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On the mechanics of cerebral aneurysms: experimental research and numerical simulation

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Abstract. This research extends existing experimental data for CA tissues [1, 2] and presents the preliminary results of numerical calculations. Experiments were performed to measure aneurysm wall stiffness and the data obtained was analyzed. To reconstruct the geometry of the CAs, DICOM images of real patients with aneurysms and ITK Snap [3] were used. In addition, numerical calculations were performed in ANSYS (commercial software, License of Lavrentyev Institute of Hydrodynamics). The results of these numerical calculations show a high level of agreement with experimental data from previous literature.

1. Introduction

A cerebral aneursm (CA) is a vascular disease of the human brain, with an incidence of approximately 1 in 50 people [4]. Despite their relatively high occurrence, CAs are rarely diagnosed. It is of interest to neurosurgeons to know whether a given aneurysm is likely to rupture or not. The statistics inform us that approximately only 1-2% of unruptured aneurysms will rupture at some future point in time. To determine which aneurysms are likely to rupture, it is necessary to investigate: local stiffness of the vessel wall, the wall structure of the CA, the geometry of the CA, biochemical processes in the vessel wall, the hydrodynamic parameters of the flow through the CA, etc. It is a tremendous problem to consider all of these simultaneously, but doing so is nevertheless expedient: the accuracy of the prediction for aneurysm rupture increases with knowledge of the aneurysm. The mechanical properties of unruptured CAs were first considered in [2] and the most recent contributions to this field of research can be found in [5]. The hydrodynamical properties of unruptured CAs have been investigated in many studies, including, but not limited to, those in [6] and [7]. In all of the studies published, the results from different experimental approaches were coupled. This is because the mechanism of aneurysm formation is not currently well understood. The aim of recent experiments has been to obtain some biophysical markers to help predict future CA rupture, with this particular paper investigating different techniques for measuring the relevant data. In particular we desire to obtain values for measurement error and vessel elasticity, for the cases of three different patients presenting an CA.

Many researchers consider numerical calculations to be the best method for predicting the rupture of an aneurysm. Generally we agree with this, but only when the relevant calculations

are performed in an adequate way. Firstly, the validity of the geometric model needs to be determined. In addition, sometimes boundary conditions may lead to interesting results [8]. However, it is of paramount importance to determine whether these boundary conditions accurately model reality, or whether they are unrepresentative of reality due to some shortcomings of the experiment.

2. Materials and methods

2.1. Population

This paper considers three cases, with each case being a tissue exhibiting an CA from distinct patients. Ethical considerations made by the Novosibirsk Centre of Neurosurgery dictate that cases will be denoted using the following convention: case X, where X represents the initial letter of the patient's surname. All patients in this study exhibited a saccular CA.

Table 1. Detailed patient information.

ID	Age	Gender	Smoking	A history of diabetes	Aneurysm location
CaseR	63	Female	No	No	MCA
CaseK	63	Female	No	Yes	MCA
CaseV	63	Female	No	No	ACA

Table 2. Cross-sectional area parameters for the samples.

ID	Mean thickness (mm)	Mean width (mm)	Mean cross-sectional area (mm2)
CaseR	0.2	3	0.6
CaseK	1.8	5	9
CaseV	0.85	3.75	3.19

3D models for these aneurysms were produced using ITK-Snap software [3], and the shape (look at Figure 1) of each sample was optimized for using in ANSYS software (licence of Lavrentyev Institute of Hydrodynamics).

2.2. Mechanical technique

Following neurosurgery treatments, tissues exhibiting an CA were harvested and delivered to the laboratory, being preserved using sodium 0.9%, +2°C-+5°C. As was shown in [9], results for refrigerated aneurysms vary slightly with respect to the temperature of storage. At the laboratory, the rupture of the tissues was investigated using a rupture machine (Zwick/Roell Z010, Germany). The tissue under consideration perishes very quickly, and so this affords only one series of experiments for each case of CA tissue. The speed of pulling was the same for all experiments and equal to 1mm per minute.

For each of the three cases, we conducted experiments using several different values of the pulling force. We now proceed to describe the method for these experiments. We were unable

