Evaluations of Steady and Unsteady Blood Vessel Wall Stresses of an Artery with a Cerebral Aneurysm

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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. Consequently the enhancement in diagnosis accuracy for cerebrovascular disorders is still important to reduce the mortality caused by these diseases. 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. The first year report presented the result of CFD analysis and a preliminary study of structural analysis of an artery with a typical large cerebral aneurysm that was chosen from our 312 cases collected for the current research program. In the current second year report, the accuracy of the structural analysis has been improved and an unsteady structural analysis has been introduced to develop a risk assumption methdology for aneurysm ruptures.

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

1. Introduction

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. Consequently the enhancement in diagnosis accuracy for cerebrovascular disorders is still important to reduce the mortality caused by these diseases.

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 in consideration of 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 (X-ray CT). 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 [13]. 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.

The first year report [14] presented the result of CFD analysis and a preliminary study of structural analysis of an artery with a typical large cerebral aneurysm that was chosen from our 312 cases collected for the current research program. In the current second year report, the accuracy of the structural analysis has been improved and unsteady structural analysis has been introduced to investigate unsteady stresses in fatigue limit diagram-like format.

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 CT data that were diagnosed and treated in recent a couple of years. One case of typical large cerebral aneurysm was chosen for the present 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 mainly 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 at the center height of the cerebral arterial aneurysm. Figure 2 shows a X-ray CT slice image near the center height of the same cerebral arterial aneurysm. However the X-ray CT slice planes are 30 degree upward-inclined toward the face side while the MRI slice planes are located horizontal. The top sides of Figs. 1, 2 are the face sides. The cut sections of the aneurysm can be seen around

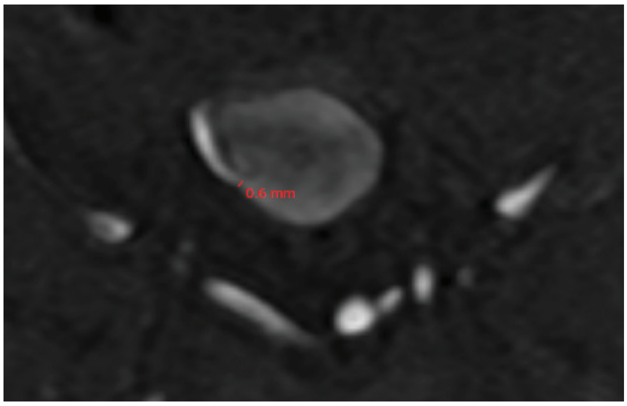

Fig. 1 MRI slice image near the center height of a cerebral arterial aneurysm (face is upper side).

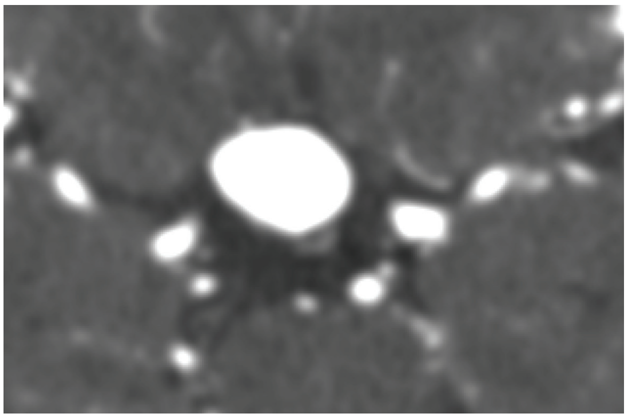

Fig. 2 X-ray CT slice image near the center height of a cerebral arterial aneurysm (30 degree upward-inclined toward face side).

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. 1. However, there was very thin wall region that was 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.). Figures 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).

Fig. 3 Volume data around a cerebral arterial aneurysm, an elevation view (left) and a plain view (right).

3. Fluid dynamic analysis

The stereo lithography (STL) geometry data was generated from the volume data of this artery with a cerebral aneurysm. The computational mesh for the fluid dynamic analysis was generated from this STL data using the un-structured mesh generation software (FINE/Open, NUMECA Corporation).

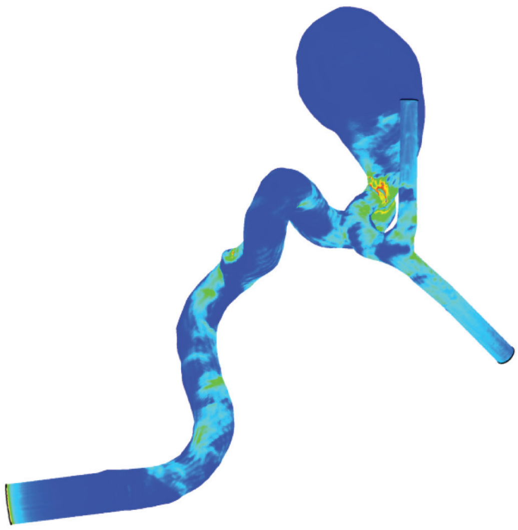

Fig. 4 Viscous stress contours on the wall.

