Measurement of nonlinear elasticity depending on the applied static load by the acoustic method in gel-like media

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Abstract. An algorithm has been developed for measuring the shear modulus in an anisotropic media – along and across the organic or artificial fibers that cause the anisotropy. The algorithm is based on the well-known and widely used method for generating shear waves in homogeneous isotropic media. Shear modulus depending on the static load applied to the studied media is shown. It tends to grow nonlinearly as the load increases.

The study of mechanical properties of viscoelastic materials including such soft solids as rubbers, polymers and biological tissues has become a problem of current interest. Typically, these materials are viscoelastic. Particular attention is paid to the development of new coatings and artificial materials that can act the same way as the organic objects. Different types of exoskeletons with viscoelastic coatings are able to release human muscle taking a part of the load. Soft biological tissues are usually inhomogeneous in structure. Muscles are objects with unique viscoelastic properties. Creation of artificial coatings that can mimic muscle properties assumes that these properties should be carefully measured and then reconstructed. Soft tissues are solid incompressible media. Their shear moduli vary from a few kilopascals for mammary glands, liver, adipose tissue and relaxed muscles to several megapascals for tense muscles, connective tissues and dermis. For comparison, the shear moduli of cartilage and epidermis range from several tens to several hundred megapascals, and the shear moduli of bones reach tens of gigapascals. The shear modulus is uniquely related to the shear wave velocity and together with the $\lambda$ parameter, determines the longitudinal wave velocity. Along with the shear modulus, Young's modulus is also a convenient characteristic of elasticity. The bulk modulus of soft tissues $K$ exceeds the shear modulus by several orders of magnitude. Therefore, $\mu \ll K$. In this approximation, the $\lambda$ parameter is approximately equal to the bulk modulus, Young's modulus is three times greater than shear modulus, and Poisson's ratio is equal to $1/2$. Due to the fact that the shear modulus in soft tissues varies over a much wider range than the bulk modulus, and also changes with the physiological state of the tissue, shear waves in soft tissues are a highly accurate diagnostic tool.

The inhomogeneities in gel-like media that mimic the muscles can be generated artificially. Different types of inclusions are popular for lightening the weight of the samples. Structural inhomogeneities lead to inhomogeneities in shear elasticity [1] and have an influence on the resonance characteristics of the samples. The presence of inhomogeneities significantly affects the nonlinear parameters of the medium and leads to different nonlinear effects. Ultrasonic elastography is a new technology with many potential applications. It is highly effective in diagnostics due to its ability to measure the elastic properties of tissue-mimicking materials [2]. In this paper, the elastography...
method is suggested that is appropriate both for clinical applications and for the measurement of the shear moduli in muscle-mimicking samples prepared from an artificial polymer with ultrasonic scatterers and regular rubber fibers inside (figure 1).

**Figure 1.** The direction of the axes according to the fiber direction. The muscle mechanical properties are assumed to be invariant under rotation about axis $z$.

Modern medical ultrasound is performed mainly using the echo-pulse approach and the brightness mode of display (B-mode) [3]. The basic principles of visualization in B-mode today are almost the same as several decades ago. The approach is to send small ultrasonic pulses from an ultrasonic transducer into the body. Since ultrasonic waves penetrate into the tissues of the body with different acoustic impedances, some of them are reflected back to the transducer (echoes), and some continue to penetrate deeper. Echoes resulting from the reflection of a series of consecutive pulses are processed and combined to generate an image. Thus, the ultrasonic transducer works both as a transducer (generating sound waves), and as a receiver (recording sound waves). The ultrasonic pulse is actually quite short, but since it passes along a straight path, it is often called an ultrasonic beam. The direction of propagation of ultrasound along the line of the beam is called the axial direction, and the direction in the image plane perpendicular to the axial direction is called the lateral direction. Usually only a small part of the ultrasonic pulse is returned as a reflected echo after reaching the surface of the body tissue, and the rest of the pulse continues to propagate along the beam line to a greater depth in the tissue. Measurements in the B-mode give only qualitative ideas about the state of the tissue, and the result of these measurements is not always accurate. There are more accurate methods of noninvasive diagnosis, based on the fact that the presence of heterogeneities in the tissues and various pathological changes has a strong effect on their shear elasticity.

