Effect of Flow Around Three-Dimensional Micro-Geometric Structures on Adhesion Phenomena

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Abstract

Thrombus formation on biomaterial surfaces with microstructures is complicated and not fully understood. We assumed that the micro-stagnation generated around microstructures is one factor to enhance thrombus formation. In our prediction, the micro-flow around microstructures causes blood components to adhere physically in a low Reynolds number region. The objective of this study is to investigate the micro-flow around three-dimensional micro-geometric structures and the aspects of physical adhesion affected by the micro-flow. Flow simulation and quantitative assessment of adhesion rates around micro-columns was conducted as a basic study. The particle pathlines and average shear rate around a column were calculated through computational fluid dynamics analysis. The simulation showed that low shear rate distribution caused by flow-stagnation is generated around a column, even if it is in micro-flow in a low Reynolds number region. Physical adhesion tests using micro-beads showed that the average adhesion rate around the column was higher than that in the neighboring plane area. A low shear rate region generated by microstructures may increase the potential for adhesion of substances, which enhances thrombus formation even when the scale of flow is of the order of micrometers.

Key Words:
adhesion phenomena, micro flow effect, three-dimensional micro-geometrical structure, surface roughness

1. Introduction

Thrombo-embolic complications have been reported in clinical use of cardiovascular devices such as a ventricular assist device (VAD) or an artificial valve. In particular, small detached thrombi that are carried into brain capillaries are a cause of brain infarctions, posing a serious problem in cardiovascular treatment.

Considerable effort has been spent to understand this thrombus cascade process in order to prevent thrombi forming on device biomaterial by ensuring proper surface chemical properties. For example, anti-thrombotic biomaterials and a technique to coat devices with heparin, thrombomodulin or 2-methacryloyloxyethyl phosphorylcholine (MPC) polymer have been developed as chemical and electrical approaches for anti-thrombogenesis.

However, the sites of greatest risk for thrombus formation in cardiovascular devices are evaluated in clinical use, and the results are reported to the developers of each device.

The concept that not only chemical and electrical factors but also morphological factors, such as surface roughness, induce thrombus formation has been long established by clinical experience. Linneweber et al. has reported increased platelet adhesion with increased surface roughness in the blood pump. There are some reports about morphological design and thrombus formation. However, the mechanism of thrombus formation on rough surfaces is not fully understood yet because the mechanism is so complex. Some factors are predicted to affect thrombus formation on biomaterial with complex morphologies. For example, the disturbed micro-flow from rough surfaces may stimulate platelets, and blood substances may be trapped by rough surfaces containing micro-geometric structures.

We assume that hydrodynamic effects, such as micro-stagnation caused by rough surfaces with micro-geometric structures, are one cause of enhanced physical adhesion of blood substances. Flow stagnation occurs around obstacles, and it can cause particles to remain in front of the obstacles on the order of millimeters. For example, flow stagnation at a connecting part of a tube and an inflow cannula results in thrombus formation. The flow stagnation on the order of millimeters causes blood components to stay at a...
step of the connecting part. It is not known whether this occurs on the order of micrometers. Our target is the fluid condition in the micro-geometrical structures that are present in the boundary layer in a fluid channel on the order of millimeters. This is different from the fluid situation in micro-total analysis systems (micro-TAS), in which flow is affected by surface tension, rather than by gravity and inertial force. In addition, the flow speed in our target is higher than that in micro-TAS. The objective of this study is to prove the existence of micro-stagnation around micro-geometrical structures in the boundary layer in a fluid channel on the order of millimeters, and study the effect of micro-stagnation on physical adhesion phenomena. As the first step in this study, we investigated the flow at low shear rate to evaluate the laminar flow region.

The purpose of this study is to investigate the micro-flow around three-dimensional micro-geometric structures and the aspects of physical adhesion affected by the micro-flow. Fluid flow around a simple micro-geometrical structure was simulated by computational fluid dynamics (CFD) to investigate the micro-flow specifically. In addition, physical adhesion tests with micro-beads on test pieces with 3-D microstructures constructed by microelectromechanical systems (MEMS) were conducted to investigate the aspects of physical adhesion affected by the micro-flow.

2. Material and Method

2.1 The experimental equipment for perfusion test

Silicon test pieces with 3-D micro-geometric structures were constructed by MEMS technology as shown in Fig.1.

![Test piece](image)

Fig.1 Test piece.

Nine rows and five lines of micro-cylindrical structures are constructed on the test piece. The micro-columns have a diameter of 50 µm and a height of 10 µm. Flow fields on the test piece had been simulated with CFD before the design of the test piece, and the distance between 45 columns were set to 1000 µm to avoid flow interference between the columns.

