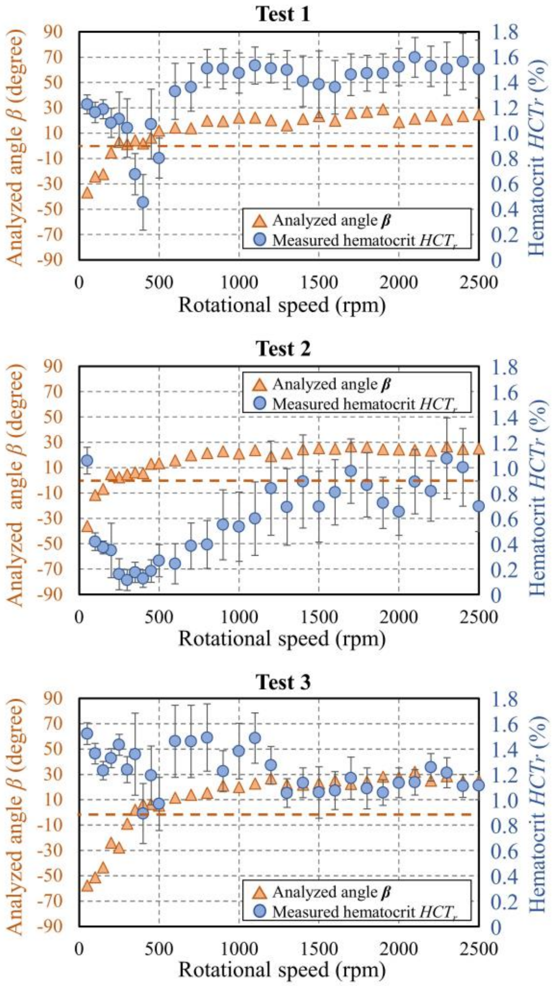

Figure 6. Results of measured hematocrit HCT_r, and the analyzed angle β for three blood tests.

lowest measured hematocrit decreased to 0.45% at a rotational speed of 400 rpm for test 1; hematocrit decreased to 0.11% at 300 rpm; hematocrit decreased to 0.89% at 400 rpm. It is shown that the angle was in the range of -10 degrees to 10 degrees when there was the lowest hematocrit in all three tests. Besides, Fig. 7 shows examples of combined images of moving RBCs. The small paired arrows on the left bottom side of the image indicate the direction to the outlet in the center of the plate and the rotational direction in the circumferential direction. The black dotted line marks the tangent line of the ridge. The black arrows illustrate the flow direction of RBCs.

IV. DISCUSSION

Through analyzing the hematocrit and the flow characteristic of RBCs in the bearing gap with various rotational speed conditions, the hypothesis that the angle between the flow directions of RBCs and the tangent line of the ridge indeed has a significant influence on plasma skimming has been testified. The mechanism of the phenomenon that declining the angle improved the plasma skimming effect will be studied in future study.

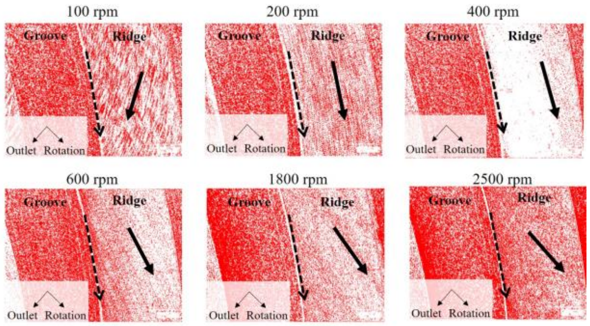

Figure 7. Combined images showing flow directions of RBCs at different rotational speed conditions.

According to Fig. 6 and Fig. 7, the flow direction of RBCs altered gradually towards the circumferential direction as the rotational speed increased. When the rotational speed increased over 1200 rpm, the flow of RBCs was dominated by the high shear force because of the high rotational speed and the narrow gap size. It is noted that when the RBCs direction changed from the converging direction with the tangent line of the ridge to the diverging direction, there were the least RBCs left in the ridge opening. This result suggests that designing the groove shape along the flow directions of RBCs in the ridge opening might lead to a high plasma skimming effect in the bearing gap.

Inside the narrow bearing gap of the hydrodynamic bearing, it is reported that the RBCs tend to remain in the grooves [16]. Therefore, we simply assumed that the RBCs inside the groove flow along the groove from the inlet to the outlet of the bearing gap as shown in Fig.8. When the shear force caused by the bottom surface of the rotor and the flow in the gap has an angle with the local tangent direction of the groove, the component of the shear force that perpendicular to the tangent direction of the groove will induce the RBCs to flow across the openings above the ridge. Since our target is to exclude the RBCs from these high shear openings, it is intuitive to design the groove shape concerning the local flow directions of RBCs inside the bearing gap for improving the plasma skimming effect. The current centrifugal rotary blood pumps commonly have a working rotational speed ranging from 1800 rpm to 4000 rpm [17]. Thus, it is necessary to design the groove shape with the deliberation of the flow direction of RBCs based on the actual flow condition inside the bearing gap.

Though the design proposal of groove shape design aiming for enhancing plasma skimming effect has been suggested, several limitations address the future studies for groove shape design. In this study, we focused on investigating the hematocrit and the RBCs flow inside the bearing gap. The

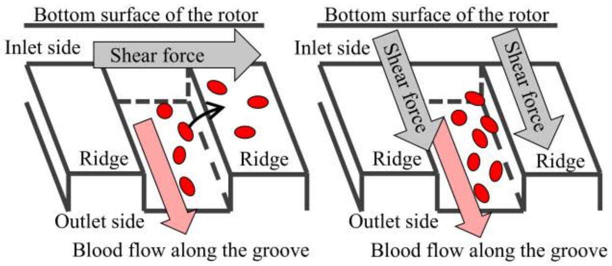

Figure 8. Illustrations of assumed RBCs flow inside the bearing gap.

load-carrying capacity, washout effect of the secondary flow, hemocompatibility should also be taken into consideration of the groove shape design for hydrodynamic bearings. Computational fluid dynamics (CFD) analysis is commonly applied to evaluate the comprehensive performance of hydrodynamic bearing [14, 18]. Therefore, evaluation of the plasma skimming effect is also expected in the future CFD analysis for the hydrodynamic bearing design.

Though the evaluation of hemolysis is not included in this study, high efficiency plasma skimming is considered potentially to prevent hemolysis caused by RBCs damage. To reduce hemolysis, it is necessary to generate complete plasma skimming at the working condition of the hydrodynamic bearing inside rotary blood pumps. Therefore, optimized groove shape and gap management of hydrodynamic bearings for that purpose are necessary.

Another limitation in this study is that the working fluid for the *in vitro* blood test was far diluted than the physiological level of whole blood. In this study, we chose the hematocrit of working fluid to obtain a clear vision of RBCs and avoid the influence of overlapping RBCs on evaluation. Different hematocrits of blood have different viscosity and cell interaction, which might influence both RBCs flow and plasma skimming effect in the bearing gap. Hence, further study on designing groove shape will be conducted with the physiological hematocrit conditions.

V. CONCLUSION

By analyzing the flow direction of RBCs inside the bearing gap, this study testified that the measured hematocrit in the openings decreases as the angle between RBCs flow direction and the tangent direction of groove declines. The findings in this study suggest a design proposal for SGB groove shape that designing the groove shape concerning the flow direction of RBCs in the ridge opening may lead to a better plasma skimming effect. For optimizing the SGB shape with better hemocompatibility, the consideration of plasma skimming should also be included in the future design of hydrodynamic bearings.

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