Evaluations of Fluid Dynamic Forces and Blood Vessel Stresses of an Artery with a Cerebral Aneurysm

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The enhancement in diagnosis of cerebrovascular disorders and the reduction of mortality caused by these diseases should be contended with much further because the receive rate of medical treatment for cerebrovascular disorders with hospital stays was the highest among all disorders according to the 2008 statistical data by Japan Health, Labor and Welfare Ministry and the woman's mortality of these diseases was the third highest while the man's mortality of these diseases was the fourth highest among all diseases according to the 2009 statistical data by Japan Health, Labor and Welfare Ministry. In our project, we introduced the rupture strength diagram to explain the mechanical root causes of originations, enlargements and the rhexis risks of cerebral aneurysms. Because the blood vessels are composite materials with some viscoelastic living materials, the time axis should be considered. Then we introduced several kind of rupture strength diagrams with the frequency of the heart pulsing motion and some dominant frequencies in the power spectrum of an artery system with a cerebral aneurysm. In this first year report, the result of CFD analysis and structural analysis of an artery with a typical large cerebral aneurysm that was chosen from our 312 cases collected for the current research program.

Keywords: Cerebral Aneurysm, Blood Vessel, Fluid dynamics, Stress Analysis

1. Introduction

The improvement in diagnosis of cerebrovascular disorders and the reduction of mortality caused by these diseases should be contended with much further because the receive rate of medical treatment for cerebrovascular disorders with hospital stays was the highest among all disorders according to the 2008 statistical data by Japan Health, Labor and Welfare Ministry and the woman's mortality of these diseases was the third highest while the man's mortality of these diseases was the fourth highest among all diseases according to the 2009 statistical data by Japan Health, Labor and Welfare Ministry.

There are three effective analytical approaches to investigate the mechanical phenomena of cerebrovascular disorders. The first approach is the fluid dynamical approach to analyze the blood flows through the brain blood vessels with cerebrovascular disorders. The second approach is the structural dynamical approach to analyze the stresses and strains of the brain blood vessels result from blood pressures, blood flow shear forces and other forces from the surrounding area. And the third approach is the integrated approach that couples the fluid and structural dynamical approaches to study the both dynamics and the reciprocal interferences between the fluid and structural phenomena.

To investigate the originations, enlargements and the rhexis risks of cerebral aneurysms, there were many studies with the fluid dynamic approach and some studies using the structural dynamic and the coupled approaches from 1990's. Yamaguchi et al [1][2] presented the strong correlation between the wall shear stress gradient and the origination site of cerebral aneurysms measuring the wall shear stresses and their gradient with a laser Doppler anemometer in a scale model of anterior communicating artery (ACA). They also reported that there were periodic vibrations in blood flows through branch artery form an aneurysm. Ujiie et al.[3][5] introduced the aspect ratio (aneurysm depth/neck width, AR) as an parameter of blood flow stagnation in an artery using the similar experiment of blood flow visualizations and their clinical study information. They presented that there was a threshold AR around 1.6 between un-ruptured and ruptured aneurysm and blood flow stagnations in arteries were deeply related with the processes of aneurysm ruptures. They indicated the possibility that the high frequency vibrations occurred around aneurysms stimulate enlargements of aneurysms. Ohshima et al. [4][6][7][8] conducted coupled computer simulations of fluid an structural dynamic analyses to simulate the reciprocal interferences between the blood flows and artery wall motions and deformations using three-dimensional geometry data around artery in the brain observed with a X-ray computed tomography. They presented that the wall shear stresses were affected by the geometry of the branches of the artery and the deformations of the wall. They also conducted simulations of computational fluid dynamics (CFD) on twenty cases of un-ruptured and ruptured aneurysms in the middle cerebral artery (MCA) and evaluated the correlation between the wall shear stresses and the AR. The Department of Neurosurgery of Teikyo University had joined these CFD studies. Funazaki et al. [9][10] conducted coupled computer simulations of fluid an structural dynamic analyses to simulate the Mises stress distributions of the artery walls around un-ruptured aneurysms at two artery branches. Recently, Harada et al. [11] and Murayama et al. [12] presented that the pressure or energy losses of blood flows through aneurysms can be used as a parameter to explain the differences of the blood flows between un-ruptured and ruptured aneurysms statistically.