The column size is limited by our MEMS technology to over 10 µm; therefore, the columns were made 10 µm high. The diameter of the column was made wider than 10 µm because a wide and short column is considered a stable construct. The micro-columns were constructed with wide separation to evaluate specifically the flow around the microstructures and the aspects of physical adhesion affected by micro-flow. All test pieces were inspected for defects and breakage of columns with a 3-D laser measuring microscope (LEXT OLS4000-SMT, Shimadzu Co.) before physical adhesion tests.

An acrylic perfusion chamber for the physical adhesion test is manufactured as shown in Fig.2 (a). The fluid in the perfusion chamber exhibited plane Poiseuille flow. The test piece was set in the 11 mm square pocket in the perfusion chamber.

The test equipment is assembled as a closed circuit with perfusion chamber as shown in Fig.2 (b). Flow rate in the perfusion circuit was measured by an electromagnetic flowmeter (MFV-2100, NIHON KOHDEN).

![Perfusion chamber and physical adhesion test circuit](image)

Fig.2 Perfusion chamber and physical adhesion test circuit.

(a) Perfusion chamber. Flow fields in the perfusion chamber had been simulated with CFD before the design of the perfusion chamber, and the inlet and outlet sides were designed with angles of 15° to prevent secondary and eddy flows in the perfusion chamber. (b) The test circuit consists of a peristaltic tube pump (RP-2100, Tokyo RIKAKIKAI Co.), an air chamber, the perfusion chamber and 500 mL of a beaker set in a thermostat water bath with connecting silicon tubes which have an inner diameter of 4 mm (Fig.2 (b)). The air chamber was connected to circuit in series to suppress the pressure fluctuation generated from the peristaltic tube pump.

2.2 CFD analysis for flow visualization on the test piece

A steady-state analysis was performed using commercial code ANSYS CFX Ver. 14.0 (ANSYS Ltd.) to simulate flow around the micro-columns on the test piece.

The CFD analysis is based on the Navier–Stokes equation, which is written in tensor representation as follows:

\[
\frac{\partial \rho}{\partial t} + \sum_{i=1}^{3} \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cd - 50
First, a “macro-model” was built for the CFD model to simulate the flow in the perfusion chamber including all regions of the test piece as shown in Fig.3 (a), (b). As the first step in this study, we investigated the flow at a low shear rate to evaluate the laminar flow region. Watanabe et al. reported(10) that the main factor causing platelet adhesion in experiments was a shear rate of less than 1000 s⁻¹. Therefore, we considered that the physical adhesion phenomena on a rough surface mostly occur at a shear rate of less than 1000 s⁻¹. Two values of 250 and 500 s⁻¹ were used to investigate the influence of different shear rates on the micro-flow in this CFD analysis.

In the result for particle pathlines, flow stagnation was observed in an area with a diameter of 82 µm around the column; this area is defined as ‘near the column area’. The area, which is obtained by subtracting the area of a circle of 82 µm diameter from that of a square of 150 µm is defined as ‘around the column area’. ‘Near the column area’ and ‘around the column area’ were separated on the upstream and downstream sides. The area of a square with edge length 150 µm, which is at a distance of 116 µm from the column, is defined as ‘plane area’. The average shear rates were calculated at five areas.

### Table 1 Detail conditions of CFD analysis

| Working fluid | Viscosity [Pa.s] | Density [kg/m³] |
|---------------|-----------------|-----------------|
| Water         | 0.001           | 997             |

#### 2.3 Physical adhesion test with micro-beads

(1) Conditions of physical adhesion test

Physical adhesion tests using micro-beads were conducted using a perfusion circuit. The micro-beads were made from aggregated albumin because of its good adhesion possibility as glue to eliminate consideration of activation mechanisms for adhesion in order to evaluate the aspects of physical adhesion only affected by micro-flow. 5 mg albumin micro-beads (Albumin particles 37-00-203, Micromod Co. Ltd) of were mixed in 200 ml of pure water to create the working fluid. The albumin micro-beads have an average diameter of 2 µm; it is technically possible to generate this size. The micro-bead solution was perfused in the circuit with a flow rate of 96 mL/min or 203 mL/min by peristaltic tube
pump for 60 min. These two flow rates were chosen to investigate how aspects of physical adhesion were influenced by differences in flow rate. The Reynolds numbers in the region around the column were 0.195 and 0.320, at a flow rate of 96 and 203 mL/min, respectively. The Reynolds numbers were calculated using the following equation:

\[ Re = \frac{\rho U L}{\mu} \]  (2)

where \( Re \) is the Reynolds number, \( U \) is the velocity at the top of the column, \( \rho \) is the density of water (997 kg/m\(^3\)), \( \mu \) is the viscosity of water (0.001 Pa.s), and \( L \) is the diameter of the column (50 µm).

