

NON-LINEAR MECHANICAL BEHAVIOR OF VISCO-ELASTIC BIOLOGICAL STRUCTURES - MEASUREMENTS AND MODELS

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Summary: Mechanical properties of biological structures affect functional ability of organism. Current knowledge is prevalently concentrated on static characteristics. The present work analyzed dynamic mechanical responses of various biological materials. Following biological structures were measured: samples of aorta walls of human origin and from model organisms, human body surface, and samples of bones of various types and origin. Linear approximation leads in case of aortas and bones to simple Voight's model. Modules of elasticity (in tensile loading) of aortas were from 10^2 kPa to 10^3 kPa. Module of elasticity of bones were from 10^6 Pa to 10^{10} Pa. Viscous coefficients of aortas were from 10^2 Pa.s to 10^3 Pa.s. Viscous coefficients of bones were from 10^0 Pa.s to 10^2 Pa.s. Nonlinearities: We found that following types of nonlinearities are significant: strain-stress relationship, time-dependent changes in elastic as well as viscose bodies. Strain and stress is well approximated by quadratic function $\sigma = a \varepsilon^2 + b \varepsilon + c$ with parameters $a = 1833$, $b = 135$, $c = 20.0$ (porcine aorta). Time-dependence in elastic coefficient: At the beginning of responses the elastic coefficient was of 42% lower then at 0.02 s of duration of the response (porcine aortas). Analogical results follow also from experiments on other structures (skin, bones).

Key words: *Biomechanics; Non-linear models; Dynamic toughness; Elasticity; Visco-elasticity; Veins; Bones; Skin*

Introduction

Mechanical properties of biological structures affect functional ability of organism. Changes in biomechanics are connected with the process of aging as well as with numerous diseases. Knowledge of mechanical behaviour of biological materials is further crucial for assessment of mechanical compatibility of artificial materials that are in mechanical contact with organism.

From the phenomenological point of view, the interrelations between mechanical stresses and corresponding deformations are used as fundamental characteristics of mechanical behaviour. An extensive bibliography exists in this field (1,9,10,13,14). Nevertheless, the works are prevalently concentrated on static mechanical characteristics of materials, namely on static deformation responses on loading or on elastic module.

The dynamics of mechanical responses is researched considerably less, in spite of the fact that biological materials (veins, bones and others) are loaded dynamically in physiological conditions. The problem is (among others) in availability of convenient experimental methodology. The currently applied apparatuses for measurement of dynamics of visco-elastic materials are, as a rule, primarily designed for measurement of industrial plastics, the appliances are

expensive and (more or less) unfit to the measurement of biological materials. The unavailability of convenient instruments results also in unsatisfactory knowledge of non-linear behavior of biological structures in static regime and in virtually no knowledge of dynamic nonlinearities.

With regard to this fact, the dynamic biological elastometer was designed and tested in our laboratories. The apparatus enables measurement of static as well as dynamic deformation responses of biological materials, including veins, in tensile, pressure, or torsion loadings. The appliance is based on innovated version that is described in our previous papers (3,6,7). The application scope of the device includes also identification of linear dynamic models and further also determination of non-linear character of parameters of biological mechanical systems.

In our previous research, the mechanical parameters of following biological structures were measured: samples of aorta walls of human origin and from model organisms (4), human body surface (skin) *in vivo* (2,5) and samples of bones of various types and origin.

In physiological range of loadings, the structure of rheological models of aorta walls and bones corresponds to simple Voight's model (Fig. 1). Modules of elasticity of Hooke's (H) bodies of aorta walls were of order from 10^2 kPa to 10^3 kPa and viscous coefficients of Newton's bodies

(N) were of order from 10^2 Pa.s to 10^3 Pa.s, in case of linear approximation. Modules of elasticity of bones were of order from 10^6 Pa to 10^9 Pa, viscous coefficients of bones were of order from 10^0 Pa.s to 10^2 Pa.s, also in case of linear approximation.

The structure of rheological model of human skin consists of combination of two Voight's structures (Fig. 2). Time constant of dominant structure (corresponding to about 90% of static deformation) was in interval from 10^{-2} s to 10^{-1} s, time constant of secondary structure was of two orders slower.