As explained above, existent studies have demonstrated the relationship between the blood flow phenomena around aneurysms and the originations, enlargements and the rhexises of cerebral aneurysms successfully. However, the approaches that can be used by medical doctors in clinical practices should be developed for the next step.

In general, the rupture strengths of elastic materials are able to be depicted as two dimensional envelope diagrams with steady stress and unsteady stress as the abscissa and vertical axis respectively. In our current study, we introduced this rupture strength diagram to explain the mechanical root causes of originations, enlargements and the rhexis risks of cerebral aneurysms. However the blood vessels are composite materials with some viscoelastic living materials, the time axis should be considered. Then we introduced several kind of rupture strength diagrams with the frequency of the heart pulsing motion and some dominant frequencies in the power spectrum of an artery system with a cerebral aneurysm.

In this first year report, the result of CFD analysis and structural analysis of an artery with a typical large cerebral aneurysm that was chosen from our 312 cases collected for the current research program.

2. Three dimensional geometrical modeling from medical image data

For the current program, we have collected 312 cases with Magnetic Resonance Imaging (MRI) and X-ray computed tomography (CT) data that were diagnosed and treated in recent a couple of years. One case of typical large cerebral aneurysm was chosen for the first CFD and finite element analysis (FEA) to evaluate actual fluid dynamic forces and blood vessel stresses of an artery with a cerebral aneurysm. While both MRI and X-ray CT data can be used for the geometrical modeling, MRI data was used for the current study because we needed to estimate the wall thickness of an aneurysm and blood vessels.

Figure 1 shows a MRI slice close-up image near the top of a cerebral arterial aneurysm that was chosen for the first CFD and finite element analysis (FEA). Figure 2 shows MRI slice image near at the center height of the same cerebral arterial aneurysm. The top sides of Figs. 1, 2 are the face sides. The cut sections of the aneurysm can be seen around the center of the both figures. The actual maximum diameter of this aneurysm is around 20 mm. This size is larger than the average size of cerebral aneurysms. Some cut sections of artery can be seen around the aneurysm near the bottom sides of these figures. The aneurysm wall actual thickness was measured as 0.6 mm at the back left side of Fig. 2. However, there was very thin wall region that was

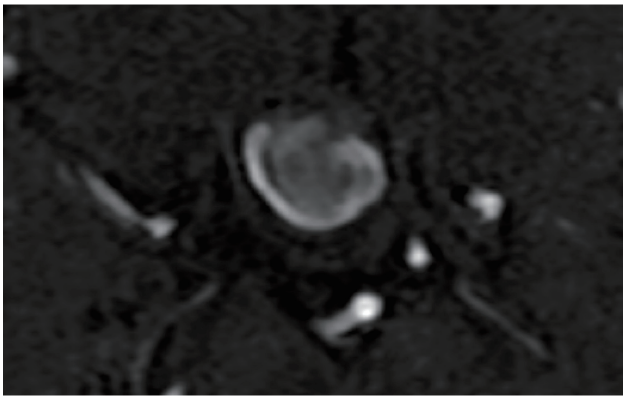

Fig. 1 MRI slice image near the top of a cerebral arterial aneurysm.

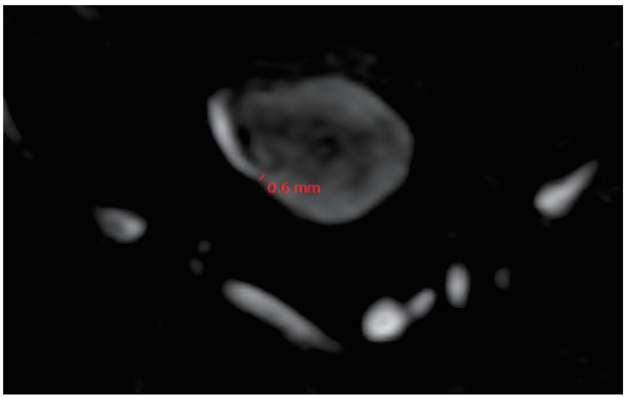

Fig. 2 MRI slice image near the center height of a cerebral arterial aneurysm.

