Experimental study of the mechanical properties of materials for physical modelling of biological tissues

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Introduction

Testing of the different modes of surgical devices includes tests on autopsy material. In this case, the major limitations are difficult biological samples acquisition, the heterogeneity of tissue properties and the dependence of mechanical properties on storage time and temperature.
An alternative to testing on autopsy materials is the modeling of surgical intervention. Modeling can be physical, analytical and computer-simulated.
Computer-simulated modeling (finite element analysis) has the advantage of unlimited ranges of parameter changes in the study. However, the parameters for the analysis are rarely fully described for biological tissues. Also, the computer modeling is a solution to a simplified task, which do not reflect all processes occurring in a real operation. Analytical modeling offers investigation of mathematical models of biological tissues, but the modeling of surgical exposure is also simplified.
Physical modeling offers a possibility to study the effect of surgical intervention on the physical model of tissue (phantom). The physical model simulates the target tissue. It is made from material that fits best the required criteria, for example the Young's modulus. Therefore, in tests on blood vessels, for example, it would be much easier to have a model that could mimic the physical vascular properties.
A paper review of the values of the Young's modulus for various vessels and their layers showed that according to [1], the static Young's modulus of the coronary artery is 2.3 MPa with a tensile pressure of 100 mm Hg. For the abdominal aorta the Young's modulus lies in the range from 0.1 MPa to 1.2 MPa at a tensile pressure from 1 mm Hg. to 90 mm Hg. [2]. According to [3], the Young's modulus of the coronary artery in men, depending on age, lies in the range from 0.9 MPa to 5 MPa. For women, the range is from 0.9 MPa to 4 MPa.
Physical models allow tests on large volumes of samples, in comparison with the autopsy material. Homogeneity of phantom properties increases the repeatability of results. The method of physical modeling allows to more accurately estimate the influence on tissue comparing to analytical and finite element modeling.
Materials used for physical modeling are often made by mixing two components: the main component (MC) and the supplementary one. When the ratio of MC in the mixture changes, the mechanical properties of the model also change. In this paper, the criterion for the similarity of material and biological tissue are mechanical characteristics. The main mechanical characteristic of the material is the Young's modulus, so the selection of the material is based on the correspondence of the Young's modulus to the real tissues.
For some materials, there is a wide range of values. It is due to the dependence of the mechanical properties on the ratio of mixing components in it. Ranges of possible values of the Young's modulus for some materials are presented in Fig. 1. [4]