The temperature in the perfusion circuit was kept at 37 °C with the thermostat water bath. After perfusion, the test piece was removed, soaked and rinsed in the pure water for 1 min and dried naturally. To avoid water agglomeration at the base of the column, the upside (the standing side of the columns) of the test piece were turned upside down during natural drying without touching the column to anything. Adhered micro-beads around the columns and the plane area between columns on the test piece was observed and scanned by using a 3-D laser measuring microscope (LEXT OLS4000-SMT, Shimadzu Co.) after drying. As a control, the test piece was soaked in the micro-beads solution for 60 min and scanned by the 3-D laser measuring microscope. The adhesion tests were performed 10 times in each condition.

(2) Image processing for quantification of the adhesion rate on the test piece

The adhesion rates of the micro-beads on the test pieces were obtained using the image processing software Image J. The 150*150 µm area around the column was the observation area because the area has a flow slower by more than approximately 20 % compared to the other area according to the CFD analysis. Fig.4 shows the image processing procedure. The images were binarized with a threshold value of 128, which is the half value in 8-bit grayscale (the maximum value is 255). Background color is sufficiently lower than 128 in grey scale. Converted black areas are assumed to be the adhesion areas of albumin, and they are summed. Each image is divided into the following four areas: (1) near the column on the upstream side, (2) around the column on the upstream side, (3) near the column on the downstream side, and (4) around the column on the downstream side. The magnitude of each area is the same as that of the separation area when the average shear rate is calculated in the CFD analysis. The average adhesion rates at four areas were calculated using the following equation:

\[ R_{ad} = \frac{A_{ad}}{A_{total}} \times 100 \]  (3)

where \( R_{ad} \) is the adhesion rate, \( A_{ad} \) is the summed adhesion area, and \( A_{total} \) is the total area. In addition, the adhesion rate at the plane area (area (5)) was calculated. The average adhesion rates were calculated at five areas.

The data at the edge of the test pieces were eliminated because flow velocity of that area was high in the CFD analysis macro-model. The average adhesion rate was calculated for the results of 10 adhesion tests. The F-test and T-test were conducted to statistically compare the average adhesion rates.

3. Results

3.1 The CFD simulation

From the results of the macro-model, the average velocities at 300 µm up from bottom surface were \( 1.34 \times 10^{-3} \) m/s for a flow rate of 96 mL/min and \( 2.19 \times 10^{-4} \) m/s for a flow rate of 203 mL/min, respectively. These results were applied to the top surface velocity in the micro-model as described in material and method.

Estimated flow around an individual column in the micro-model are shown in Fig.5. The flow upstream of the column was separated into two flows around the sides of the column, and the
two flows join downstream of the column. The Karman vortex was not present behind the column because the Reynolds number around the column was small. The vortex around the column is shown in Fig.5(a)' and (b)'. The flow was slower by more than approximately 20% compared to that in the area of the square with edge length 150 µm.

Fig.6 shows particle path-lines travelling from left to right. The path-lines flowed toward the bottom surface upstream of the column, and vortexes were created. The path-lines of the upper half of the column flowed over the top of the column, and the path-lines of the lower part of the column flowed toward the bottom surface and made vortexes. This pathway was similar between different flow rates, and the velocity made little different near the column.

When the flow rates were 96 mL/min and 203 mL/min, the vortex sizes were 35.3 and 35.8 µm², respectively.

Fig.7 shows the contours of shear rate around the column at the bottom surface when the flow rate is 203 mL/min. Low shear rate was observed at ‘near the column area’.

3.2 Adhesion results with albumin micro-beads

Fig.8 shows images of the adhesion around a column and at plane areas at different flow rates. There were obvious differences between the results of the adhesion test without perfusion and a flow rate of 0 mL/min and the adhesion test with perfusion with flow rates of 96 and 203 mL/min. The amount of adhesion at a flow rate of 203 mL/min was clearly higher than at a flow rate of 96 mL/min. Next, the amounts of adhesion at different flow rates were quantitatively compared to each other.