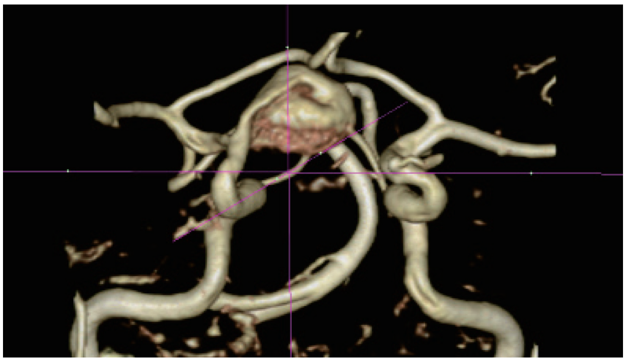

Fig. 3 Volume data around a cerebral arterial aneurysm.

difficult to be measured near the face side, we assumed the wall thickness as 0.3 mm for the FEA.

After removing the image of cranial bones and surrounding tissues, the range of MRI values for blood flows and walls of aneurysm and artery was searched using a three dimensional boxel data visualization and edit software (INTAGE Volume Editor, CYBERNET SYSTEMS Corp.). Figure 3 shows volume data around a cerebral arterial aneurysm extracted using this information of the range of MRI values for blood flows and walls of aneurysm and artery from the original boxel data as the format of Digital Imaging and Communications in Medicine (DICOM).

3. Fluid dynamic analysis

The stereo lithography (STL) geometry data was generated from the volume data of this artery with a cerebral aneurysm.

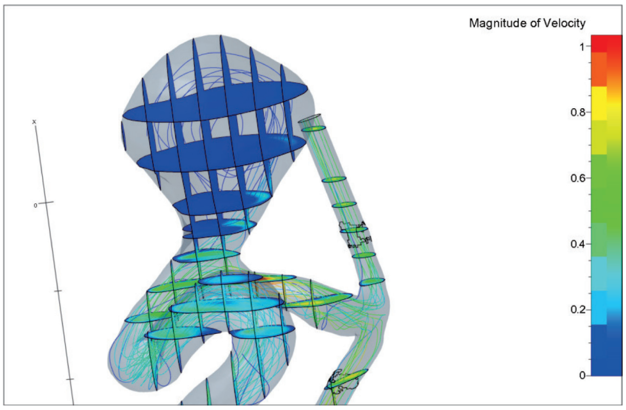

Fig. 4 Streamlines & velocity contours of blood flow.

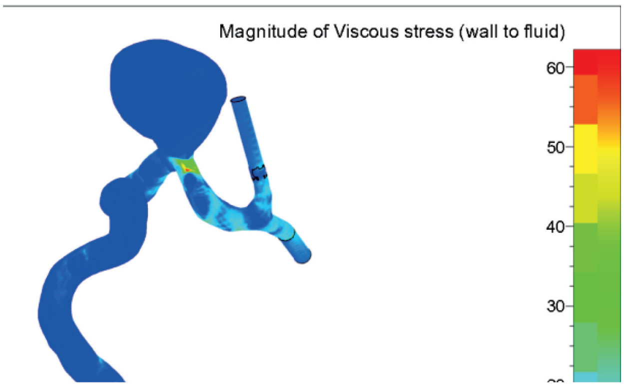

Fig. 5 Viscous stress contours on the wall.

The computational mesh for the fluid dynamic analysis was generated from this STL data using the mesh generation software (FINE/Open, NUMECA Corporation).

The results of fluid dynamic analysis are shown in Figs. 4 and 5. Figure 4 shows streamlines and velocity contours of blood flow in the aneurysm and the artery. A low speed vortex flow was generated inside the aneurysm and the maximum velocity (around 1m/s) is generated in the artery near the outlet of the aneurysm. Figure 5 shows viscous stress contours on the wall. The maximum viscous stress occurs on the inner wall of the artery at the maximum velocity section stated above.

