Acta of Bioengineering and Biomechanics
Vol. 9, No. 2, 2007

Laboratory tests for strength paramaters of brain aneurysms

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The presentation is focused on the analysis of biophysical properties of cerebral aneurysms, diagnosed and delineated in living human individuals. An aneurysm is a bulging out of a part of the wall of a blood vessel. The aim of our research was to delineate flow patterns inside the aneurysm and its parent artery, to estimate stresses at critical points of the aneurysm wall, to model the haemodynamic effect of different surgical and endovascular tools in order to define the optimal one in a particular case, and to estimate the likelihood of a later aneurysm rupture. For this reason we carried out a lot of different laboratory tests to analyse the mechanical parameters of the aneurysm wall. We made a comparative study of some material models reported in the literature to describe the mechanical response of arteries. These are models for incompressible materials. For this reason we perform uniaxial and biaxial measurements to have appropriate parameters for the models of underlying material.

Key words: arterial tissue, cerebral saccular aneurysm, material model, vascular biomechanical properties, viscoelasticity, flow and solid, finite element modelling

1. Introduction

Brain arterial aneurysms are common forms of arterial deformation occurring in about 5% of the adult population. The aneurysm is a bulge along the artery hanging there embedded in the surrounding tissue. In most situations, it usually appears around a joining of two arteries. This bifurcation is the part of the supplier of the brain vascular bed system so if its blow-out (rupture) causes unpredictable chain reaction, there is no safe solution without any side-effect to assure the patient against unpleasant consequences. In the majority of the cases, the patient does not notice anything from the presence of the aneurysm; in some cases, however, the aneurysm bursts leading to stroke and immediate death. At present, the therapeutic decision for unruptured aneurysms is made purely on the basis of the size and location of the lesion in a belief that those are the only factors influencing the likelihood of rupture. Our work will provide the physicians – and the patients – with an accurate prognosis of the disease. We note that besides of its scientific merit, the potential for providing information about the prognosis of the disease and about the optimal technique for its treatment would greatly enhance the value of the modern angiography systems.

The description of the flow in arteries is one of the great challenges of current fluid mechanics research. The flow is unsteady, the walls are flexible with complex elastic properties, the geometry is very complicated. The living tissue reacts to fluid mechanical changes in unpredictable ways which

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Received: February 16, 2007,
Accepted for publication: May 30, 2007.

again influences the flow properties. The elastic deformation of the wall interacts with the flow in a complex way. The non-Newtonian properties of blood also play a role in some cases. There are huge variations in all the parameters from patient to patient so it is difficult to draw general conclusions. In addition, it is extremely difficult to make in vivo measurements to test theories or simulations. Nevertheless, the importance of this area cannot be overestimated – the most important causes of death in developed countries are arterial deceases. Research budgets and public interest in this subject grow continuously.

2. Methods

2.1. Research strategy

The geometrical and morphological data as well as physiological parameters of the patients collected at the National Institute of Neurosurgery are combined with physiological information on the vessel wall and aneurysm wall provided by the Department of Human Physiology (Semmelweis Medical University, Budapest). The determination of the material parameters of the aneurysm wall is the first step of our work. Based on this information, we prepare 3D coupled (flow and solid) finite element models of the aneurysms. Strength calculations are done on these models in order to predict their mechanical strength (allowable blood pressure, etc.) and to compare the effects of different possible medical treatments. This is the second step of the research activity. The final goal of the research project is to work out non-invasive diagnostic tools detecting the presence of aneurysms and to assess the necessity of medical intervention. We have studied in detail the fluid mechanical behaviour of the blood near aneurisms on the one hand and the elasticity behaviour of the blood vessel wall on the other hand. These are performed using commercial software tools. Since the elastic deformation of the wall and the flow in the arteries are highly coupled, the solution is far from trivial. After performing simulations on rigid models for fluid mechanics and wall only models for the elasticity studies, the next step is to couple both phenomena, and the data will be transferred in each time step to provide time-dependent boundary conditions for both simulations. When the simulations in the realistic model are considered to be reliable, the haemodynamic and the wall stress data are carefully analysed and diagnostic criteria for intervention are derived.

2.2. Material parameters

One of the problems is that the different constitutive models in the literature are based on data from different types of arteries. Moreover, cardiovascular diseases like human cerebral aneurysm can only be studied in detail if a reliable constitutive model of the arterial wall is available. In order to get acquainted with the sterically inhomogeneous behaviour of cerebral aneurysms, first we measured in uniaxial tests the in vivo mechanical properties of the aneurysm tissue as a function of strain in different regions (thin and thick) and in different directions (meridional and circumferential). Saccular aneurysm specimens were obtained from patients and 3 mm wide strips were cut out. The strips were incubated in the Krebs–Ringer solution at 37 °C and were stretched in a uniaxial biomechanical apparatus by 200 μm in every 2 min until being torn. Force was computer recorded, and wall stress (σ) and strain (ε) were calculated. Biomechanical properties were cross checked with clinical data and histological results. The strips from aneurysms showed typical hyperelastic–plastic behaviour at the stress–relaxation tests. After this we present the uniaxial and biaxial clinical studies and on the basis of this we quantify material properties such as the Young's modulus.