The results of fluid dynamic analysis are shown in Fig. 4. A low speed vortex flow (around 0.1 m/s) was generated inside the aneurysm and the maximum velocity (around 1 m/s) is generated in the artery near the outlet of the aneurysm. Figure 4 shows viscous stress contours on the wall of the artery and the aneurysm. 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 [15] that is better suited for parallel computing with high performance computing infrastructures including the earth simulator.

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. However we had found that some dimples on the aneurysm shown in Fig. 3 caused some affected peaks of computed stress on the aneurysm. These dimples on the surface of the aneurysm seem to be due to the incompleteness of the automatic data translation process form voxel data to STL data. Consequently the STL geometry data made from the MRI data shown in Fig. 1 was modified manually using the X-ray CT slice image data shown in Fig. 2. Figure 5 shows the modified geometry for FEA computational mesh around the aneurysm where some modified areas are colored with moss green.

Figure 6 shows the FEA mesh skewness contours on the FEA computational mesh of the artery with a cerebral aneurysm.

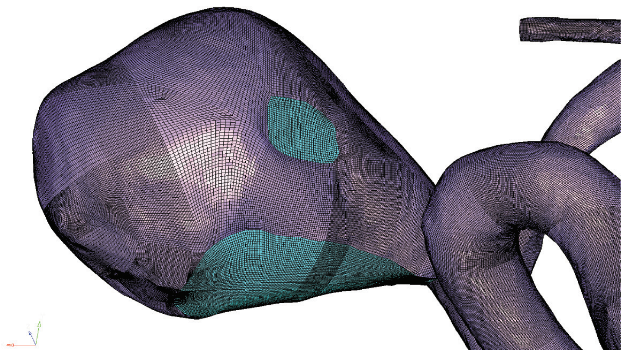

Fig. 5 Modified geometry for FEA computational mesh around the aneurysm.

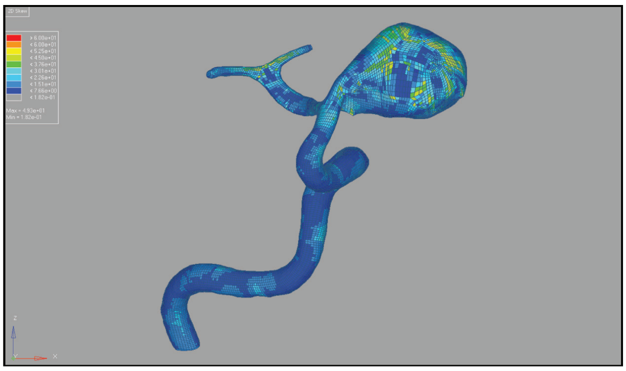

Fig. 6 FEA mesh skewness contours on the FEA computational mesh around the artery with the cerebral aneurysm.

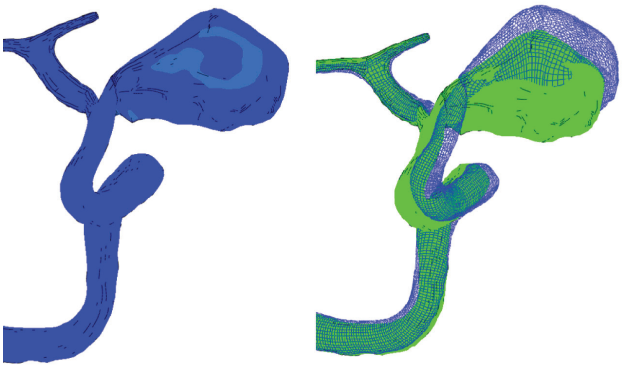

Fig. 7 Assumed mesh geometry in stress-free (without blood pressure) condition (left) and overwrap view of a stress-free (green) and normal condition (blue: with blood pressure) geometries.

Mesh skewness is one of important parameter of generated mesh for computing. The skewness contours in Fig. 6 are acceptable for high accurate FEA.

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.

For the initial geometry of the current FEA, we need to assume the geometry of the artery with the cerebral aneurysm without pressure difference between inside and outside of the artery and the aneurysm. Figure 7 shows the assumed mesh geometry in stress-free (without blood pressure inside and brain pressure outside) condition (left) and overwrap view of a stress-free (green) and normal condition (blue: with blood pressure inside and brain pressure outside) geometries. This stress-free geometry have been assumed using FEA iteration studies where the deformed geometry calculated with the blood pressure inside and the brain pressure outside had become almost the same geometry introduced from the MRI and the X-ray CT after some iterations.