4. Structural analysis

Structural analysis was conducted using the FEA software, FrontISTR [13]. The computational mesh for FEA was generated from the same STL geometry data that was used for the CFD mesh considering the blood vessel thickness. Figure 6 shows the volume data around a cerebral aneurysm including blood vessel wall for FEA. Because the deep concave geometry on the surface of the aneurysm was due to the incompleteness of the automatic data translation process form voxel data to STL data, the concave geometry was modified manually. The yellow color surface was modified manually in Fig. 6. Figure 7 shows the FEA computational mesh of the artery with a cerebral aneurysm.

As the boundary conditions, inlet and outlet ends of artery were supported simply, inside of the artery and the aneurysm was pressurized with 100 mmHg steady blood pressure while outside was pressurized with 100 mmAq steady brain pressure.

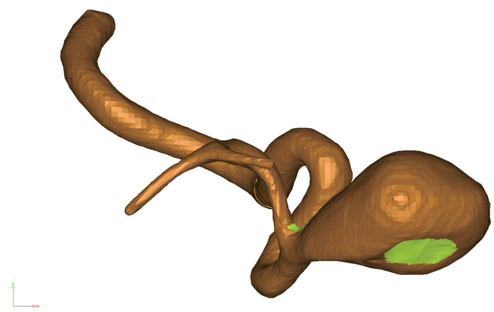

Fig. 6 Volume data around a cerebral arterial aneurysm including blood vessel wall for FEA.

Fig. 7 FEA computational mesh of the artery with a cerebral aneurysm.

The calculation results are show in Figs. 8 and 9. Figure 8 shows the calculated stress contours on the wall of artery and the aneurysm. Maximum stress was founded on the aneurysm wall and this maximum stress was roughly five times of the average stress in the normal artery. Figure 9 shows the calculated stress contours on the inside and outside of the cerebral arterial aneurysm (cut view). Since the large stress occurs at the bottom of the concave geometry, the measurement accuracy of the aneurysm geometry is important.

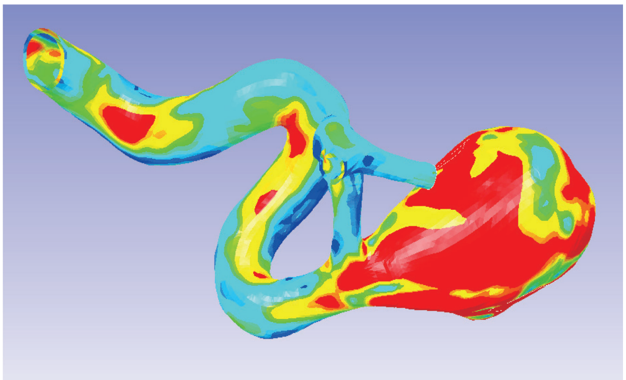

Fig. 8 Stress contours on the wall.

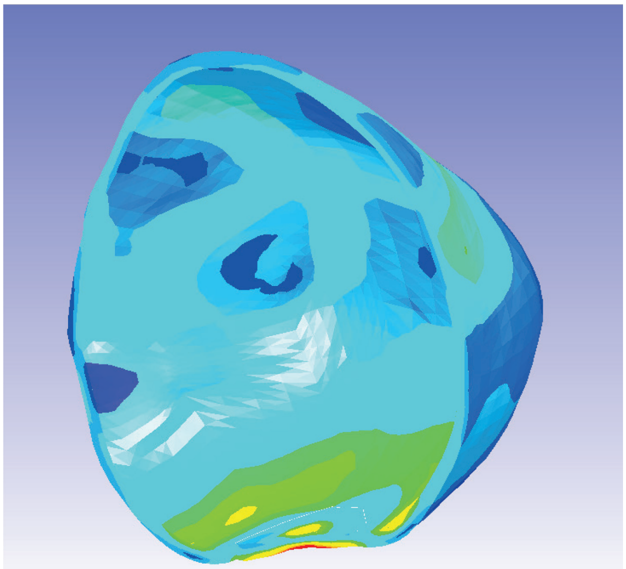

Fig. 9 Stress contours on the inside and outside of the cerebral arterial aneurysm (cut view).