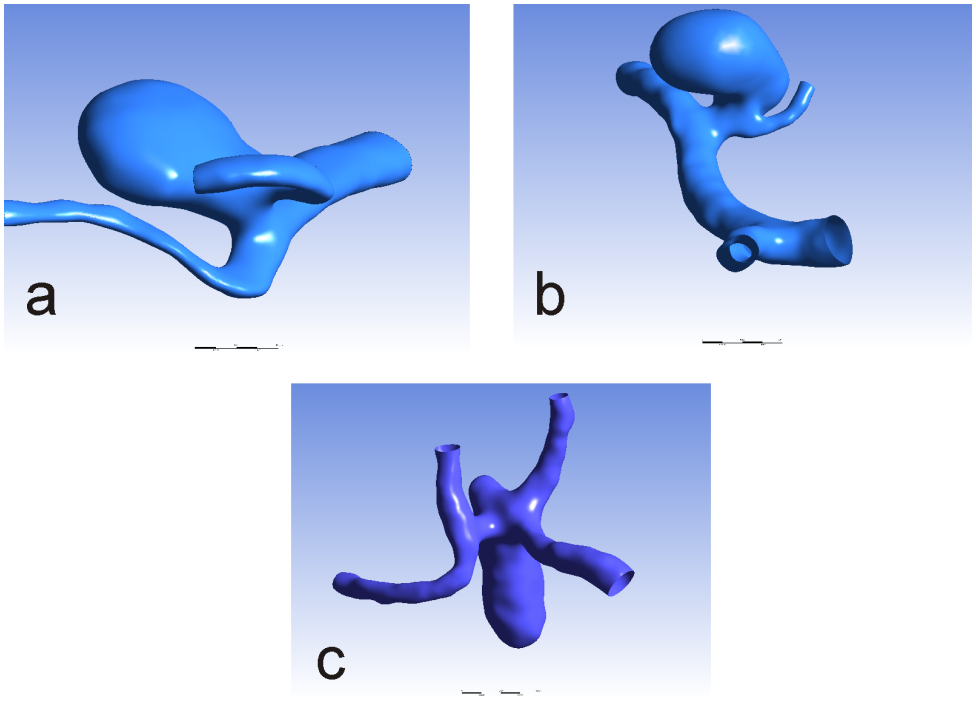

Figure 1. 3D Constructed model of samples. Case R (a), Case K (b), Case V (c).

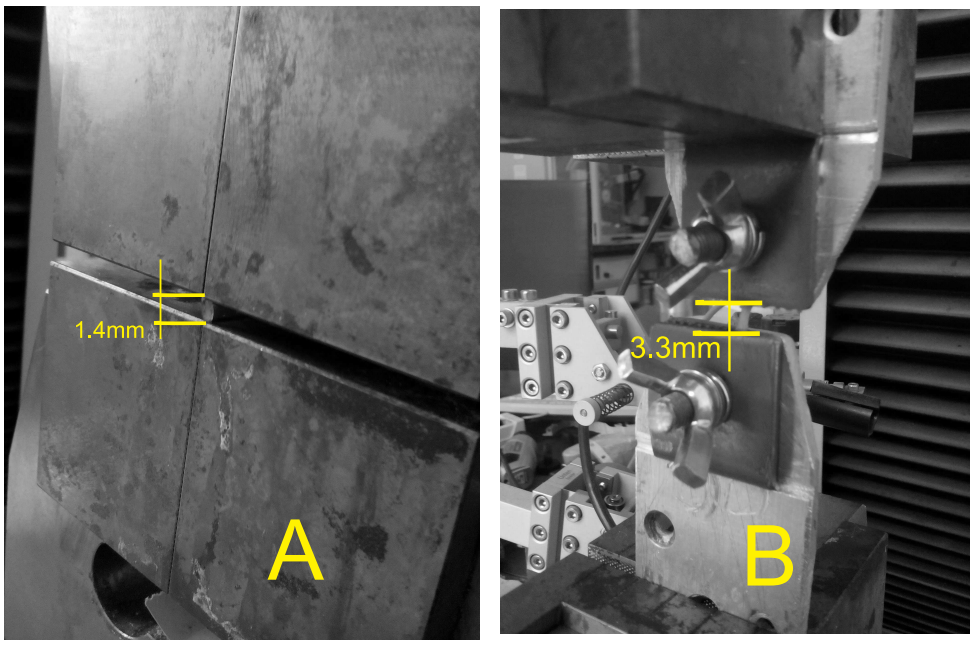

Figure 2. Method of mechanical experiment. A – tissue was fixed directly to the machine. B – tissue was fixed using anchoring device.

to find any prior research data regarding measurement error, but we are without doubt that

such errors were present. We therefore calculated the error for each of the three cases of CA tissue. The first step in calculating this error was to perform measurements with the tissue present in the machine and afterwards to perform measurements, for the same value of force applied, without any material fixed in the machine. After each stage of the experiment, i.e. after subjecting a sample to a given force, the sample was hydrated with sodium 0.9% . We then calculated the mean average of the data for both sets of measurements (tissue present and tissue absent).
For the Cases R and K the aneurysm tissue was in the machine exactly as shown in Figure 2. The small dimensions of Case R aneurysm tissue only permitted us to perform one measurement for this sample. The purpose of this particular experiment was to determine mechanical properties of the aneurysm tissues, such as their Young's modulus, and compare this result with those previously determined in [1].