The calculation results are show in Figs. 8, 9 and 10. Figure 8 shows the stress contours on the inner and outer wall surface of the aneurysm. Figure 9 shows the stress contours on a cut surface of the aneurysm. And Fig. 10 shows the stress contours on a cut surface of the blood vessel near the inlet boundary.

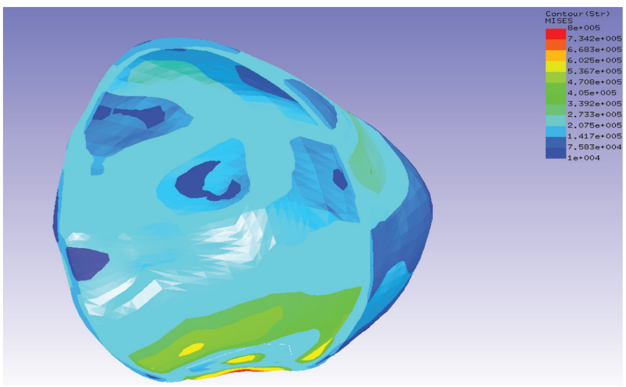

Fig. 8 Stress contours on the inner and outer wall surface of the aneurysm.

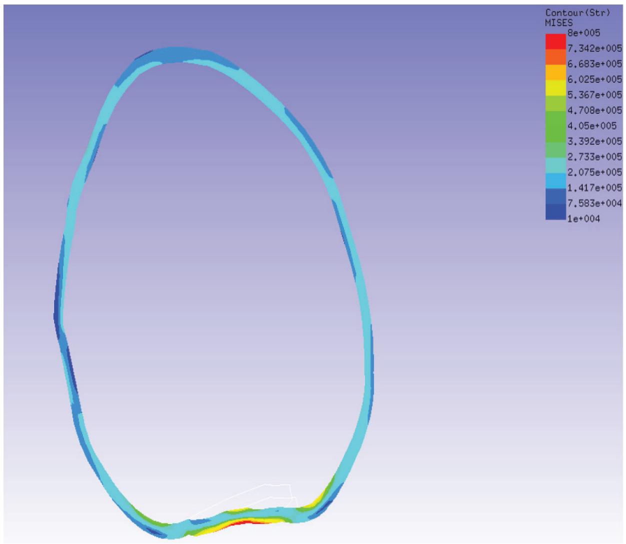

Fig. 9 Stress contours on a cut surface of the aneurysm.

Maximum stress was founded on the aneurysm wall and this maximum stress was roughly five times of the average stress in the normal artery. Since the large stress occurs at the bottom of the concave geometry, the measurement accuracy of the aneurysm geometry is important.

Because the geometry of the artery blood vessel near the inlet boundary is similar to a thick-walled cylinder. The stress distribution is very similar to the well-known hoop stress equation as follows.

$$\sigma_t = \frac{[p_1 r_1^2 (r_2^2 + r^2) - p_2 r_2^2 (r_1^2 + r^2)]}{(r_2^2 - r_1^2) r^2}$$

Where p is static pressure, r is radius and the suffix 1 and 2 is inside surface and outside surface respectively.

Using the hoop stress equation, the FEA computed result in Fig. 10 was verified. Figure 11 shows the theoretical solution of the radial hoop stress distribution of the thick-walled cylinder with the same conditions as the present artery. The

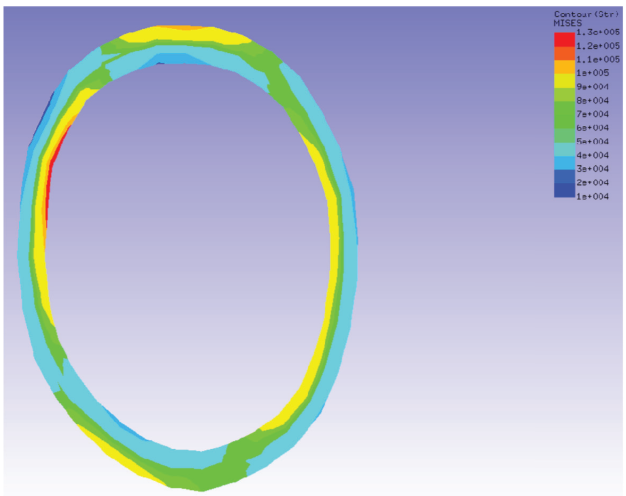

Fig. 10 Stress contours on a cut surface of the blood vessel near the inlet boundary.

circumferentially averaged stresses from Fig. 10 are almost similar to the theoretical solution in Fig. 11.