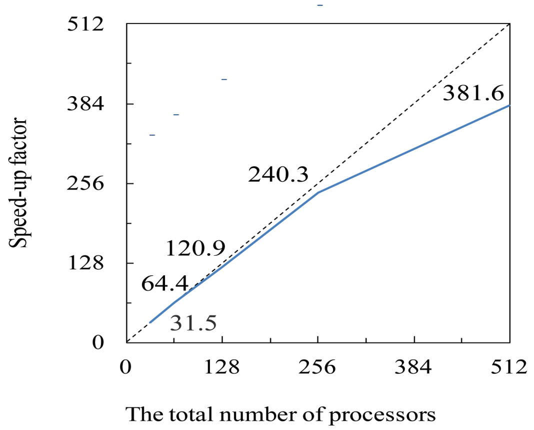

Fig. 10 The relationship between the total number of processors and the speed-up factor of the Earth Simulator.

The FEA software FrontISTR was optimized on the Earth Simulator to be used faster and efficiently. Figure 10 shows the relationship between the total number of processors and the speed-up factor measured on the Earth Simulator using a 100 million mesh for our benchmarking.

5. Conclusions

The calculated maximum stress on the aneurysm was roughly five times of the average stress in the normal artery while the maximum viscous stress is very small (less than 100 Pa). The maximum stress on the aneurysm was less than a published aneurysm strength data. However, if we would consider more high blood pressure case or actual pulsing blood pressure, the maximum stress would be increased near the similar level that might cause some damage on the aneurysm wall.

The result of first year study of our Earth Simulator Project shows that the steady structural analysis brings important information concerning the risk of aneurysm ruptures in case of large size cerebral aneurysms.

For the second year research program, we are planning to start the integrated approach that couples the fluid and structural dynamical analysis to study the both dynamics and the reciprocal interferences between the fluid and structural phenomena. This coupled analysis study will bring more accurate information on the risk of cerebral aneurysm ruptures even in cases of small size aneurysms.

Acknowledgment

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脳動脈瘤を含む血管系の流体力と応力の評価

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本プロジェクトの目標は、精度の高い流体解析と構造解析、及び流体構造連成解析を行って、脳動脈瘤の発生、増大、破裂のプロセスを力学的に明らかにして、医師が臨床の場で活用できる解析法及び解析法の結果を用いて脳動脈瘤の破裂または出血のリスクを予測する方法を確立することである。

脳血管疾患を含む血管系疾患に関しては、血管内を流れる血流に対する流体力学的なアプローチと血管に作用する血流の圧力とせん断力及び血管を取り囲む周辺部位からの力学的影響を評価する構造力学的アプローチ、そして流体解析と構造解析を連成して、双方の作用が相互に及ぼす影響を含めて評価する統合的なアプローチが有効と考えられ、これまで国内及び国外において数多くの研究がなされてきた。これまでの研究によって脳動脈瘤周辺の流動と脳動脈瘤の発生、増大、破裂との関連が明らかにされつつあり、次のステップとして医師が臨床の場で実際に利用できるアプローチが必要とされている。

一般に弾性材料の変形と破壊は部材にかかる定常応力を横軸、非定常応力を縦軸とした 2 次元グラフ中の領域で示すことができる。血管は一般的には粘弾性体としてモデル化することが適切と考えられているが、私達のグループでは、単純に時間軸を追加する方法に加えて、非定常応力の power spectrum 中の卓越する複数の周波数帯において前述した定常、非定常応力の 2 次元グラフ上で変形及び破断のリスクが高い領域を可視化する方法を目指している。

初年度の定常解析で計算された大型動脈瘤の最大主応力は推定される血管壁の引張強度より小さいが、渦流などの非定常成分を含む流体力と相乗することで血管壁に損傷を与えるオーダーであると考えられる。引き続き、小型動脈瘤も含めて、相乗効果を考慮した流体構造連成解析を行い、臨床的なリスク予測が可能な解析法の検討を行う。

キーワード:脳動脈瘤, 血管, 流体解析, 構造解析