2.3. Numerical calculations

Numerical calculations were performed in ANSYS (commercial software, License of Lavrentyev Institute of Hydrodynamics), with the rigid walls model^{TM} being used for this stage of our research. The Navier-Stokes equations were solved with a steady inlet flow rate, and for all cases the blood flow rate was taken to be as in [10]. No slip condition was used for the walls. Blood was assumed to be a viscous incompressible fluid with rheology as described in [11]. The calculation was performed using a homogenous mesh.

3. Results

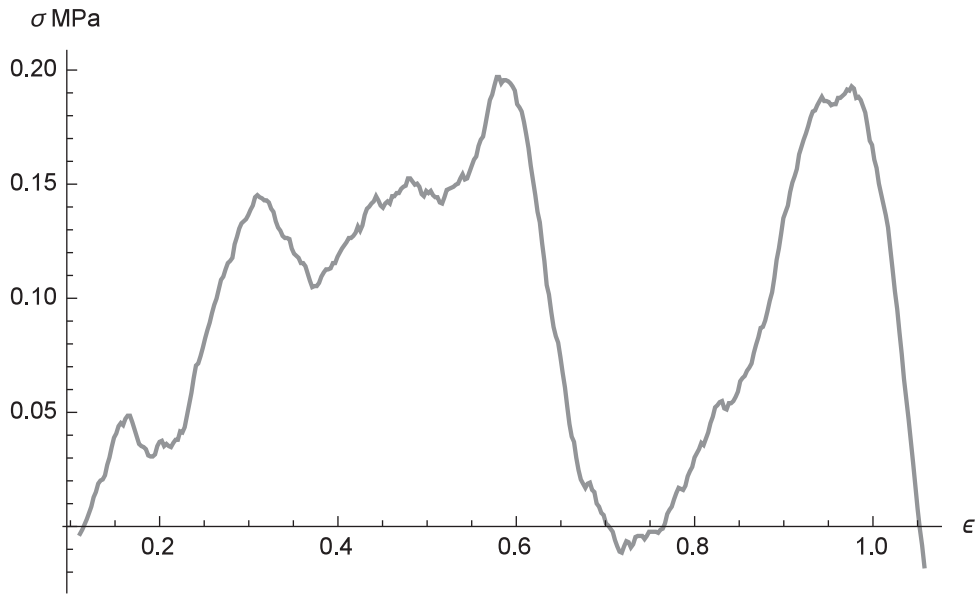

Figure 3. Stretch-strain graph for Case R Aneurysm.

The cross-sectional area of each sample was measured. This data is shown in Table 2. For the first experiment (Case R), the force was applied until the tissue ruptured. As can be seen in Figure 3 there are two local maximums, corresponding to the fact that the tissue ruptured in two distinct stages, due to the tissue consisting of two distinct layers. Firstly the tissue ruptured approximately midway between the fixing clips. This event corresponds to the point on the curve where a decrease occurs following the first local maximum. Following this, the limit of

elasticity of the first layer was reached, and then the second layer also ruptured (corresponding to the second local maximum in Figure 3). For the second experiment nonelastic deformation is shown in Figure 4 was performed. The third sample was investigated with another technique

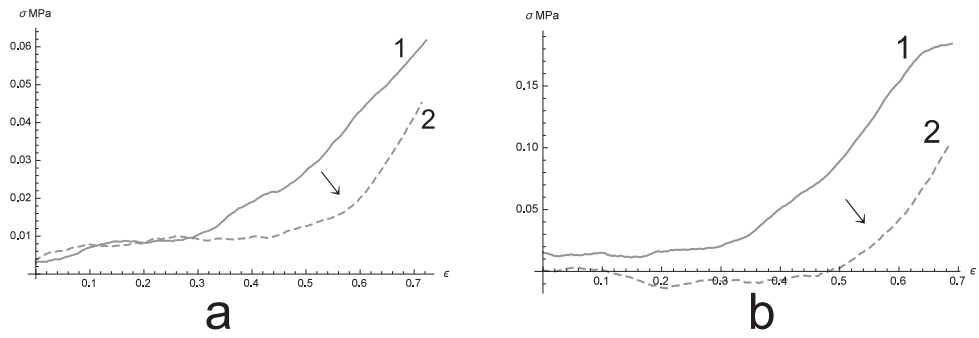

Figure 4. Stretch-strain graph for Case K (a) and Case V (b) Aneurysm. After the deformation 1 deformation 2 was performed

of anchoring. In Figure 4 nonelastic deformation is also shown. The ultimate stress for each sample was reached. The values of ultimate stress are $0.2, 0.19, 0.15(MPa)$ for the cases Case R, Case K and Case V respectivly.