2.3. Typical mechanical behaviour of arterial walls

In an in vitro experiment, the complex anisotropic materials of arteries do not change their volume in the physiological range of the deformation, consequently they can be regarded as incompressible – rubber-like – materials. Therefore we set ourselves the task to determine the mechanical properties in biaxial tests, too: uniaxial extension tests are certainly insufficient to completely quantify the mechanical behaviour of arterial walls. The mechanical behaviour of arteries was tested in appropriately oxygenated, temperature-controlled salt solutions. The exact shape of the stress–strain curve representing blood vessels depends on the anatomical site, but the general mechanical characteristics are the same. The artery is a heterogeneous system and it can be regarded as a fiber-reinforced composite biomaterial.

2.4. Our laboratory tests and results

In our program – based on our laboratory tests – we applied the most common strain-energy functions. Our uniaxial and biaxial test machines are connected to a computer. Incremental stretch resulted in stress relaxation of the tissue specimens. Tensile strength of strips from unruptured aneurysms was significantly higher than that of the ruptured ones. We conclude that a uniform weakening of the aneurysm walls leads to their eventual rupture. Based on these experiments we calculated the material parameters of the Mooney–Rivlin and Neo–Hooke nonlinear hyperelastic models (see the table). Making use of simple finite element tests all material parameters were checked. Uniaxial techniques used frequently to characterize the biomechanics of living tissues and biocompatible materials provide rather restricted quality and amount of information about the two-dimensional behaviour of the tissue samples. Limitations of isometric strip and ring preparations are well recognized, because the isometric force and the length changes provide only one-dimensional characteristics of the vessels. As an example, biomechanical characterization of circumferential and meridional strips of a saccular cerebral aneurism individually does not reflect the mechanical interaction between these perpendicular segments. In order to study the anisotropic stress–strain characteristics of miniature samples of living soft tissues, as well as living tissue equivalent and biocompatible materials, we developed and tested a novel planar biaxial (X–Y) system. As can be seen in figure 1, our biaxial measuring system is based on two force meters positioned perpendicularly to each other. The design allows measuring as small as 2×2 mm miniature tissue region located between the holders of a 5×5 mm sized sample. Computer-aided large strain simulations were carried out under planar stress–strain conditions in order to reveal stress development and distribution within a linear elastic sample. The force meters were tested using samples of biocompatible isotropic silicone rubber sheets cut to 7×7 mm size.

Table. Linearly elastic, Mooney–Rivlin and Neo–Hooke material parameters calculated from experiments

	ε		σ [MPa]		E [MPa]	
	Feminine	Masculine	Feminine	Masculine	Feminine	Masculine
Circumferential, thick	1.80	1.10	0.70	0.14	0.39	0.12
Circumferential, thin	0.90	0.60	0.93	0.55	1.34	1.08
Meridional, thick	0.40	0.70	0.40	0.34	0.65	0.49
Meridional, thin	0.60	0.55	1.00	0.84	1.67	1.52
	Mooney–Rivlin				Neo–Hooke	
	C10		C01		C10	
	Feminine	Masculine	Feminine	Masculine	Feminine	Masculine
Circumferential, thick	0.052	0.016	0.013	0.004	0.065	0.020
Circumferential, thin	0.179	0.144	0.045	0.036	0.224	0.180
Meridional, thick	0.087	0.065	0.022	0.016	0.109	0.081
Meridional, thin	0.223	0.203	0.056	0.050	0.028	0.253

Making use of angiography we can build a model of an existent aneurysm, and this model can also be used for finite element analysis calculations. This is the other part of our research. The angiography allows us to build a real three-dimensional model with the original geometry. Using the data of aneurysm material parameters the system could help the doctors to answer the question whether or not a patient needs an urgent operation. Many different tests are needed to declare that the system works reliably. Thanks to the engineers of General Electric, we are able to gain three-dimensional geometrical data from angiography. The well-known finite element method was applied as a numerical approximation in these two different systems. We used MSC Marc and Ansys for both strength calculations. Figure 3 shows the details of the calculated wall stresses at the maximum systole pressure at the real geometry. Our connected system is able to calculate the dynamic flow parameters of blood and from this effect it can determine the displacements and stresses in the vessel wall. In the future, we plan to continue our work with the refinement of the finite element mesh and then we want to simulate the load bearing capacity of the rupturing balloon of the aneurysm sack.

