Dynamic Measurements of Soft Tissue Viscoelastic Properties with a Torsional Resonator Device

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Abstract. A new method for measuring the mechanical properties of soft biological tissues is presented. Dynamic testing is performed by using a torsional resonator, whose free extremity is in contact with a material sample. An analytical model of a semi-infinite, homogenous, isotropic medium is used to model the shear wave propagation in the material sample and allows determining the complex shear modulus of the soft tissue. By controlling the vibration amplitude, shear strains of less than 0.2% are induced in the tissue so that the material response can be assumed to be linear viscoelastic. Experiments are performed at different eigenfrequencies of the torsional oscillator and the complex shear modulus is characterized in the range 1-10 kHz. First in vitro experiments on bovine liver confirmed the sensitivity of the proposed technique. The experiment does not damage the soft tissue and allows a fast and local measurement, these being prerequisites for future applications in-vivo during open surgery.

1 Introduction

Measurement of the mechanical properties of biological tissues is required for medical applications, such as diagnostics, surgery simulation and planning [1]. The characterization of the soft tissue mechanical response contributes to a great extent to the reliability of any simulation of organ deformations. Different approaches can be used in testing biosolids, mainly divided in destructive and non-destructive techniques. Destructive testing utilizes material samples extracted from the organ and experiments are performed according to standard methods of material characterization such as tensile tests [2] or compression tests[3]. Non destructive techniques present the great advantage of a possible direct application in-vivo, during open surgery, eliminating the uncertainties due to the alterations of the material in-vitro. Techniques based on tissue indentation are used in in-vivo tests [4,5], the control of the boundary conditions being the major obstacle in data analysis for quantitative evaluations. The aspiration experiment originally developed by Vuskovic [6] provides well defined kinematic and kinetic boundary conditions and allows accurate fitting of material parameters. Application of this quasi static test on soft human organs [7] provided quantitative

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sets of material parameters for use in large deformation calculations with "slow" deformations.

Testing the materials at high deformation rates provides additional information on the constitutive behavior of the tissue, with applications in diagnostics and trauma research [3]. Dynamic methods for testing soft biological materials range from standard rheometers operating at 0.01 to 10 Hz [8], to devices suitable for modelling the behavior at loading rates up to 350 Hz [9]. Rotary shear tests have been proposed for in-vivo tests by Kalanovic et al. [10] for the low frequency range (up to 20 Hz).

A new non-destructive method for dynamic testing of soft tissues is presented in this paper and is used in our laboratory in order to complement the quasi-static tissue characterization obtained from the aspiration experiments [11]. With the new technique the mechanical properties are derived from the material response to harmonic shear in the linear viscoelasticity range at high frequencies (1-10 kHz). The material is in contact with the free end of a torsional resonator and influences the dynamic behavior of the resonator. The use of a phase locked loop technique provides a high sensitivity to the device. The measurement is fast and, due to the small contact area, a local characterization is achieved. Adherence of soft tissue and torsional oscillator is ensured by vacuum clamping. The soft tissue is modelled analytically as a semi-infinite, homogenous, isotropic medium; a suitable kinematic boundary condition is applied in correspondence of the contact with the resonator. The analytical model consists of a torsional radiating source on a semi infinite space [12,13,14] and is used to extract the material parameters. A mapping procedure and reference tables enable real-time parameter extraction. The results obtained in vitro on bovine liver are reported and discussed, showing the sensitivity and the repeatability of the measurements.

2 Dynamic Torsion Test

2.1 Experimental Details

The Torsional Resonator Device (TRD) is depicted in figure 1. It consists of a rod with circular cross section, excited around the first five torsional eigenfrequencies (in the range of 1-10 kHz) by two electromagnetic transducers, which represent the actuator and the sensor. When the free end of the resonator is in contact with a soft tissues, changes occur in the dynamic properties of the vibrating system. Two parameters, characterizing the dynamic behavior of the system, can be measured: the resonance frequency f_{res}, and the quality factor Q, a measure of damping. Figure 2 shows the typical transfer function of the system, vibrating at resonance during a calibration (without soft tissue contact) and a measurement run (with contact). The damping characteristics and the resonance frequency are inferred from the control variables of a phase stabilization loop, using a technique already employed in viscosimetry [15]. With this method, the measurement can be performed in short time: typically 20 seconds are necessary

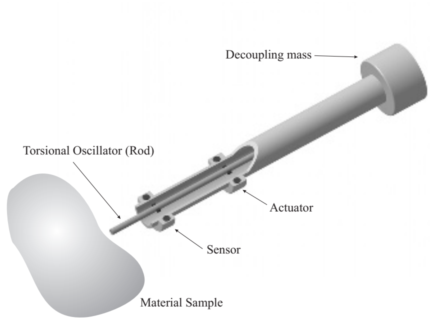

Fig. 1. Torsional Resonator Device (TRD)

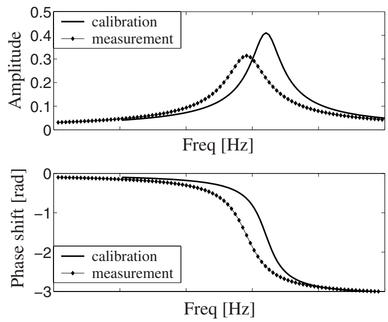

Fig. 2. Transfer functions of the vibrating system

to analyze each resonance frequency, obtaining the corresponding values of Q and Δf_{res} from the control electronics.

