The study of the strength properties of the human dura mater: the experience of one research center

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Abstract. The study of a human dura mater is an important task of modern neurosurgery for trauma, as well as surgery for changing volume fractions of the liquid media of the brain (hydrocephalus, hypertension, etc). This paper presents the first results of a study of the strength properties of a human dura mater. A description is given of the preparation of the sample for the experiment and the experimental technique. A comparison was made of the strength properties of the studied samples with samples of cerebral aneurysms and healthy cerebral vessels. For the first time the differences between dependence of stress and strain obtained from traverse and video extensometer are shown, which are statistically significant ($p < 0.98$).

1. Introduction

Dura mater (DM) is an elastic membrane of the brain that separates the brain from the skull. The structure of these material consists of two components: the periosteal/endosteal layer and the meningeal layer [1]. This membrane of the brain performs a dividing function, however the study of its strength properties is extremely important, since it can be damaged during car accidents and other events. Its mechanical properties are extremely important due to several aspects. Firstly, as already mentioned above, it can be significantly damaged during accidents, and in such cases a flap of biocompatible tissue (up to 100 sq cm) is required, which is necessary to restore the dura mater. Such tissue should have similar mechanical and transport properties, since in addition to the brain-retaining functions, DM is involved in cerebrospinal fluid transport (via arachnoid granulation) in the intracranial space. Secondly, special techniques for excision of the dura mater are used in the treatment of the Moyamoya disease, in those cases when recirculation is restored on its own through large arteries located in the dura mater.

The most common methods for study of DM is the investigation of the mechanical properties of cadaveric specimens. This is usually associated with ethical standards (the impossibility of taking a sample of DM from a healthy person within the framework of ethical protocols) and established clinical protocols. In a clinical protocol developed jointly with the Federal Research Center (Novosibirsk), a DM sample is taken during a microsurgical treatment of vascular pathologies of the brain at the time of the end of the operation when a DM flap is sewn back, a small piece of tissue is separated, which is superfluous due to a small swelling of the DM tissue resulting from the microsurgical intervention.

The aim of this work was to evaluate the mechanical properties of fragments of dura tissue of one patient, cut in different directions from one specimen of a living patient. As described...
above, the collection and transportation of samples was performed according to the clinical protocol approved by the ethics committee. Particular attention was paid to the zone of small deformations.

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** Dura matter specimen before the experiment. Zones influenced by the clamps, as well as the free zone of the sample, are noted.

**Figure 2.** The specimen prepared for the loading. Marks are glued to the sample with the water-resistant glue.

### 2. Methods

**Ethical protocol and transportation**

Dura mater specimen were obtain during neurosurgeries as described above. Intracranial aneurysm tissue specimens were harvested during the microsurgical clipping. This part of research was carried out in cooperation with Federal Neurosurgical Centre of Novosibirsk. The obtained tissue was preserved with saline 0.9% at $+2\div5^\circ$ C during transportaton (12÷48h). According to [2] refrigerated vessel walls, being loaded, show slightly different results from freshly obtained tissue with relation to used temperature. Similar protocol was used earlier in the study of the rheology of cerebral aneurysms. After delivery to the laboratory, rectangular shape is cut from the specimen, and its size measured (Fig 1). Then the sample was fastened in tensile machine Instron 5944 and a series of experiments was performed.

**Experimental setup protocol**

The most common experimental approach is uniaxial loading on a tensile machine. A similar approach was used in such works as [3, 4, 5] for vascular tissues and in [6] and others. Standart Instron clamps with a small notch were used for fastening.

An uniaxial tensile machine Instron 5944 was used for mechanical testing of the dura matter. Despite the fact that one of the methods of sample preparation is the cutting a sample in the "dog-bone" shape, we used a rectangular shape of the sample for testing, firstly for ease of processing of experimental data, and secondly due to the inability to prepare samples of sufficient width. Our clinical approach to tissue collection assumes the maximum safety of tissue extraction for the patient, so only a small fragment of DM is taken, which would be excised in any case.
A video extensometer (lens from Fujifilm) was used to measure the local deformation in the sample. Small bright plastic marks (1.5 mm diameter) were glued on the sample for the extensometer to capture gauge length (Figure 2). Due to the very limited amount of samples and their small size it was not always possible to measure the local deformation correctly. The focal length of the video extensometer lens is 16mm.