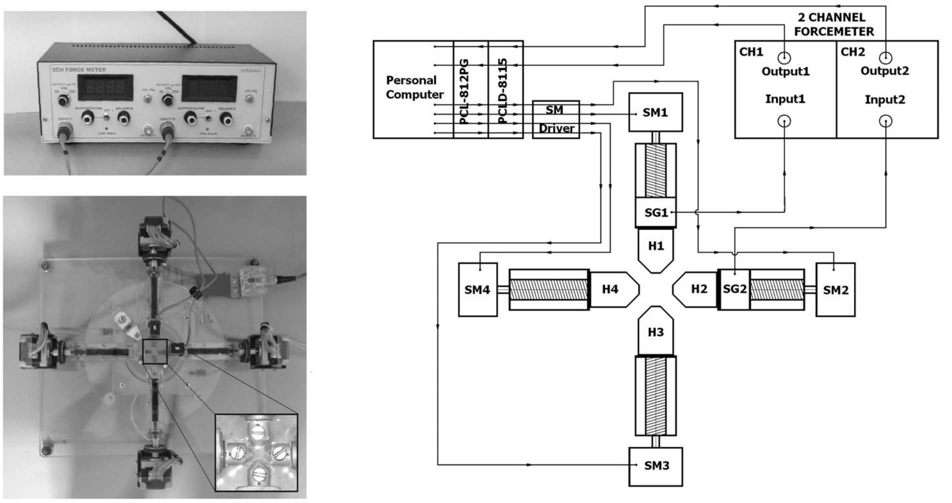

Fig. 1. Major components and the block diagram of the biaxial setup

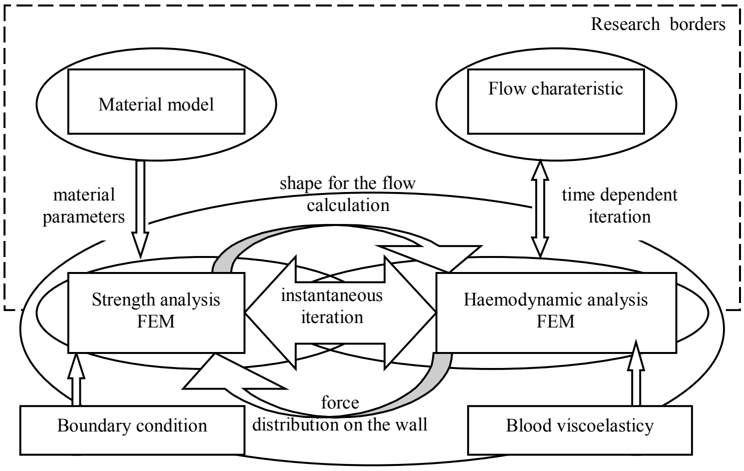

Fig. 2. The basic mechanism of the model

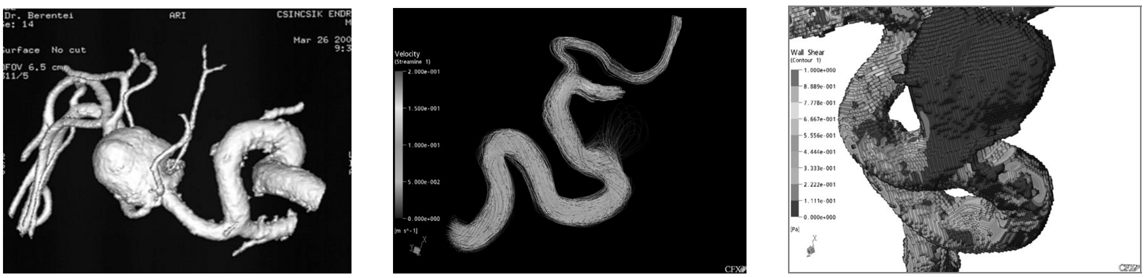

Fig. 3. General electric angiograph picture. Velocity parameter. Shear stress in the artery wall

3. Summary

All the models discussed above are based on phenomenological approach in which the macroscopic nature of blood vessels is modelled. From this study it may be concluded that there is a need for a constitutive model which describes the viscoelastic behaviour of the human arterial wall. In cooperation with the co-workers of the National Institute of Neurosurgery and Human Sciences we made the first steps towards the complex numerical simulations of brain aneurysms.

Acknowledgement

This work was done with the help of an OTKA grant (principal investigator Dr. István Szikora, Nat. Inst. of Neurosurgery).

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