The area of contact with the material sample at the lower extremity of the resonator has a radius $R = 2.55mm$. Despite the small contact area, significant changes occur in the dynamic characteristics of the system, as demonstrated in section 3. It is of course important to prevent sliding between the resonator and the soft tissue sample, since perfect adherence will be assumed in the analytical model for parameter extraction. For this reason, a disc with micro-openings, shown in figure 3, is bonded at the extremity of the resonator. The resonator consists of a tube with controllable internal pressure. By evacuating the internal volume of the tube, adherence between resonator and soft tissues is obtained by vacuum clamping. The small dimensions of the disc openings (width= $30\mu m$, figure 3) and the pressure applied in the tube ($0.2bar$ absolute pressure) ensure that no damage occurs in the tissue. The vibration amplitude of the resonator is small so that the material response can be assumed to be linear viscoelastic. To this end the maximum rotation amplitude is kept below $0.001rad$, therefore limiting the shear strains to $\gamma_{max} = 0.2\%$, for the materials and range of frequencies considered here.

A typical experimental procedure with TRD consists of the following steps: (i) a calibration run is performed; (ii) the resonator is put in contact with the material sample, and the internal pressure of the tube is decreased; (iii) once the contact condition is ensured, the measurement run is performed. The whole procedure takes approximately 20 seconds, and is repeated for the first five torsional eigenfrequencies of the resonator. At the characteristic frequencies of these experiments, the observation time leads to several thousands oscillations periods, so that a steady harmonic response state is reached in the system.

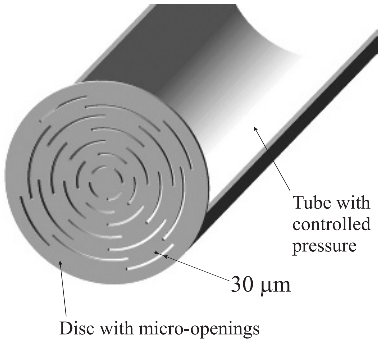

Fig. 3. View of the contact surface

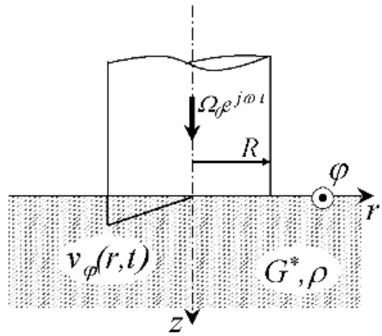

Fig. 4. Soft tissue half-space

2.2 Tissue Modelling and Parameter Extraction

An analytical model is applied to determine quantitatively the mechanical parameters of the soft biological tissue. The soft tissue is considered to be homogeneous and isotropic. This assumption is justified for "bulky" soft organs with no or limited reinforcement by muscular fibers, such as liver and kidney.

With reference to figure 4, the tissue is modelled as a semi-infinite viscoelastic space. A cylindrical coordinate system (r, φ, z) is used. The torsional resonator touches the tissue surface, vibrates around the z-axis and excites shear waves with displacement in the r-φ plane (SH-waves) in the tissue. Linear viscoelasticity is employed to describe the tissue behavior in shear deformation:

$$\tau(t) = \left(G(0) + \int_0^\infty e^{-j\omega s} \dot{G}(s) ds \right) \cdot \gamma(t) = G^* \gamma(t) \tag{1}$$

$$\gamma(t) = \gamma_0 e^{j\omega t} \tag{2}$$

$$G^* = G_1 + jG_2 \tag{3}$$

where $\tau(t)$ and $\gamma(t)$ represent the shear stress and strains, respectively, and G^* is the complex shear modulus of the material, with the real and imaginary components G_1 and G_2, called respectively storage and loss shear modulus. Due to the kinematic boundary condition at the tissue surface, the displacement vector in the half space can be described as in equation 4, thus reducing to the azimuthal component u_φ only:

$$\bar{u} = u_r \hat{r} + u_\varphi \hat{\varphi} + u_z \hat{z} = u_\varphi \hat{\varphi} = u_\varphi(r, z, t)\hat{\varphi} \qquad u_r = u_z = 0 \tag{4}$$

$$\frac{\partial^2 u_\varphi}{\partial z^2} + \frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial(r u_\varphi)}{\partial r}\right] + \frac{\omega^2}{c_{SH}^2} u_\varphi = 0 \qquad c_{SH}^2 = \frac{G^*}{\rho} \tag{5}$$

The equations of linear momentum and the kinematical relations reduce here to the SH-wave equation in a viscoelastic half-space, equation 5, where c_{SH}