Mechanical behavior of biological structures is generally non-linear. The nonlinearities of type hysteresis, non-sensitivity, saturation, Bingham's liquid, St. Venant's body etc. are mentioned in theory of visco-elasticity. Nevertheless, in our experiments we found that only following three types of nonlinearities influence the mechanical behavior of structures under study: strain-stress relationship (mainly in aorta walls), time-dependent changes in elastic as well as viscous bodies during mechanical dynamic response.

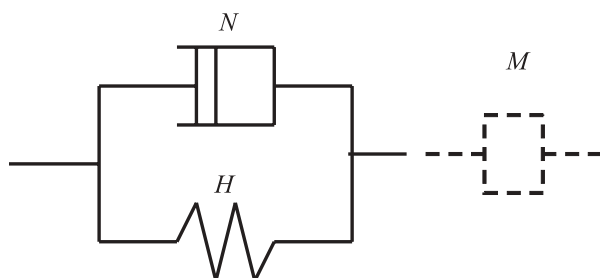


Fig. 1: Structure of linear rheological model of aorta walls and bones (full line). Inertial body (dotted line) represents the aggregate mass of moving part of mechanical system.

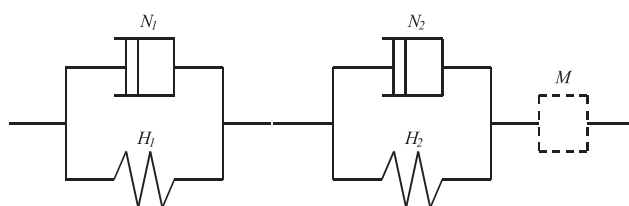


Fig. 2: Structure of linear rheological model of human body surface.

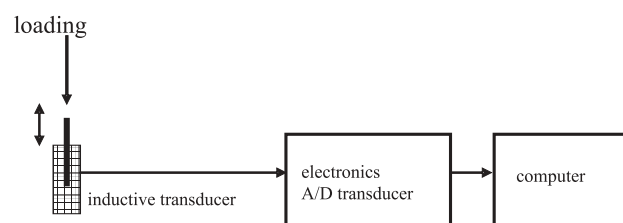


Fig. 3: Block diagram of the appliance.

As the non-linear nature of mechanical behavior of biological structures (notably veins) is often crucial for many aspects, and virtually unknown, we will further deal with this topic in more detail.

Methods

Measuring appliance

Applied version of the apparatus (Fig. 3) enables measurement of samples of material (length 5–50 mm, width 1–10 mm) in tensile stress. In pressure and torsion loadings it is possible to measure samples of length in range from 10 mm to 50 mm, the cross section area of samples is of range from 1 mm^2 to 100 mm^2 . Samples are fixed and connected with gauge (mass of gauge is 12.6 g). Changes of deformation are detected by means of inductive transducer (coil with moving ferromagnetic rod inside). The weight of gauge represents the minimal initial loading of samples (Figs 1 and 2, element *M*). The deformation force is produced by inserting weights on a pan on the top of the gauge (electronically or manually) or, in case of impulse characteristic, is generated by quick “knock” on the gauge. The signal from transducer is processed by electronics, amplified, transformed to digital form by A/D transducer and processed in computer. The time constant of electronics is 1.25 ms. Minimal detectable change of deformation is about $2 \text{ }\mu\text{m}$, it depends on the level of interfering random errors (mainly due to vibrations and electromagnetic disturbances).

Material

a) Aorta walls

Samples of walls of porcine *aorta thoracica* obtained from young 18 pigs (6 months, male, *Sus scrofa f. domestica*) in transversal (circumferential) direction were measured in two successive series. The aim of first series (10 aortas) was to verify methodology. In the second series, 8 aortas were examined using standard procedure. In the following text, the results of second series are described.

Further, samples of walls of human aorta (*pars thoracica*, 5 men, 8 women, age from 37 to 78 years) and samples of walls of aorta of 8 young pheasants (*Phasianus spp.*, hen, age 3 months) were measured, also in transversal direction.

b) Bones

Samples of bones (*caput femoris, substantia compacta*, human cadavers, 2 men, 7 women, age from 52 to 79 years) maintained for several weeks in conservation solution were measured. Measurements were performed on grindings ($35 \times 8 \times 8 \text{ mm}$) in flexion and torsion strains.