Fig.9 shows the graphs of average adhesion rates around each column at each flow rate condition. (a) Flow rate of 0 mL/min, (b) 96 mL/min and (c) 203 mL/min. The data at the edge of the test piece were excluded because the CFD results showed flow interference by the space between the test piece and the pocket in the perfusion chamber. Numbers 1 to 9 represent the rows of columns, and the 1st to 5th lines represent the lines of columns. The 5th line, 1st row, and 9th row of columns are not shown, because they were excluded from the calculation of the average adhesion rate.

Fig.9 shows the graphs of average adhesion rates around each column for each value of the flow rate. These rates are the averaged results of 10 adhesion tests. The adhesion rates for all columns at the flow rate of 203 mL/min were higher than that in a
flow rate of 0 mL/min. The adhesion rates at the 96 mL/min flow rate showed variability based on the column position. The maximum adhesion rate was 17.0 % and the minimum rate was 2.3 %.

![Flow direction](image)

**Fig.10** Shear rate and mean adhesion rate

(a) Results of average shear rate and average adhesion rate at each area ((1)-(5)) when the flow rate is 96 mL/min. (b) Results of average shear rate and average adhesion rate at each area ((1)-(5)) when the flow rate is 203 mL/min.

**Fig.10** shows the graphs of average shear rate and net average adhesion rate at four areas around the column and for the plane area, when the flow rates are 96 and 203 mL/min. The bar graphs show the average shear rate and the line graph shows the net average adhesion rate. The net average adhesion rate was calculated by subtracting the average adhesion rates when the flow rate is 0 mL/min from those when the flow rates are 96 and 203 mL/min, for each column. The net average adhesion rate at ‘near the column area’ was significantly higher than that at the ‘plane area’. There was no significant difference between the net average adhesion rates on the upstream and downstream sides. The net average adhesion rate was high when the average shear rate was low.

### 4. Discussion

#### 4.1 The relationship between simulated micro-flows and physical adhesion test results

The static adhesion rate at a flow of 0 mL/min as a control value shows the bonding strength between the micro-beads and the surface of the test piece without any hydrodynamic effect. When the static adhesion rate is subtracted from the adhesion rates for flows of 96 and 203 mL/min, the net adhesion rate for the 203 mL/min flow is one and half times that of the 96 mL/min flow. The net adhesion rate, which is hydrodynamically affected, may be affected by the flow rate. When the flow rate is 203 mL/min, the vortex size at upstream side of the column is almost equal to the vortex size when the flow rate is 96 mL/min in the CFD results. These results indicate that the difference in the net adhesion rates between the two flow rates is not caused by vortex size, but by the passing frequency of the micro-beads on the test piece during perfusion. The passing frequency increases with the flow rate. In addition, a few of the particles are detached when the flow velocity is high. In this experiment, this detachment was not observed at low Reynolds numbers.

The net average adhesion rate near the column, where the average shear rate was the lowest, was higher than that for the plane area, for all adhesion tests under all conditions. Particles in a fluid stagnate at low shear rates behind an obstacle whose size is of the order of meters. However, it is important to note that even though the flow field is strongly affected by viscous forces in a laminar boundary layer, adhesion phenomena are affected by micro-flow stagnation around an obstacle even when the scale of flow is of the order of micrometers. There is a slight difference between the average adhesion rates for the upstream and downstream areas (area (1) and (3)) when the flow rate is 203 mL/min. It is possible that the vortex of the particle pathlines on the upstream side of the column affects the difference between the average adhesion rates upstream and downstream from the column. This implies that the vortex front of microstructures may increase the potential for adhesion of substances, which enhances thrombus formation even when the scale of flow is of the order of micrometers.

In this paper, only the CFD results obtained using water are described. However, we conducted a CFD analysis using the values of the viscosity (0.003 Pa.s) and density (1050 kg/m³) of blood, and the micro-flow around the columns were observed to be the same as that in the CFD results obtained using water. These results suggest that micro-stagnation generated around micro-geometric structures may increase the possibility of adhesion of substances in the blood at the low Reynolds number region. In further studies, it is necessary to investigate the adhesion rate at a high shear rate in a blood pump.
4.2 Limitation of this study

A simple microstructure is used in this study. However, micro-flow is more complex on the rough surfaces. It is possible that different micro flows and low shear rate distribution around the column are generated with different microstructures. As a next step in this research, we would like to evaluate the differences of micro-stagnation flows generated with different sizes and shapes of microstructures, and compare their adhesion effects quantitatively to clarify the relationship between micro-stagnation and adhesion. The flow visualization technique in the micrometer region should be developed further to verify the micro-stagnation.

