Characterization of Flow Dynamics in Intracranial Cerebral Aneurysm Using In Vitro Modeling Techniques

T. Yagi , Y. Qian, M. Hukushima, A. Kamoda, A. Sato, K. Iwasaki, M. Umezu,
H. Takao, Y. Murayama

Abstract— **The rupture of intracranial aneurysms is widely believed to have a close relationship with the blood flow, but the mechanism has yet to be clarified. The characterization of the hemodynamics plays a critical role for establishing the risk management of the aneurysm rupture. Until now, a number of researchers worldwide have studied the aneurismal flow using in vitro measurements or computational fluid dynamic techniques. However, there is still no fluid dynamic indicator, by which the risk management of the aneurysm rupture could be attained in clinical practice. To this end, the present study aimed to clarify the differentiation of the aneurismal hemodynamics between pre-ruptured and unruptured cases using in vitro modelling techniques. The patient-specific elastic replica of intracranial aneurysms was fabricated and evaluated hemodynamically using Time-resolved Particle Image Velocimetry technique. It was found that the flow in the pre-ruptured case exhibited the jet flow pattern, whereas others more likely showed the swirling flow pattern. It is concerned that the jet flow produced the abnormal fluid-dynamic stimuli for the aneurismal wall, and thereby promoting the risk of rupture.**

I. Introduction

The blood flow in intracranial aneurysms is widely believed as one of the primary causes for the rupture and the subsequent subarachnoid hemorrhage. Although the occurrence rate of the rupture is only 10 cases per 100,000 persons approximately [1], it has a significant impact on the life since subarachnoid hemorrhage has a devastating mortality rate. In the United States, the number of persons with intracranial aneurysms is currently estimated to reach as much as 10 to 15 millions including the potential [1]. Thus, there is a significant demand in establishing the risk management of the rupture. However, the characterization of flow dynamics between pre-ruptured and unruptured aneurysms is not straightforward due to a variety of complex anatomy.

Until now, a number of researchers worldwide have tried to characterize the blood flow in an effort to establish a fluid-dynamic indicator, by which the risk management of the aneurysm rupture could be reliably attained [2-4]. However, none of parameters proposed, such as high wall shear stress (WSS), low WSS, or its temporal fluctuation, has yet to be confirmed as a reliable indicator of the rupture.

Wall shear stress is a local hemodynamic force applied on the aneurismal wall, which is inherently very much sensitive to the geometry of the aneurysm. Since the aneurismal hemodynamics is deeply correlated with the geometry of the parent vessel as well, the effect of the parent vessel further complicates the hemodynamic characterization if it is solely done by the local parameter. In fact, the significant variation of WSS can be observed individually, which makes it difficult to compare and differentiate the flow between pre-ruptured and unruptured cases.

In order to establish the flow parameter for the risk management of the rupture, it is mandatory to compare the flow by defining a flow parameter robust enough against a wide variety of anatomy depending on patients. To this end, it is indispensable to have the better understanding of the flow pattern, especially for the differentiation between pre-ruptured and unruptured cases. However, such a systematic understanding of the aneurismal hemodynamics is not necessarily established. Most of the studies have focused on a local flow parameter that is significantly sensitive to the complex anatomy of aneurysm, and a global parameter that can simply compare the flow pattern has yet to be proposed. It is believed that the global, rather than local, parameter should be firstly achieved to realize the risk assessment of the aneurysm rupture in clinical practice.

This study aims to characterize the flows among 4 cases including the one pre-ruptured using in vitro modeling techniques. Special focus is given to obtain the global understanding of the aneurismal hemodynamics in an effort to establish the robust flow parameter for the risk management of the aneurysm rupture among a large number of patients.