Shear waves cannot penetrate at all depths necessary for noninvasive medical diagnostics of biological tissues. Thus, longitudinal ultrasonic waves are used for excitation and detection of shear waves in the investigated region to which the shear waves cannot propagate from the surface. Acoustic pulse-wave elastography was particularly popular among the methods based on the excitation of the shear waves with the ultrasound. In this paper, the acoustical radiation force impulse (ARFI) method is used, which was implemented in clinical devices since the early 2000s [4]. Quantitative estimation of shear wave velocity is realized on the basis of a well-known algorithm of excitation and registration of shear waves in tissue [5]. ARFI imaging technology consists in mechanical excitation of tissue using short acoustic impulses (pushing pulses) in the region of interest chosen by the researcher [6]. The pushing pulses excite shear waves that propagate in the region of interest, perpendicular to the acoustic pushing pulse. Shear waves cause localized micron displacements of the tissue. The pushing pulse is several hundred cycles long and differs in voltage from the B-mode pulse consisting of a short number of cycles. At the same time, imaging waves are generated. These waves are less intensive than the push impulse (1:100). Wave detection is used to determine the position of the shear wave in the tissue at each time point. The moment of interaction between the shear waves and the imaging waves indicates the period of time elapsed between the generation of shear waves and their complete passage through the region of interest. Writing the shear wave front in several places and comparing these measurements with the current time, we can determine the value of the shear wave velocity. The harder the area inside the tissue, the greater the velocity of the shear wave that propagates through this area.

Currently, ARFI technology is successfully used for noninvasive medical diagnostics of liver, kidney and other viscera [7]. The tissues studied with the help of this technology usually possess
isotropy of the shear modulus. As a result, the shear wave propagating in any direction has the same velocity, i.e. the wave velocity measured in such tissues has the same value in any direction. The values of the velocities differ only in regions of shear modulus inhomogeneity, which correspond to the areas of location of pathological changes in tissues. ARFI technology is implemented in several models of ultrasonic scanners capable of generating short-range acoustic radiation forces. The action of such forces on the tissue causes the localized small (1−10 μm) displacements inside the tissue. The response of the tissue to the acting radiation force is registered with conventional pulses that form the image in the B mode. Two-dimensional images of tissue displacement are created by repeating this process along several lines of the image. As a result of cross-correlation processing of images obtained in the B-mode, the tissue displacement is monitored at different times. Thus, the shear wave velocity in the tissue is determined.

The algorithm that is described above is appropriate both for muscle tissues and tissue mimicking artificial media that we are going to use in our further investigation. The first step is a careful measurement of the viscoelastic properties of human muscle tissues. And here the result of these measurements is presented. The measurements have been carried out in Russian Scientific Center of Surgery in Moscow. The qualified doctor of medicine used the Acuson system to measure the shear wave velocities along and across the biceps in healthy volunteers. The load was applied with the help of the barbell plates.

![Graph showing measured shear moduli against the load applied.](image)

**Figure 2.** Measured shear moduli against the load applied. Along the fibers: green rhombs – 1 cm below the surface; red triangles – 2.5 cm below the surface. Across the fibers: green circles – 1 cm below the surface; red crosses – 2.5 cm below the surface. Along the fibers 1 min after the load removal: black squares – 1 cm below the surface; white triangles – 2.5 cm below the surface.

Measured shear moduli against the load applied to the volunteer’s biceps are presented on the graph (figure 2). Under the load applied, the values change extremely along the biceps. These are the green rhombs corresponding to 1 cm below the skin and the red triangles corresponding to 2.5 cm below the skin. The values measured across the biceps remain almost the same. They are depicted with the green circles for 1 cm and with the red crosses for 2.5 cm.
After each measurement the load was removed and the velocity was measured along the biceps again in one minute after removal. The results in the relaxed biceps are depicted with the black squares for 1 cm and with the white triangles for 2.5 cm. Each depth corresponds to the middle position in the certain head of the biceps.

In case the wave that propagates in a certain direction is weak, there is a modification which assumes that the beam is focused in a special shape, so called "blade". This shape lets the excited wave propagate in a certain direction. It means that the shear wave propagates along the transducer from its center to the left and to the right. Thus, we can observe the inhomogeneities on a simple B-mode image and adjust the position of the transducer with respect to the inhomogeneities. The transducer can be applied along the fibers that cause the inhomogeneity and anisotropy, across them, or at any angle, say 45°. We excite the shear wave in certain directions deep inside the tissue with the pushing pulse from the transducer. In our previous experiments we excited it along the muscle fibers, across them and at the angle of 45°. We showed [8] that the main difference is observed between the velocities measured along and across the fibers. The values measured at the angle of 45° appeared to be almost the same as across the fibers.

The algorithm reported in this paper has been developed for measuring the shear modulus in an anisotropic medium – along and across the organic or artificial fibers that cause the anisotropy. Although, algorithm is based on the well-known and widely used method for generating shear waves in homogeneous isotropic media, it was modified for measurements of inhomogeneities of shear moduli. Shear modulus obtained from the shear wave velocity that was measured along the fibers tends to grow nonlinearly as the static load increases.

The algorithm is implemented as an experimental setup. Its efficiency is shown both for organic and artificial anisotropic media. It has been found that the velocity of shear waves that propagate along the fibers that cause the inhomogeneity increases as the load on the muscle increases. For waves propagating across the fibers, constant velocities are observed with increasing load. The algorithm was tested on the standard clinical equipment. With its help, it is possible to control the reconstruction of the unique properties of the skeletal muscles during the development of new artificial objects that can release the muscles and take a part of their load.

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