Flow in a Tube with an Aneurysmal Sac: Effect of Aneurysm and Stent

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Summary

Ruptured saccular aneurysms were severe condition for intracerebral Condition. And the cause for their rupture is not yet clear. In this study (I), since the configurations of aneurysms are considered to be a factor for the rupture of aneurysms, several shapes has been modeled using

Aspect ratio AR and inclination angle of saccular aneurysms. In vitro the parametric study has been conducted on the range of Reynolds Number in human blood flow for aneurysmal models of AR=2.1 and 1.3 and $q = 90^\circ$ and 70° . As results, it was confirmed that there are characteristic flow patterns with Reynolds Number, And that the aneurysmal configuration has effects on the shear stress and pressure losses. II) The object of this paper is to study the effects of STENTS. We made the model of aneurysm and performed in vitro study in range of Reynolds number of human blood flows using three kinds of STENTS. As results, it was confirmed that flow pattern and pressure loss changes with the kinds of STENTS. This study aims the accumulation of data to predict the hazard of aneurysmal rupture by their shapes and STENTS.

Introduction

Ruptured cerebral aneurysms are the principal cause of subarachnoid haemorrhage, so it is important to determine how aneurysms rupture during their development and growth. Blood flow and the vessel wall play key roles in the

process of rupture, but these are still not well understood.

At present, physical factors such as blood flow-induced wall shear stress and pressure as well as local factors such as morphology and arterial wall damage are thought to be important in the rupture of aneurysms. Recently, intravascular therapy using coils and stents has been performed for aneurysms, but blood flow changes due to such intravascular therapy have not been elucidated.

The present study investigated the effect of aneurysm morphology on blood flow using a sac attached to an acrylic tube to model the aneurysm with the aspect ratio (AR) and inclination (q) as parameters.

The effect of aneurysm shape was investigated on the intra-aneurysmal flow pattern and shear stress, as well as the pressure drop across the aneurysm at selected Reynolds numbers corresponding to the blood flow in the human body (Study 1). To investigate the effects of stenting, the flow velocity and shear stress inside aneurysm models were measured as well as the pressure drop across a model including an aneurysm and a stent (Study 2).

STUDY 1: EFFECTS OF AN ANEURYSM

Methods

Experimental System and Equipment

The system consisted of the straight tube with an aneurysm. To obtain non-pulsated

Figure 1
Schematic view of experimental.

steady flow, an overflow head tank was used and the flow rate was adjusted with a bulb reservoir. The operating fluid consisted of water, which behaves as a Newtonian fluid. After injection of a liquid tracer, the lateral perpendicular (side view) and horizontal (bottom view) sections of the system were illuminated by laser sheet light. These cross-sections were taken with a video camera and the flow rate was measured by particle image velocimetry. The pressure drop across a 100-mm segment of the tube including the aneurysm was measured using a micro-manometer.

Aneurysm Models

Aneurysm models were prepared by attaching a sac-like glass reservoir to the acrylic tube. The shape was specified by the following parameters: aneurysm neck diameter (n), neck height (h_1), the height of the main body of the aneurysm (h_2), aneurysm diameter (d), and the angle between the central axial line of the aneurysm and the direction of flow through the tube (inclination: q). The aspect ratio (AR) was calculated as $AR = h/n$ ($h = h_1 + h_2$: aneurysm height). The inner diameter of the tube (D) was set at 14 mm, the aneurysm neck diameter (n) was 14 mm, and the neck height (h_1) was four mm. Four model aneurysm shapes were pre-

pared, with AR of 2.1 ($h = 29.4$ mm, $d = 25$ mm) or 1.3 ($h = 18.2$ mm, $d = 18$ mm), and with q of 90° (perpendicular) or 70° (inclined).

Experimental Conditions

The Reynolds number (Re) for flow in a tube is given by $Re = UD/n$, where D is the tube diameter, U is the mean flow velocity in the tube, and n is the coefficient of the kinematics viscosity of fluid. The Reynolds number for blood flow in the human body is reported to reach about 10,000 at maximum, so we obtained data with Reynolds numbers of 7,000, 2,800, and 840, which occurred in the laminar flow zone, transition zone, and turbulent flow zone of the tube, respectively. Reynolds numbers of 7,000 and 2,800 correspond to aortic flow in the human body, whereas 840 corresponds to cerebral artery flow^{1,2}.

Results

Flow Pattern

The three-dimensional flow pattern in model aneurysms with an AR of 2.1 and q of 90° or 70° was observed at $Re = 7,000$, 2,800, and 840. Under the conditions of $q = 90^\circ$ and $Re = 7,000$, the side view showed that the flow stream rebounded off the downstream side of the aneurysm

neck and hit the left lower wall of the aneurysm, then flowed counterclockwise along the wall before becoming detached from the wall to return to the circulation. The bottom view showed that the flow entering from the downstream side separated into two streams that swirled in opposite directions. At $Re = 2,800$, the side view showed flow into the aneurysm from the downstream side of the aneurysm neck that moved clockwise along the wall. At $Re = 840$, very slow circular flow occurred inside the aneurysm and there was almost no inflow into the aneurysm. Under all Re conditions, the flow pattern at $q = 70^\circ$ was almost the same as the flow pattern at $q = 90^\circ$ and $Re = 7,000$.