II. Methods

Fig.1 shows the 3D-DSA (Digital Subtraction Angiography) image of intracranial aneurysms studied. Table 1 summarizes the patient information. All intracranial aneurysms occurred in internal carotid artery: one pre-ruptured and three unruptured. The pre-ruptured case sized around 6 mm at maximum at the age of 74, whereas unruptured cases around 16, 11 and 9 mm at the age of 54, 63 and 60 respectively. These vessel geometries were reproduced as a patient-specific replica by using a lost-wax casting technique as shown in Fig.2. The replica consisted of a thin transparent silicone-rubber membrane whose mechanical properties were evaluated by incremental distensibility. Since the mechanical property of the aneurysm is still lacking, that of the patient-specific replica was adjusted to match that of the anterior cerebral artery in healthy conditions [7] .

Then, the patient-specific elastic replica of intracranial aneurysms was set in a pulsatile flow simulator that can mimick the realistic flow conditions, as shown in Fig.3. The setting of the pulsatile flow was as follows: a heart rate of 70 bpm and a systolic fraction of 35%. The resulting flow rate was 330 mL/min as a cycle average with a physiological pressure condition. The working fluid as a substitute of the blood was a mixture of glycerol and water with a fraction of

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T. Yagi, Y. Qian, M. Hukushima, A. Kamoda, A. Sato, K. Iwasaki and M. Umezu are with the Umezu Laboratory from Graduate School of Integrative Bioscience and Biomedical Engineering, Waseda University, Tokyo, Japan (Corresponding author: T. Yagi, phone: 813-5369-7331; fax:813-5269-9062; e-mail: takanobu_yagi@ akane.waseda.jp).

H. Takao and Y. Murayama are with the Department of Neurosurgery, Jikei University School of Medicine, Tokyo, Japan.

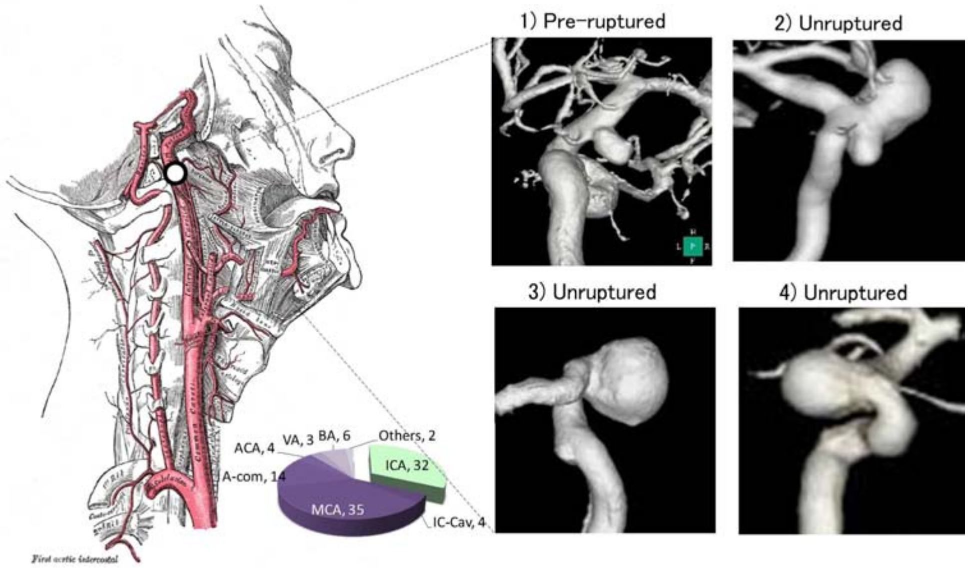

Fig.1. Intracranial cerebral aneurysm treated in this study. All the aneurysms were located at internal carotid artery. The skema of human anatomy was modified from the literature [5]. The diagram of the regional incidence of cerebral aneurysm was referred from the literature [6]. ICA stands for internal carotid artery.