Watanabe et al. have reported how platelet adhesion to collagen is affected by the shear rate. They used a model of the injured vessel as a target for platelet adhesion as an experimental setup. Their results show that the peak of platelet adhesion existed around a 283 s⁻¹ shear rate. They considered that once platelets adhered to collagen, their adhesion remained steady at lower shear rates. However, as the flow became greater than 283 s⁻¹, it became more difficult for platelets to adhere to collagen. Considerable adhesion was observed in the results of the physical adhesion test when the shear rate was approximately 200 to 350 s⁻¹. Our target for physical adhesion is not injured vessels but the material surface. These differences in adhesion behavior are considered to be caused by differences in bonding strength between Albumin/Silicon wafer (in our adhesion test) and platelet/collagen surface (in the platelet adhesion test for Watanabe et al.). In addition, the albumin micro-beads were used as glue to express micro-flow results in our adhesion test.

In this study, only the simple physical effect of micro-stagnation on adhesion was investigated. As a next step, we would like to conduct adhesion tests using platelet-rich plasma for evaluating the effect of activation of platelets by shear rate on adhesion phenomena, in addition to the simple effect of micro-stagnation on adhesion phenomena. In addition, the chemical and electrical effect of surfaces on adhesion phenomena, and the biochemical effect on the thrombus cascade should be considered. We would also like to investigate the relationship between blood substances and microstructures using whole blood.

5. Conclusion

The micro-flow simulation around three-dimensional micro-geometric structures by CFD analysis and the quantitative evaluation of adhesion rate using micro-beads around columns assembled by MEMS were conducted to investigate the hydrodynamic effect around three-dimensional micro-geometric structures on adhesion phenomena. The experimental adhesion tests with micro-beads indicated that the average adhesion rate around the micro-columns is higher than at the plane area in low shear flow conditions. There is considerable adhesion when the shear rate is low, even though the flow field is strongly affected by viscous forces in a laminar boundary layer at micro-scale.

Reference

1) JK. Kirklin, DC. Naftel, FD. Pagani, RL. Kormos, LW. Stevenson, ED. Blume, et al., Seventh INTERMACS annual report: 15,000 patients and counting. J Heart Lung Transplant 2015; 5-7.
2) K. Ishihara, N. Nakabayashi, L. Fukumoto, J. Aoki, Improvement of blood compatibility on cellulose dialysis membrane I. Grafting of 2-methacryloyloxyethyl phosphorylcholine on to a cellulose membrane surface. Biomaterials 1992; 13(3): 145-149.
3) J. Linneweber, P. Dohmen, U. Kertzschker, K. Affeld, Y. Nosé, W. Konertz, The effect of surface roughness on activation of the coagulation system and platelet adhesion in rotary blood pumps. Artif Organs 2007; 31(5): 345-351.
4) N. Fujisawa, L.A. Poole-Warren, J.C. Woodard, C.D. Bertram, K. Schindhelm, A novel textured surface for blood-contact. Biomaterials 1999; 20(10): 955-962.
5) E.A. Rose, H.R. Levin, M.C. Oz, O.H. Frazier, Q. Macmanus, Burton NA et al., Artificial circulatory support with textured interior surfaces. A counterintuitive approach to minimizing thromboembolism. Circulation 1994; 90(5 pt 2): II87-91.
6) L. Chen, D. Han, L. Jiang, On improving blood compatibility-From biospired to synthetic design and fabrication for biointerfacial topography at micronano scale. Colloids Surf Biointerfaces 2011; 85(1): 2-7.
7) Y. Yamada, T. Nishinaka, T. Mizuno, Y. Taenaka, E. Tatsumi, K. Yamazaki, Neointima-inducing inflow cannula with titanium mesh for left ventricular assist device. J Artif Organs 2011; 14(4): 269-275.
8) T. Miyamoto, T. Nishinaka, T. Mizuno, E. Tatsumi, K. Yamazaki, LVAD inflow cannula covered with a titanium mesh induces neointimal tissue with neovessels. Int J Artif Organs 2015; 38(6): 316-324.
9) X. Ye, Y.L. Shaoa, M. Zhoua, J. Li, L. Cai, Research on micro-structure and hemo-compatibility of the artificial heart valve surface. Appl Surf Science 2009;255(13-14):6686–6690.
10) N. Watanabe, K. Affeld, J. Schaller, S. Schmitmeier, A.J. Reininger, L. Goubergrits, et al., Investigation of human platelet adhesion under low shear conditions in a rotational flow chamber. J Biorheol 2011; 25(1): 64-70.