Further samples of pheasant scapula (*Phasianus spp.*, hen, age 3 months) were measured immediately after sacrificing animals. Whole bones were measured in flexion strains.

c) Humen skin *in vivo*

Two groups consisting of 15 men and 27 women (age range from 20 to 58 years) were used in experiment. The deformation response was measured on the left palm (above the middle of *abductor pollicis brevis*) in pressure strain.

Results

a) Non-linearity in static regime

The results of experiments on human aortas proved to be close to analogical results on pigs. Consequently, the porcine aortas seem to be good model of mechanical behavior of human veins. Above it, in case of pigs, we used more extensive and more homogenous set. Therefore, the results obtained on the basis of measurement of porcine aortas are presented in following text.

The relationships between strain and stress (Fig. 4) was derived on the basis of steady state levels of transient characteristics. Nonlinearity of the relation was proved by statistical test of sequential differences (s.l. = 0.05). For the data shown, the relation is well approximated by quadratic function $\sigma = a \varepsilon^2 + b \varepsilon + c$ with parameters $a = 1833 \pm 449$, $b = 135 \pm 75$, $c = 20.0 \pm 2.6$.

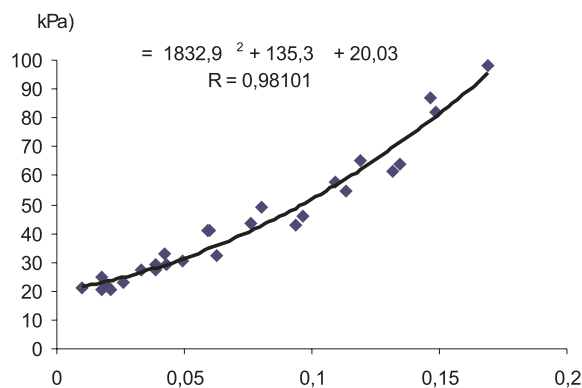


Fig. 4: Relationships between deformation and loading in transversal (circumferential) direction in pig aortas (pigs 6 months, males). The grey area indicates interval of loadings corresponding to physiological range of pressures inside aorta.

b) Non-linearity in dynamic regime - dependency of elastic element on time during deformation response.

At the beginning of responses the value of the elastic coefficient (Fig. 1, element H) was, in average, of 42% lower than at 0.02 s of duration of the response (in case of porcine aortas). The difference is statistically significant for s.l. = 0.01 (proved by Student's t-test). The lower interval estimate of the difference of means assures the minimum change 20 % ($p = 0.95$). It seems to be probable that the magnitude of elastic coefficient is asymptotically increasing with time to the level in steady state. Analogical results follow also from experiments on human and pheasant aortas.

Similar tendency was found in case of elastic element of pheasant scapula (increase 10%) and human skin (increase 60 %). On the contrary, elastic element of samples of bones (*caput femoris*) maintained in conservation solution was constant during dynamic response.

c) Non-linear behaviour of viscose element

Analysis of dynamic responses indicates non-linear behavior of viscose elements in all experiments, with exception of human bones maintained in conservation solution. Preliminary results suggest the decrease of the value of viscose element with the increasing strain and probably also with duration of the response.

Discussion

The aim of presented work is to contribute to better understanding of mechanical behavior of biological materials. Especially, we focused on non-linear dynamics of mechanical responses.

In static regime, we found that the strain-stress curves of aorta walls may be approximated by quadratic function. In other words, we found that differential elastic module decreases linearly with stress. The toughness increases distinctly if the pressure inside aorta exceeds physiological levels. Albeit the non-linear nature of static response of is known and in some extent described, we elucidate this phenomenon in more details. This finding is important, among others, for the study of hypertension.

We believe that the time-dependent character of mechanical parameters of biological materials has not been described till now. This phenomenon, consisting in growing toughness during dynamic response, may be important for biomechanics in general and especially for understanding of principles of biophysics of circulatory system.

Obviously, the more detailed study is necessary in future. Also the elucidation of structural and molecular background of this phenomenon remains to be found.

Conclusion

The appliance for dynamic measurements of biological materials enables to obtain more detailed information on biomechanics and thus contribute to progress in this field.

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