Table 1. Details of aneurysms

Case	1) Pre-ruptured	2) Unruptured	3) Unruptured	4) Unruptured
Position	Right ICA	Right ICA	Left ICA	Left ICA
Age/sex	72/ F	54/ F	63/ F	60/F
Size mm	6	16	11	9
Bleb	○	○	×	×

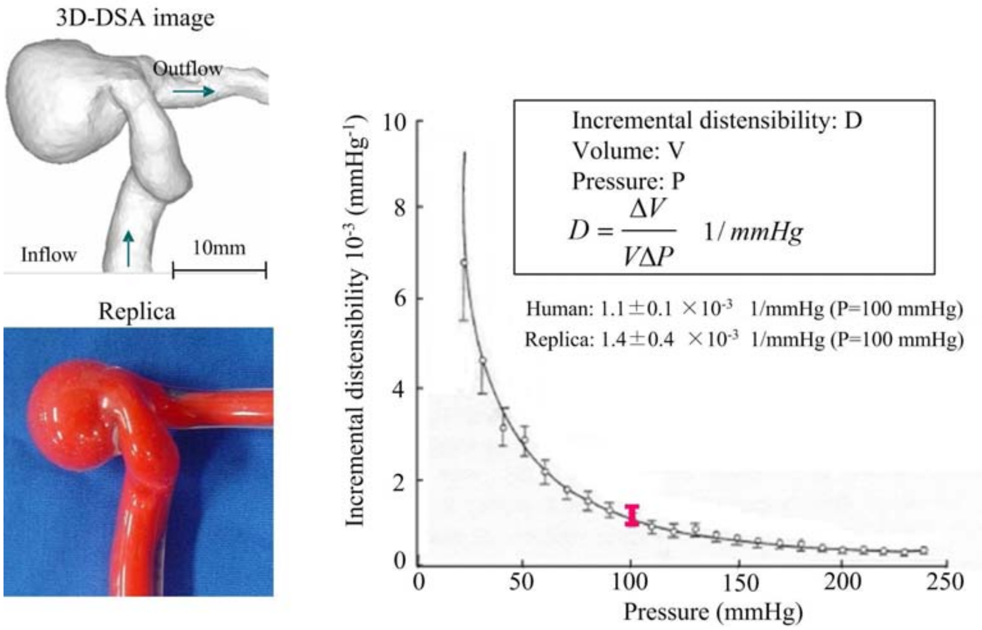

Fig.2. Patient-specific elastic replica of aneurysm. The mechanical property of the replica was evaluated by incremental distensibility according to the literature [7], which was marked by a red-colored line with a standard deviation. Note that the replica is made of a transparent silicone rubber. For visibility, the lumen is filled with a red-colored liquid.

46 and 54, respectively, which mimicked the kinematic viscosity of the blood. The density and the kinematic viscosity of the blood-mimicking fluid was 1100 Kg/m^3 and 3.3 cSt, respectively. The liquid was seeded by fluorescent particles with the diameter and density of 10 μm and 1100 Kg/m^3, respectively (Fluostar, EBM corp., Tokyo). Then, Time-resolved Particle Image Velocimetry (TR-PIV) measurements were carried out. A long-pass fluorescent filter was used to eliminate the optical noise due to the reflection. The fluorescent particles featured a significant brightness, enabling the good signal-to-noise ratio in the near-wall measurement (Fig.4). Since the aneurismal flow is highly three-dimensional, the multiple-plane measurements were carried out to characterize the global flow pattern.

