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FINDING OF VISCOELASTIC CHARACTERISTICS OF BIOLOGICAL SOFT TISSUES FROM THE MECHANICAL IMPEDANCE MEASUREMENTS

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Within the framework of the models of vibrating disk interaction with the layered soft biological tissues offered earlier (models with the Pressure Source of Vibrations with Friction) some methods have been suggested of viscoelastic parameters reconstruction of tissues from the impedance characteristics measured in experiment. Description of the offered methods is presented in this paper, as well as description of ways to test these methods and the results of testing.

It is well known that characteristics of shear elasticity of biological soft tissues are very sensitive to their structure and condition [1]. Different ways of "elastography" (ultrasonic, MR and other) are in active development on this base in the last years [2]. Those are the ways of tissues heterogeneity visualization by finding distributions of shear elasticity parameters upon tissue volume. At the same time, traditional measurements of mechanical characteristics of biological soft tissues stay to be vital for objective characterization of their condition, changing under the influence of different physical or physiological factors: heat, chill, light, humidity, zero gravity, electrical stimulation, massage, athletic drill, drug treatment etc. One of the most suitable ways of measuring the mechanical parameters of biological soft tissues for this purpose is a way based on registration of mechanical impedance characteristics of tissues (stiffness K and impedance Z) when touching them by vibrating disk. This way has been developing by some researchers, including authors [3-15]. The first experiments of authors with registration of tissue impedance characteristics were carried out on the stationary laboratory setup, based on the Bruel & Kjer vibration exciting and vibration measuring technique, firstly by the method of harmonic deformation [6], then by the method of noise like deformation with registration of frequency dependencies by means of a spectral analyzer [7]. The autonomous electronic circuits were built later realizing the method of harmonic deformation and monitoring the temporal dynamics of impedance characteristics to make easy performing experimental studies outside the laboratory and to broaden the field of studies [8]. Still later two generations of hardware software complexes were built, realizing similar measurements by means of managing programs, accordingly, in MS DOS and in MS Windows 95/98/ME [9-13]. In the most recent time similar complexes of the third generation have been built, based on the signals acquisition into a computer through the USB bus or through the Line-In entry of a sound card, working in part on portable computers and in MS Windows 2000/XP.

Alongside with the development of computer-based devices for experimental studies of impedance characteristics of biological tissues the development of corresponding models of vibrating disk interaction with layered tissues was also conducted [11-15]. The built models were used for interpreting experimental data by solving the direct problems, as well as for the estimate of rheological parameters of tissues via the impedance characteristics by solving the inverse problems. The aim of this paper is a systematization of main results of different ways testing of such estimates.

All the ways offered can be separated into two main groups. First are the ways based on digital Solving of a System of nonlinear algebraic Equations, obtained by equating theoretical and experimental values of impedance characteristics on discrete frequencies ("SSE - ways"). Second are the ways based on minimization of approximation errors of impedance characteristics spectra ("Minimization - ways"). Differences between the ways inside the groups are related to the tissue model (semi-space, single homogeneous layer on a rigid base or bi-layer on a rigid base), with the given pressure distribution under the disk (even or hyperbolic), with the number of spectra and with the number of points in each spectrum, used for approximation. The simplest example of an "SSE - way" is a way to estimate the effective modules of shear elasticity μ and shear viscosity η of tissues from the harmonic measurements of impedance characteristics K_1 and Z_1. The system of two ordinary nonlinear algebraic equations can be written by equating experimental values to theoretical expressions, corresponding to the measurement conditions (the frequency of disk vibrations and its diameter d), to find the unknown parameters μ and η:

$$K_1 = \operatorname{Re} K1(\mu,\eta), \quad Z_1 = \operatorname{Re} Z1(\mu,\eta). \tag{1}$$

This way can be realized within the framework of different models. In the models with a pressure source of vibrations, where tissues are regarded as a semi-space, the density of tissues and velocity of longitudinal waves in them have to be assigned alongside with the measurement conditions. In the case of tissue regarding as a homogeneous layer it is necessary to assign additionally its thickness *H*. In the multilayered tissue models the rheological parameters of any layer can be determined thereby, in principle, when its thickness is known as well as all parameters of resting layers. In the models with the pressure source of vibrations with friction (PSVF-models), which will be the matter of consideration hereinafter, for such estimates it is necessary to fix in addition a friction coefficient α between the disk and the tissues.