The idea of numerical calculations at this stage of the research is to show that the reconstructed

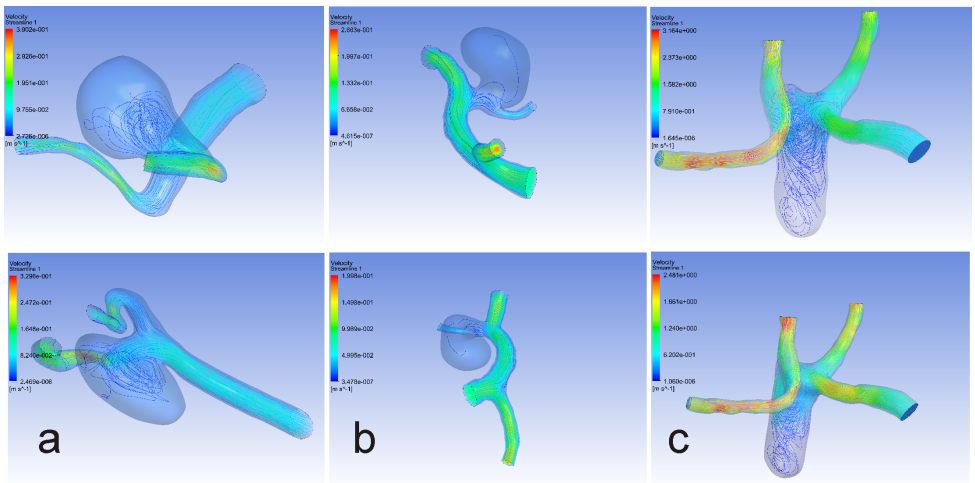

Figure 5. Velocity streamlines for cases Case R (a), Case K (b) and Case V (c). Maximum (top) and minimum (bottom) inlet blood flow rates are used for the calculations (correspondint to [10]).

3D models are plausible and able being used for numerical calculations. The values of hydrodynamical quantities (velocity, pressure) calculated through the vessel model show (look at Figure 5) have a good agreement to experiment data [10]. This fact is not obvious due to only good reconstruction gives plausible values of the pressure and velocity.

4. Discussion

In this study we discovered different behaviors of brain aneurysm tissue under the application of a pulling force. Despite the fact that the samples in Cases R and V have very similar character-

istic parameters (see Table 2), the ultimate stress curves are completely different. For Case K the value of the ultimate force, i.e. the force corresponding to ultimate stress, was as expected: the value of the ultimate force for Case K was higher than for Cases R and V. It would be of interest to conduct experiments with similar tissue, using the technique of Scott [2], in which tissues were investigated using the technique of sodium pressure.
The structural parameters of the wall wasn't considered. At the date data shows that the amount of collagen different type and fibber orientation give a food for thought. Implementation of coupled information may be very fruitfully to understand the direction of aneurysm development: whether it will stabilize or rupture.
The experiments presented in this paper did not consider the structural parameters of the vessel walls. Recently obtained data indicates that the amount of different types of collagen, and the orientation of fibres, may influence the results. Analysis of coupled information will be necessary to understand the future direction of aneurysm development i.e. whether an aneurysm with stabilise or rupture.
Our surgical practice shows that even very thin diverticula on the surface of aneurysms can be highly elastic. Therefore, considering only the parameters of an aneurysm's size and its elasticity is insufficient. The mechanical experiment for case R demonstrates this insufficiency: two distinct stages of rupturing were necessary for the complete rupture of a very thin aneurysm. For the case of a living patient, this result translates to the likely scenario of thrombosis of the aneurysm occurring following the first stage of rupture.
Our ongoing research will extend the experimental data obtained. We are of the opinion that rigid simulations performed in many previous research papers [1, 6] do not produce accurate models. Only FSI simulations tend to produce successful models of the biomechanical processes occurring in an aneurysm. However, it is debatable which the optimum type of FSI simulation to choose is. It needs to be determined how many factors, e.g. non-linear elasticity, non-homogeneous mesh grid, have to be considered to reach a sufficient level of accuracy for the model. Also time and expense constraints for the calculations need to be considered. We intend to obtain data for FSI for the samples under consideration, and to consider the effect that variations in the wall structure of aneurysms will have on the results.

5. Conclusions

This paper forms a preliminary part of our ongoing research. During this stage we have been building connections with neurosurgeons and have decided upon the logistical scheme for delivery and storage of the aneurysm tissue. Statistical data processing was applied to the data obtained in our experiments. The stretch-strain data, obtained by our experiments, shows a high level of agreement with those found in previous literature. The different data obtained by experiments in this paper will be used in our ongoing research. This research includes determining material parameters for use in ANSYS software, and determining the ultimate force required to rupture an aneurysm in FSI problems. numerical simulations, performed using the rigid walls model^{TM}, allow for the accurate construction of 3D models of CAs. Moreover this study represents our first step in producing transient patient specific numerical calculations for the FSI problem.

Acknowledgments

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