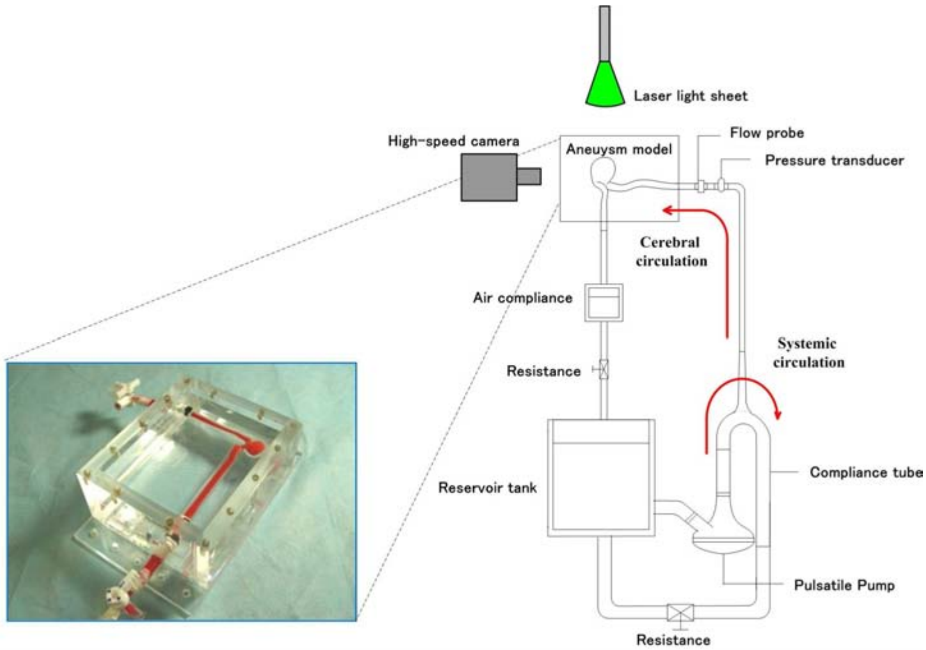

Fig.3. In vitro cerebral vascular pulsatile flow simulator

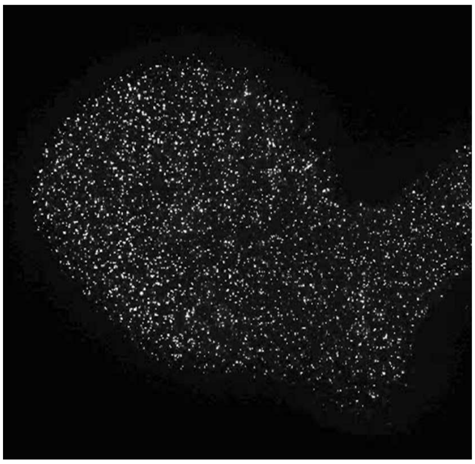

Fig.4. Fluorescent particle image (original)

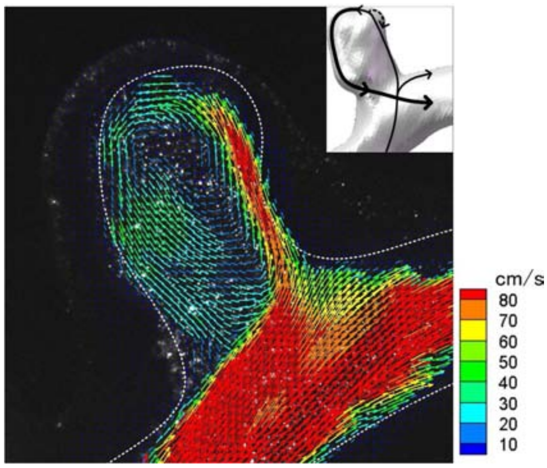

Fig.5.Aneurysmal jet observed in a pre-ruptured case. The schema shows the inflow and outflow pattern.

III. RESULTS AND DISCUSSION

The careful investigation of the aneurismal hemodynamics was conducted over multiple planes in a time-resolved manner. It was found that the pre-ruptured case exhibited a strong jet flow pattern. Fig.5 shows the mainstream observed at a peak phase. The flow in the parent vessel collided with the distal side of the aneurysm, and then the breakup of the flow led to form the intraaneurismal jet whose velocity reached up to 1.0 m/s approximately within the aneurysm and there is no marked reduction of the jet velocity from the neck to head. Noteworthy is the fact that the mainstream of the jet was observed in a single plane, indicating that the jet was rather two-dimensional, which was attributed to the curved, rather than twisting, geometry of the parent vessel at the proximal site. Although Fig.5 corresponded to the instantaneous flow pattern at the peak flow phase, there is no marked difference observed for the flow pattern during cardiac cycle. Without altering the flow pattern, the jet velocity varied according to the velocity of the flow passing through the parent vessel.