At realization the "Minimization - ways" with the objective evaluation of approximation errors, a question arises first of all about the quality criterion choice, in other words the question of function choice, which minimum have to be found. In the series of conducted calculations such function is taken as the following

$$\Delta = 100\sqrt{\frac{1}{2N}\sum_{i=1}^{N}\left[\left(\frac{KT_i - KE_i}{MK}\right)^2 + \left(\frac{ZT_i - ZE_i}{MZ}\right)^2\right]}. \tag{2}$$

Here *i* is a number of data point (corresponds to the frequency); KT_i, ZT_i, KE_i, ZE_i are theoretical and experimental values of stiffness and impedance at different frequencies corresponding to each other. Weighting factors *MK* and *MZ* have a sense of vertical axes scales of stiffness and of impedance graphs. In accordance with the used experimental data these parameters are assigned the following values: $MK = 7000$, $MZ = 2$. Function Δ has a sense of averaged absolute approximation error of one experimental point in percents relatively to the full interval of values.

All calculations have been conducted on the computer with the processor *Celeron 1400* in *MathCAD 2000*. Solving the systems of equations has been fulfilled in part by means of "*Find"* function by the Levenberg-Marquardt method (it gives a speed advantage in contrast to the method of Conjugate Gradients and to the Quasi-Newton method). Minimization has been fulfilled by means of "*Minimize*" function by Quasi-Newton method (it gives an advantage in contrast to the method of Conjugate Gradients). The single spectrum was used as a basic experimental data set for different tests, obtained on the relaxed tissues of forearm by the disk $d = 16$ mm. Operating frequency range was separated into three intervals: 20 - 50 Hz, 60 - 150 Hz and 300 - 500 Hz (they will be marked later as *A*, *B* and *C* accordingly). In the different ways of reconstruction different numbers of reference points from different intervals were used.

A–interval was selected because a layer resonance is observed here, which can not be reproduced in a semi-space model, but can be a distinctive characteristic for reconstructions of thickness of soft tissues layer in the single-layer and bi-layer models. To study the results dependency from the choice of data points, five different random variants were used of their choice in corresponding intervals of frequencies.

The reconstructed parameters were averaged and the value of approximation error *Δ* was found trough all experimental points for all parameter sets (five reconstructed and one averaged). The set of parameters ensuring a minimum value of *Δ* was chosen as a characteristic of the given reconstruction way.

Results of testing of some ways of tissue parameters reconstruction, as well as parameters found by these ways and their coefficients of variation (marked as k_x, where *x* is the found parameter), are presented in the Tables 1, 2. The following indication system is used in the names of the ways here. Symbols *S*, *L* and *B* relate to the used model type – semi-space, homogenous layer or bi-layer correspondingly. Symbols *U* and *G* relate to the pressure profile under the disk, uniform or hyperbolic correspondingly. Symbols *F* and *M* relate to the reconstruction methods, "SSE-ways" or "Minimization-ways" correspondingly. The source data of stiffness and impedance for reconstruction are marked as upper and lower indexes, where letters *A*, *B* and *C* relate to the frequency interval, but numerals relate to a number of used data points in this interval. Parameters specified parenthetically were considered as given and did not vary. The most important characteristics of different reconstruction ways are the following: reconstruction time – T, quality of approximation of the whole experimental data set by the found parameters – Δ, coefficients of variation of found parameters – k_x.

Table 1. The ways of tissue parameters reconstruction in the homogenous PSVF-models.