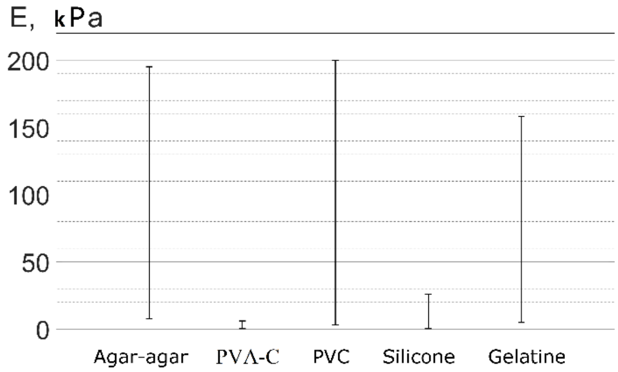

Figure 1: Mechanical properties of phantom materials

In [5] the Young's modulus for pure gelatin with concentrations of 25-30% was calculated. The range of values is 0.07-0.1 MPa. In [6] the values of the Young's modulus for gelatin mixtures are 0.4 kPa for gelatin-water mixture, 0.8 kPa for gelatin-water-sugar, 0.6 kPa for gelatin-water-sugar-citric acid.
In [7], there are dependences of the Young's modulus of gelatin and agar-agar on their concentrations $E_{gel} = 0,349 \cdot C^{1,87}$, $E_{agar} = 0,0034 \cdot C^{2,09}$, where C is the concentration in g/l of gelatin and agar-agar, respectively. Although, the chosen ranges of concentrations were not justified and these equations are applicable only within these ranges.
Taking into account the dependence of the mechanical properties on the ratio of mixing components, the most accurate simulation of the mechanical properties of biological tissue is possible by choosing the material of the most suitable concentration.
It is useful to cover the widest possible range of material properties to be able to mimic any type of biological tissue using chosen materials. According to the data shown in the Fig. 1, it is wise to choose gelatin and silicone for the current study. Gelatin is the most widely used material for physical models and therefore its mechanical properties at different concentrations are very useful to compare and refine the results of other studies. PVA-C could also be used

in this study but its drawback is a complex and long preparation procedure, especially for multi-layer structures. Unfortunately, biological tissues usually require multi-layer physical models.

However, as it was shown previously, in existing studies of the mechanical properties of materials for physical models, there is no clear dependence of the mechanical properties on the concentration under compression and stretch over the entire range of concentrations.

In this paper, we investigated the widest ranges of possible ratios of the components to be mixed when testing materials for compression and stretch. The dependence of the Young's modulus on concentration was investigated.

Materials and Methods

Materials

In the current work studies were conducted on gelatin and silicone. The dependence of the mechanical properties of these materials on the value of the mass fractions of their MC: gelatin and silicone gel, respectively, was investigated.

Mass fraction of MC can be expressed as:

$$\omega = \frac{m_{MC}}{m_{Mixture}} \times 100\% \qquad (1)$$

where m_{MC} is the mass of MC, $m_{Mixture}$ is the mass of the mixture.

The solution for the samples was made from gelatin ("Dr. Oetker" brand) by adding water at a temperature of 60-70°C. It was poured into cylindrical containers (for compression tests) or flat containers (for tension tests) and placed in the refrigerator (temperature + 4°C) for 6 hours until complete solidification. To facilitate the extraction of samples, the forms were pre-lubricated with petroleum jelly.

Gelatin was tested for compression with a mass fraction ranging from 2% to 50%. The tensile samples were tested with a mass fraction of MC ranging from 10% to 40%.

The types of silicones vary significantly from soft to hard ones, the latest can be used for example for tires production. To simulate biological tissue, that is rather fragile, we searched the softest silicone. To measure the hardness of low-modulus materials (plastics, elastomers, rubbers, etc.), a Shore hardness scale is used (fig. 2) [8].

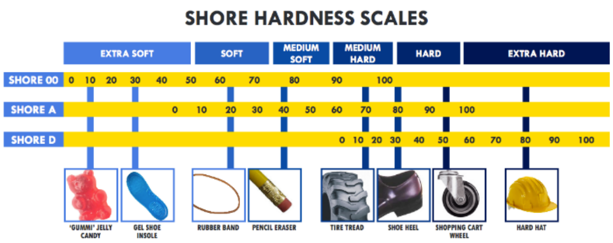

Figure 2: Shore hardness scale

From fig. 2 the softest silicone (Extra soft) is type 00. But silicones of this type are too expensive, therefore, type A was chosen for the tests. Among this type, a silicone compound Alcorsil 315 based on tin was chosen, its technical characteristics are given in the tab. 1. Compound consists of two parts - silicone gel (part A) and hardener (part B).

Table 1: Parameters of Silicone Alcorsil 315

Parameters	Values
Ratio by weight	100 A: 5 B
Viscosity of the mixture, cP	10,000 ± 2000
Life time	20-40 min
Curing time, at 23 ° C	4-6 hours
Shore A / D hardness	15 ± 2 A
Density, g / cm3	1.08
Tensile strength, MPa	≥2.75
Breaking strength, MPa	≥1.77
Elongation at break,%	≥363
Linear shrinkage,%	<1

From tab. 1, the recommended ratio of weight parts (A:B) is 20:1. the upper and lower limits of silicone hardening were investigated within ± 900%, which is from 1:1 to 200:1.