Fig.6 summarizes the main inflow pattern for unruptured cases. In order to compare the representative flow pattern among pre-ruptured and unruptured cases, the mainstream with the similar viewing angle to the pre-ruptured case was selected. The results demonstrated that although the inflow pattern in unruptured cases exhibited a jet-like pattern, there is a marked reduction of the jet velocity on the representative plane, which indicates either the sudden deceleration of the jet or the three-dimensional flow pattern, namely out-of-plane motion. In order to understand the flow structure in a three-dimensional space, TR-PIV measurements were made in orthogonal planes as shown in Fig.7. It was found that the flow more likely exhibited a swirling motion, rather than a jet. The swirling flow crossed over the measured plane, which resulted in a marked difference of the velocity measured on a representative inflow plane. The swirling flow was attributed to the

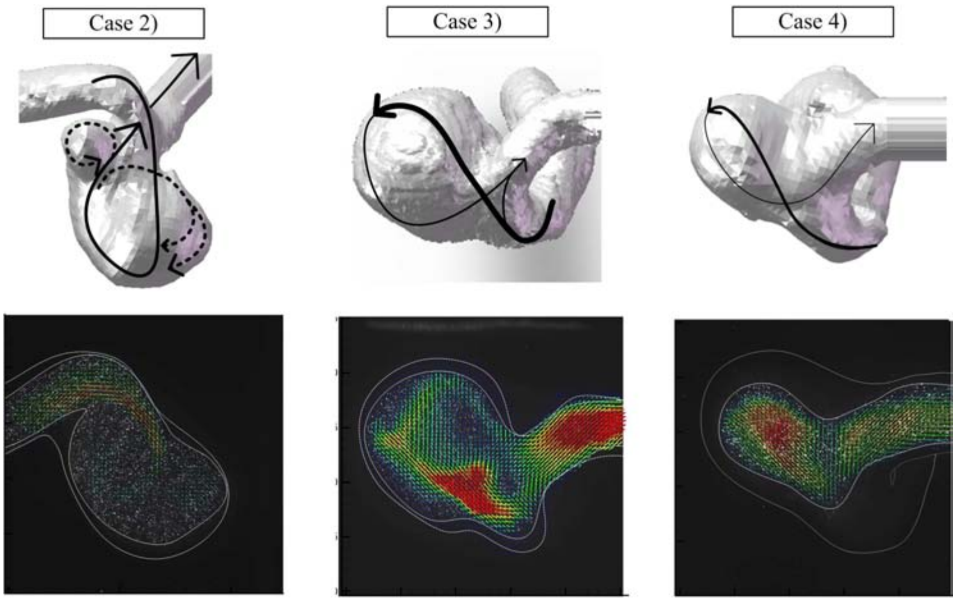

Fig.6. Comparison of inflow patterns in unruptured cases. The color range of the velocity magnitude should be referred to Fig.5.