№	Method	T, s	H, mm	k_H, %	μ, kPa	k_μ, %	η, Pa s	k_η, %	α	k_α, %	Δ, %
1	MSU_{B1}^{C1}	23			2.22	8.5	4.97	5.0	0.34	13.2	2.63
2	MSG_{B1}^{C1}	30			2.16	8.7	2.55	7.8	0.31	10.6	2.08
3	MSG_{B2}^{C2}	75			2.37	5.46	2.63	10.1	0.32	15.3	2.30
4	FSG_{B1}^{C1}	2			2.06		2.92		0.41		2.39
5	$FSG(\alpha)_{B1}$	7			2.29	9.8	2.71	20.8	0.3		2.10
6	$FLG(H,\alpha)_{B1}$	23	35		2.25	5.3	2.82	4.1	0.35		2.75
7	MLG_{A2}^{C1B1}	155	34	12.8	2.02	12.9	2.96	13.4	0.37	18.3	2.49
8	MLG_{A2}^{C2B2}	207	35	12.8	2.06	11.7	2.93	11.3	0.35	11.8	2.50

Table 2. The ways of tissue parameters reconstruction in the bi-layer PSVF-model.

№	Method	T, s	H_1, mm	k_{H1}, %	μ_1, kPa	$k_{\mu 1}$, %	η_1, Pa s	$k_{\eta 1}$, %	H_2, mm	k_{H2}, %	μ_2, kPa	$k_{\mu 2}$, %	η_2, Pa s	$k_{\eta 2}$, %	α	k_α, %	Δ, %
1	MBG_{A2}^{C1B1}	651	10	34.4	2.04	12.5	2.43	28.4	15	21.4	1.11	22.8	5.48	38.7	0.24	25.9	1.96
2	MBG_{A2}^{C2B2}	955	10	15.1	2.05	15.1	2.43	31.0	16	16.6	1.26	19.4	5.12	75.0	0.28	7.8	2.07

The following is ascertained. When realizing reconstruction by "Minimization-ways", a solution always exists. Changing the initial conditions affects essentially only a calculation time. When realizing reconstruction by the "SSE-ways", a solution can be found not always. This situation is observed, for instance, in the way of reconstructions of three parameters (μ, η and α) from two experimental points in *B* and *C* intervals (way 4 in the Table 1). But after fixing all parameters of models except μ and η a solution can be found (ways 5 and 6 in the Table 1). Using the models with the hyperbolic profile of pressure allows reaching more exact approximation at some increasing calculation time (ways 1 and 2 in the Table 1). Increasing a number of approximated experimental points brings essential increasing of calculation time, but does not give an essential advantage on approximation accuracy and on scattering of parameters found (ways 2 and 3, 7 and 8 in the Table 1, as well as ways 1 and 2 in the Table 2). Using the single-layer model improves a qualitative correspondence of calculations to the experimental data (a layer resonance is reproduced in the *A*-interval), but total error of approximation increases relatively to the semi-space model, as well as increase the variation coefficients of parameters found (ways 7 and 3 in the Table 1).

The best quality of approximation is reached in the bi-layer model from four experimental points – two in the *A*-interval and two in the *B*-interval and in the *C*-interval (way 1 in the Table 2). Increasing a number of experimental points taken for approximation enlarges quickly calculation time and makes corresponding ways little suitable for practical use.

The option of evaluation of the effective modules of shear elasticity and shear viscosity of tissues by "SSE-ways" and by "Minimization-ways" at tissue modeling as a semi-space, as a homogeneous layer or as a bi-layer is included into the managing programs of the new hardware-software complexes for impedance characteristics registration of soft biological tissues. Solving of systems of ordinary nonlinear algebraic equations and minimization of approximation errors here is realized by means of functions of GSL library (GNU Scientific Library), available in Internet. Special tests were carried out of correspondence the results of parameters evaluation in specialized programs and in *MathCAD*. Differences of parameters evaluated by the "SSE-way" via the same experimental data do not exceed

0.1% in the semi-space model, 0.4% in the single-layer model and 2% in the bi-layer model. Differences of parameters evaluated by the “Minimization way” vary in the greatly broader range - from 6% up to 40% in the semi-space model and from 2% up to 100% in the single-layer model.

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