Figure 12 shows the unsteady blood pressure distribution model data that was prepared for the current study from the existing data [13].

Figure 13 shows the unsteady stresses in fatigue limit diagram-like format that was introduced from our unsteady FEA studies [13] compared with existing measured data [16][17] using the unsteady blood pressure distribution model data shown in Fig. 12. Figure 13 shows the strong potential to introduce the risk assumption methdology of aneurysm ruptures.

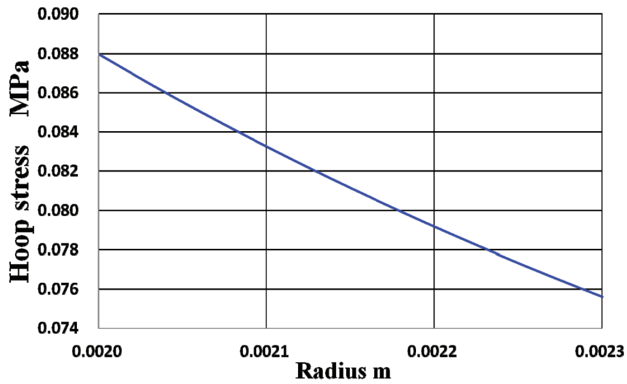

Fig. 11 Theoretical solution of the radial hoop stress distribution of the thick-walled cylinder with the same conditions as the present artery.

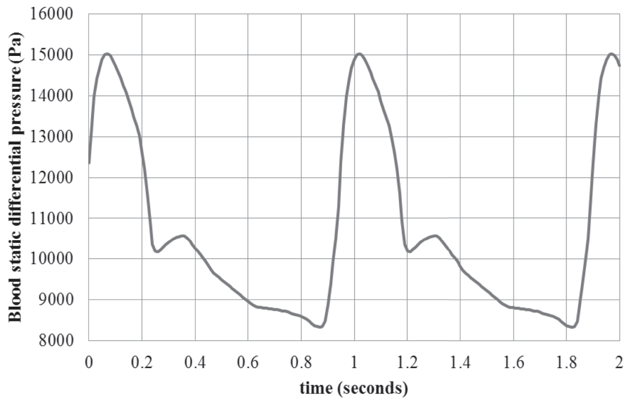

Fig. 12 Unsteady blood pressure distribution model data.

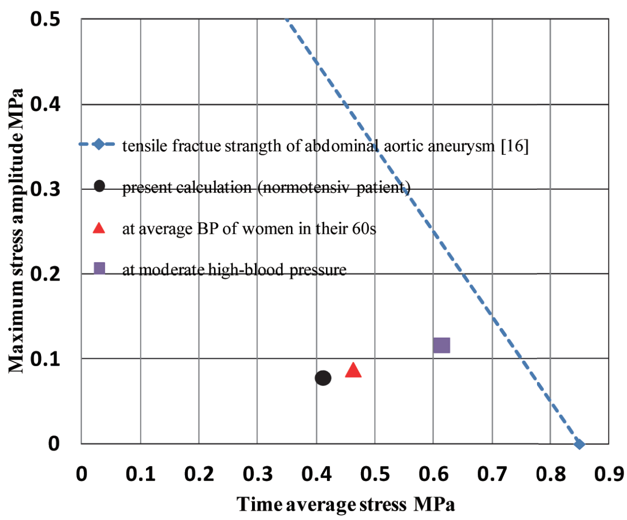

Fig. 13 Unsteady stresses in fatigue limit diagram-like format.

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 the second year study of our Earth Simulator Project shows that the unsteady structural analysis brings important information concerning the risk of aneurysm ruptures in case of large size cerebral aneurysms. The result shows the strong potential to introduce the risk assumption methdology of aneurysm ruptures.

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脳動脈瘤を含む血管系の定常及び非定常壁面応力の評価

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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。

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。

初年度の定常解析法を用いた研究により、解析で求まっ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ことが示された。

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、脳動脈瘤が発生しやすい脳動脈の部位は比較的心臓に近く、弾性材料として近似した構成方程式を用いても材料強度学的な評価を行うために十分精度ある解析が可能であると考えられる。2 年目の平成 24 年度は、対象とする脳動脈瘤と血管の部位に血圧も脳圧も加わらない初期形状を繰り返し計算により求め、この初期形状から解析を開始して、定常解析を行い、心臓から供給される代表的な血圧変動を上流境界条件とする非定常解析も実施し、定常及び非定常解析結果を用いて疲労破壊限界線図を作成した。既存の動脈瘤材料強度データとの比較により、この線図が脳動脈瘤の破裂または出血のリスクを評価する判断材料になりうる可能性があることを示した。

キーワード : 脳動脈瘤 , 血管 , 流体解析 , 構造解析