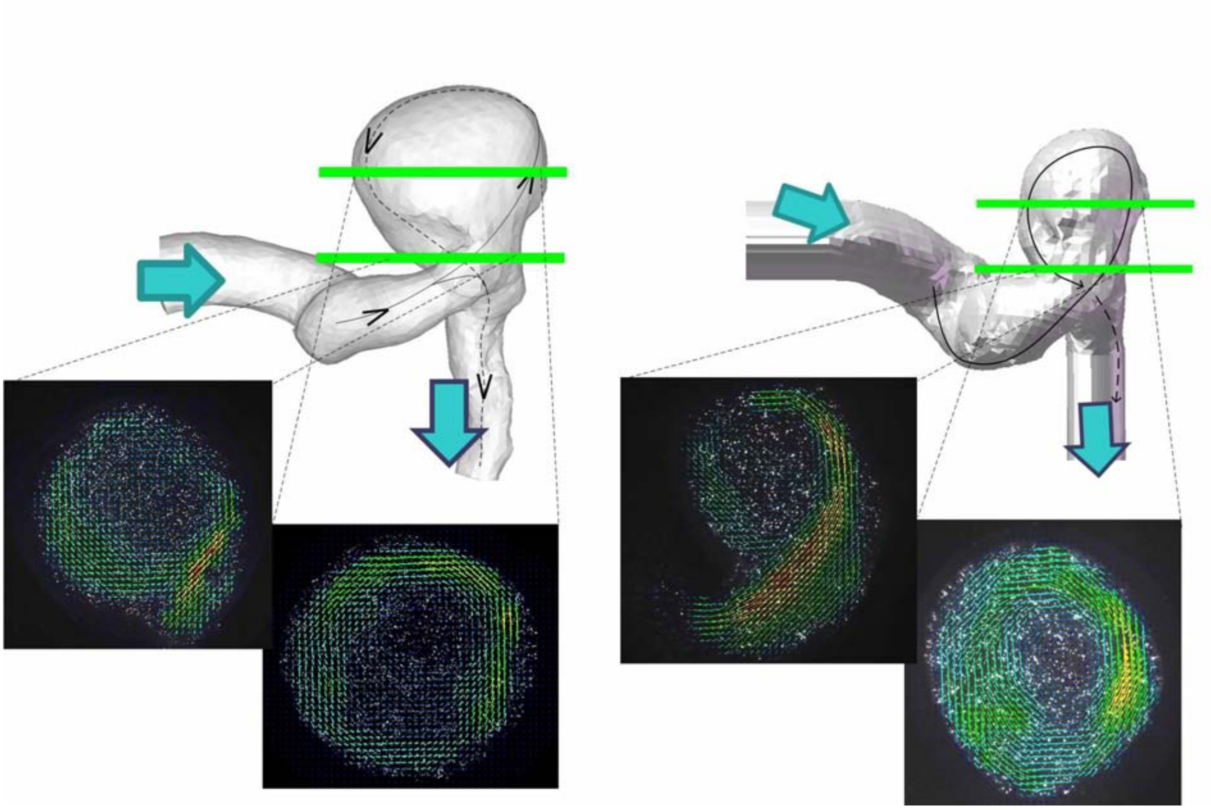

Fig.7. Swirling flow patterns observed in unruptured cases (3: left) and (4: right). The color range of the velocity magnitude should be referred to Fig.5.

geometry of the parent vessel, which exhibited a rather twisting geometry. The twisting geometry of the parent vessel at the proximal site resulted in a tangential inflow, rather than a colliding flow as observed in the pre-ruptured case, which enabled to form a swirling flow pattern. In terms of fluid dynamics, the swirling flow is much more stable due to the centrifugal force than the jet flow that can be readily unstable owing to the adverse pressure gradient along with the flowing direction. Those flow differences were believed to affect the risk of the aneurysm rupture.

IV. CONCLUSION

The present study demonstrates the possibility for differentiating the flow pattern among pre-ruptured and unruptured cases. The aneurismal flow was globally characterized by jet or swirl, which is undoubtedly attributed to the geometry of the aneurysm as well as the parent vessel. It appeared that the twisting geometry of the parent vessel at the proximal side of the aneurysm more likely produces the swirling flow due to the tangential inflow. The jet flow observed in the pre-ruptured case was located at the simply curved geometry of the parent vessel. This curved geometry produced the colliding flow at the distal side of the neck, resulting in the aneurismal jet. The future study would have to include the greater number of patients. With the global understanding for the aneurismal flow pattern, a flow indicator robust enough against the variety of complex anatomy would be proposed in the future study.

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