The usage of the video extensometer to measure local deformation allows to minimize the boundary effects, which are likely to happen in the case of measuring only traverse strain. There are known effects caused by the clamps, such as slippage of the sample: if the clamps are too loose the part of material under them can extend as well as the part outside the clamps or even slip out [7]. Also a damage to the material can be caused while fastening the sample, which causes a zones of already partly ruptured material which negatively affects the accuracy of obtained experimental data. All of that emphasizes the need to use other means of measurement apart from crosshead strain.

For each sample we performed a series of experiments each of those was divided into several stages. While carrying out the experiment, we took into account such a well-known phenomenon for biological tissues, as preconditioning [8]. We applied this technique for the initial stages (1th-5th stage for each elongation step depending on the sample), and during next stages the influence of this condition was not noticed. During our study we established that there’s no need to perform more than two preconditioning cycles. For each stage of the experiment, the specimen’s initial elongation was the same: i.e. after the completion of each stage of the loading, the machine’s clamps returned to the original, program defined position. During the experiment the sample is positioned in the sodium saline heated to the temperature of the human body. Speed of pulling was equal 2 mm per minute and was the same for all experiments. In each experiment, the sample lost its elasticity. For each sample, its loading was performed until it was separated into two disconnected segments (or a visible discontinuity of the sample appeared).

3. Results and discussion
The literature reports that ultimate stress for DM tissue reaches 3÷7 MPa [6, 9]. In the course of the experiment, we were able to confirm the similarity of the ultimate stress with the one mentioned in other works (see Table 1). However, in this paper, the main focus is on the zone of small deformations. The fact is that DM in its natural conditions is subjected to pressure up to 1 atm + (100÷200 mm Hg), adheres to the skull and experiences significantly less deformation than, for example, cerebral vessels.

Table 1. Patient data. The values of ultimate stress and strain for the ruptured, unruptured aneurysms and healthy artery were taken from [10]

| Material               | Mean ultimate stress (MPa) | Thickness (mm) |
|------------------------|----------------------------|----------------|
| Dura matter 1          | 3.16171                    | 0.8            |
| Dura matter 2          | 4.03245                    | 0.7            |
| Dura matter 3          | 2.47431                    | 0.9            |
| Healthy artery         | 2.4794                     | 0.4            |
| Unruptured aneurysm    | 1.297787                   | 0.05÷0.8       |
| Ruptured aneurysm      | 0.88516875                 | 0.15÷0.8       |

In the course of the experiment on the mechanical loading of DM samples, it was possible to obtain strain-stress diagram data for the strain data obtained both from the crosshead and
from the video extensometer with which tensile testing machine is equipped.

Figure 3 shows the strain-stress diagrams for the plot of small deformations of one of the samples (such an unusual representation of the stress-strain diagram is caused by two-channel measurement), and Figure 4 shows the relative differences between the data of these two measurement channels.

\[
\delta = \frac{(\epsilon_1 - \epsilon_2)^2}{\epsilon_2},
\]

where \(\epsilon_1\) is the deformation obtained captured through the video extensometer, and \(\epsilon_2\) is the crosshead deformation. As can be seen from Figure 4, these differences, explained by the Formula (2) are important precisely for small strains and are leveled with increasing strain of the sample. We calculated the Chi-square test for 35 measurement points (p-value=0.9807). The null hypothesis is the fit of the traverse crosshead deformation to the deformation measured by the video extensometer. This study shows a significant difference in the dependence of stress on strain in the case of reading data from the crosshead and from the video extensometer for small deformations.

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\chi^2 = \sum \left[ \frac{(\epsilon_1 - \epsilon_2)^2}{\epsilon_2} \right].
\]

4. Conflict of interests
Authors declare no conflict of interests.

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