The three-dimensional flow pattern was also observed in model aneurysms with AR of 1.3 and q of 90° or 70° . Under all conditions tested, flow was clockwise after entering the aneurysm from the downstream side of the aneurysm neck. Detachment-induced recirculation occurred under the conditions of $q = 70^\circ$ and high Re value, even in small aneurysms, but not at $q = 90^\circ$.

The flow pattern inside ruptured aneurysms often shows detachment-induced recirculation¹. The present study found that high Re value and inclined aneurysm promoted the development of detachment-induced recirculation.

Shear Stress

The maximum shear stress against maximum shear strain was determined from the velocity distribution obtained by particle imaging. The maximum shear stress was most commonly located at the wall, and wall shear stress was greater at AR = 2.1 than AR = 1.3.

Pressure Drop

The pressure drops across a 100-mm segment of tube including an aneurysm. For relatively large Re values, the pressure drop was greater as the AR increased and with inclined aneurysms.

Conclusions

We assessed the flow pattern, shear stress, and pressure drop in four models of aneurysm morphology at selected Reynolds numbers corresponding to blood flow in the human body.

1) Characteristic flow patterns were observed that depended on the aneurysm shape and Reynolds number.

2) Detachment-induced recirculation occurred more often in aneurysms with high ARs or

inclined in the direction of blood flow, and the wall shear stress was greater with high ARs. The chronic load of high shear stress and the occurrence of detachment-induced recirculation may be factors contributing to aneurysm rupture; so high AR and inclination may be important parameters.

3) For relatively large Reynolds numbers, the pressure drop was greater in aneurysms with high ARs and inclined toward the main flow stream.

STUDY 2: EFFECT OF STENTS

Methods

Experimental System and Equipment

The experimental system and equipment used for measurement were the same as in Study 1.

Aneurysm Models

Aneurysm models were prepared by attaching a sac-like glass reservoir to an acrylic tube with an inner diameter (D) of 14 mm. The aneurysm neck diameter (d) was set at 25 mm, the height (h) at 29.4 mm, and the neck diameter (n) at 14 mm, with the same shape as the model aneurysm with AR of 2.1 and q of 90° used in Study 1.

Stents

The stents were (a) a stent for large vessels (Easy Wall stent), (b) a stent for peripheral vessels (PALMAZ stent), and (c) an esophageal stent (Ultra-flex). The length of the stents was 87 mm for stent (a), 25 mm for (b), and 85 mm for (c). Stent (a) had a finer mesh than stent (b). The wall thickness of the stents was in the following order: (a) < (b) < (c).

Experimental Conditions

The Reynolds number was set at 7,000, 2,800, and 840 as in Study 1. The flow pattern and pressure drop were compared between model aneurysms without stents and with stents (a), (b), or (c).

Results and Discussion

Flow Pattern

Intra-aneurysmal flow was assessed under various conditions. In the absence of a stent and at Re of 7,000, part of the main flow stream entered the aneurysm without rebounding from the aneurysm neck and then moved counterclockwise. At Re of 2,800, the flow stream en-

tered the aneurysm without rebounding from the aneurysm neck and then moved clockwise. At $Re=840$, the flow stream entering the aneurysm did not reach the fundus, resulting in the formation of another very slow circulation zone in the lower part of the aneurysm.

In the presence of a stent and at Re of 7,000, the flow pattern with stent (c) was close to that without stent at the same Re value. However, placement of stents (a) and (b) suppressed the entry of flow into the aneurysm, with the flow pattern being close to that without stenting at Re of 2,800. At Re of 2,800, the flow pattern obtained with stents (a), (b), and (c) was similar to that seen without a stent at Re of 840, 2,800, and 7,000, respectively. At Re of 840, the main flow stream did not enter the aneurysm with stent (a) in place. However, the stream entering the aneurysm (though very slow) reached the fundus of the aneurysm with stents (b) and (c). Since stents (b) and (c) had thicker walls than stent (a), the main flow stream was disturbed and entered the aneurysm more easily. These results show that thinner stents with a finer mesh had an inhibitory effect on the entry of the flow stream into the aneurysm. Conversely, thicker stents with a coarser mesh sometimes facilitated the entry of the flow stream into the aneurysm.

Shear Stress

The mean shear stress and velocity per second at Re of 7,000 were compared between the

stents. With stents (a) and (c), flow was faster and the shear stress was greatest near the wall. However, since this did not take into account flow toward the deeper part of the aneurysm, the actual wall shear stress may not be the same.

Pressure Drop

The magnitude of the pressure drop across a designated segment including the aneurysm and stent was in the following order: no stent > stent (b) > stent (a) > stent (c). The decline of pressure was greater with higher Reynolds number. In other words, the pressure drop was greater with longer, thicker, and coarser meshed stents, and this tendency became stronger as the Reynolds number increased.

Conclusions

The following conclusions were reached.

1) Thinner stents with a finer mesh had an inhibitory effect on the entry of flow into the aneurysm. Conversely, thicker and less finely meshed stents occasionally promoted entry of the flow stream into the aneurysm.

2) Two-dimensional comparison of shear stress showed greatest shear stress near the wall, but actual shear stress could not be assessed by this model.

3) Pressure drop was greater with a longer, thicker, and less finely meshed stent, and this tendency became stronger at larger Reynolds numbers.

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