For ease of mixing, the mass ratio was converted into a volume ratio. Corresponding component densities: ρ_A = 1,125 g / cm^3, ρ_B = 0,96 g / cm^3.

The solidification threshold ratio was investigated in droplets of small volumes. The suitable lower limit of volume ratio was 2:1 and the upper limit was 40:1. At lower ratios, a homogeneous compound was impossible to achieve due to instant solidification. At larger ratios no solidification occurred even after 24 hours. The later studies showed that samples with ratios 2:1 and 3:1 did not solidify in the syringe, but only in air and therefore were also excluded from the experiment.

Thus, Alcorsil 315 was tested within the range of a mass fraction of 75 - 97.6% for tensile and 80 - 97.6% for compression.

All samples were divided into groups by material, type of test and mass fraction of MC. Each group contained 3-5 samples.

Methods

For compression, the samples were made in form of cylinders 10 mm long. The nature of the destruction of gelatin samples in compression tests depended on the concentration of MC. Low concentration samples typically split into 3-5 pieces, while high concentrations samples crushed. Dumbbell samples for tensile tests were cut with a die. During the stretching, the wide part of the sample slipped out of the clamps; therefore, to increase the friction pieces of insulating tape were glued for the gelatin samples and adhesive tape for the silicone samples (figure 3). The rupture of the silicone samples occurred layer by layer.

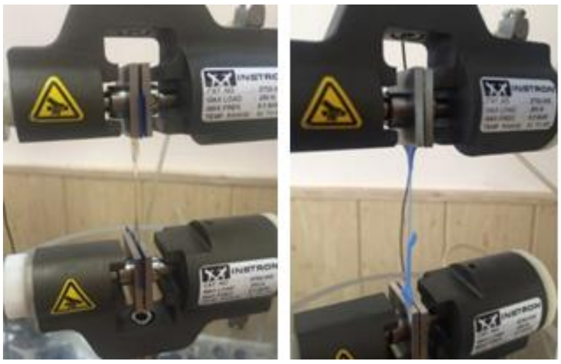

Figure 3: Stretching test of gelatin (left) and silicone (right) samples.

The thickness of the samples was measured with a micrometer. In the test on the Instron 3365 test machine, the dependence of the force on elongation was recorded. Then, from the experimental data, the dependence of the stress on the deformation was calculated as follows:

$$\sigma = \frac{F}{S};\ \varepsilon = \frac{\Delta l}{l} \qquad (2)$$

where F is the registered force, S - initial cross-sectional area of the sample, Δl - elongation, l -initial length.
The Young's modulus was calculated in the linear section of the stress-strain curve.

Results

The dependence of the average values of the Young's modulus on the mass fraction of MC for each group is shown in figures 4-7. There were 4 different groups for two types of materials and two types of tests: tension and compression.
The average value of the Young's modulus for each mass fraction is showed by an asterisk. The exact values are shown by red crosses. The error bars show the confidence interval of 95% for each mass fraction.
The average values for each group were approximated for best visualization. The lowest possible order of approximation was chosen. The order of approximation varies between different groups.

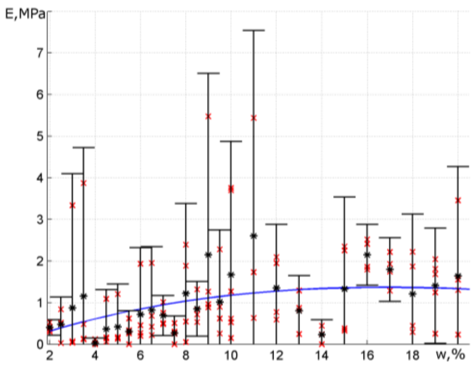

Figure 4: Dependence of the Young's modulus on gelatin concentration under compression

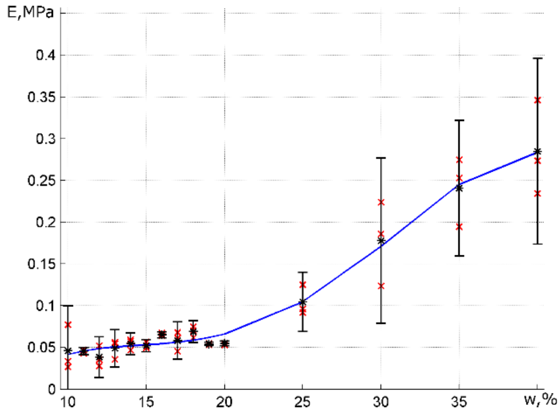

Figure 5: Dependence of the Young's modulus on gelatin concentration in tension

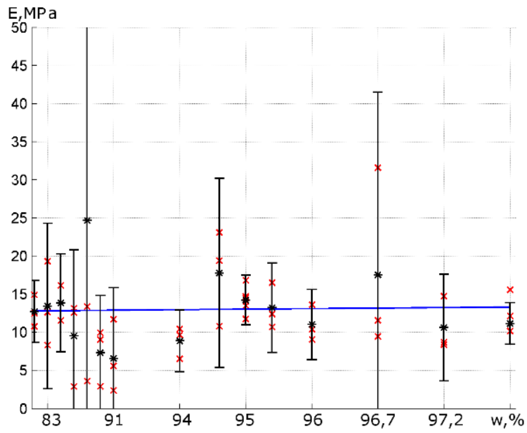

Figure 6: Dependence of the Young's modulus on silicone concentration under compression

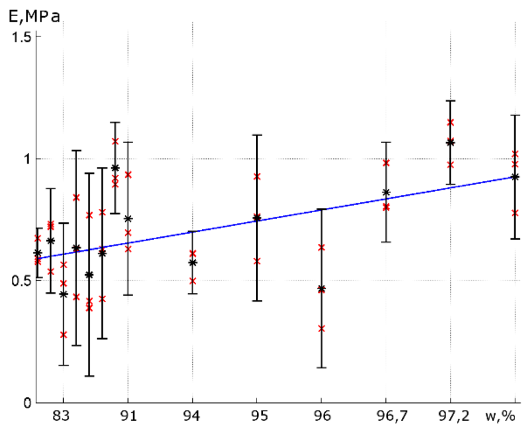

Figure 7: Dependence of the Young's modulus on silicone concentration in tension

Discussion

In this work materials for the physical modelling of biological tissues were tested under compression and stretch to find the strength properties, depending on the mass fraction of MC. The results for each group of samples were approximated.

This work allows to choose to the right concentration of material to get the physical model with exact physical properties of the target tissue.

As expected, the dependence of the Young's modulus on the mass fraction of silicone is more linear than for gelatin, which conforms well the literature review. Its Young's modulus is closer to vascular tissue so for vascular physical models it fits better. Also, silicone characteristics do not change with time and, most importantly, do not depend on temperature changes. This fact confirms the expediency of using silicone for modeling biological tissues.

According to the graphic results, we conclude that the dependence of the Young's modulus on the mass fraction for silicone is insignificant. Thus, it is necessary to choose a silicone with the Young's modulus that closely matches the parameters of the target tissue.

Gelatin required not only the exact conditions of storage and preparation, but it also quickly lost its properties due to drying or melting. Gelatin is good for model making because of its high variability of parameters. This makes it suitable for modeling a wide range of materials.

However, it should be noted that these materials are not suitable for vascular models. If we develop a blood vessel model we should use harder silicones or gelatin mixtures.

These mechanical properties were investigated only in the linear portion of the stress-strain curves. This does not fully describe the nonlinear behavior of the material. Materials for physical modeling behave nonlinearly, like biological tissues [9]. Thus, it is also planned to study nonlinear mechanical properties of materials for physical modeling for the fine selection of material concentration to model specific tissues.

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