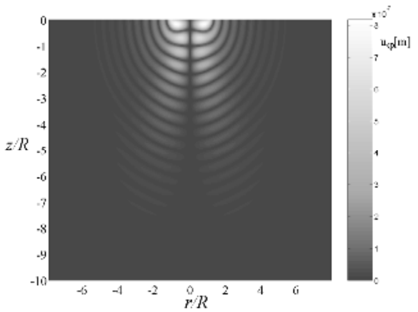

Fig. 5. Example of wave propagation pattern: amplitude of u_φ

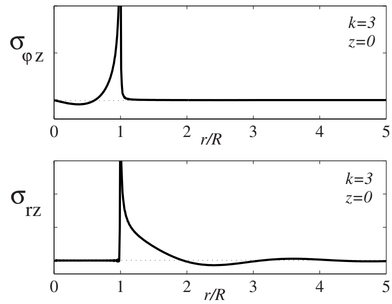

Fig. 6. Stresses at $z = 0$

identifies the shear wave speed in the material of density ρ. Considering perfect adherence at the contact location, the boundary conditions are:

$$u_{\varphi|z=0} = \theta_0 r e^{j\omega t} \qquad \text{for } 0 < r \leq R \tag{6}$$

$$\tau_{\varphi z|z=0} = 0 \qquad \text{for } r > R \tag{7}$$

where R is the radius of the contact area. The solution of the boundary value problem with mixed (kinematic and kinetic) boundary conditions of a radiating torsional source, known as Reissner-Sagoci problem [12,13], was derived by Dorn [14], using Hankel Transform methods. The torsional radiation pattern and the torsional mechanical impedance of the medium can be determined for given values of the material parameters G_1 and G_2 for each excitation frequency. In figure 5, an example of the radiation pattern generated by a torsional vibrating source is shown. Colors indicate the amplitude of the azimuthal displacement. The radiation pattern depends on the complex shear modulus $G^*[Pa]$, the exciting angular frequency $\omega[rad/sec]$ and the radius of the contact area $R[m]$, which define a dimensionless wave number k in equation 8.

$$k = \frac{\omega}{\sqrt{G^*/\rho}} R \tag{8}$$

This number characterizes the wave propagation pattern. For soft tissues and relatively high frequencies, k assumes values higher than 3, leading to waves propagating mainly in z-directions, toward the tissue interior. Typically displacements, for the viscoelastic properties of biological tissues, have negligible amplitude outside a layer of 3 to 4 times the oscillator diameter $2R$, as shown in figure 5. Figure 6 shows the components σ_{rz} and $\sigma_{\varphi z}$ of the stress vector at the tissue surface ($z = 0$). Vacuum clamping, described in section 2.1, ensures that adherence is fulfilled also for $r \to R$, where large shear stresses $\sigma_{\varphi z}$ occur. By solving the analytical problem described in equations (5), (6) and (7), the torque exerted by the soft tissue on the resonator can be expressed as a function

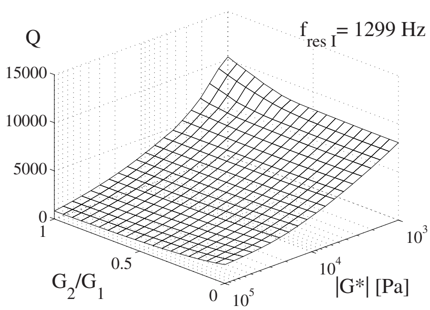

Fig. 7. Quality factor in function of G^*

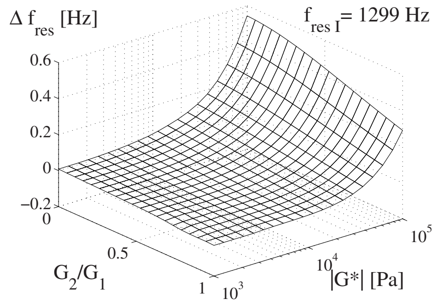

Fig. 8. Resonance frequency shift in function of G^*

of the material parameters. In this way the changes in the dynamic behavior of the resonator, i.e. the increase in damping and the resonance frequency shift, can be linked to the mechanical properties of the tissue.

The combination of the model of the resonator and the model of a viscoelastic half-space described in section 2.2 leads to the identification of the influence of the material parameters G_1, G_2 and ρ on the system's transfer function. The measured parameters Q and Δf_{res} (Q factor and resonance frequency shift) can be directly correlated to the tissue properties, as shown in figure 7 and 8 for the first resonance frequency. This mapping process allows obtaining an almost real-time measurement of the mechanical properties of soft tissues.

3 Experimental Results and Discussion

The TRD technique was applied for dynamic testing of bovine liver ex-vivo. The main purpose of these experiments was to evaluate the reliability of the TRD measurements. Adult bovine liver samples, obtained from the local abattoir, were tested at ambient temperature. Figure 9 shows the repeatability of the measurements in terms of Q and f_{res}. The first torsional eigenfrequency (1299 Hz) was considered in this analysis. A series of measurements was performed on the same organ at different locations identified by the letters A, B, C, D, E, and F. Three independent measurements have been performed within short time intervals at each location. The repeatability is within 20% and 10% for Q and Δf_{res} respectively, for the measurements at the same location. The variability of the material properties within one single organ is indicated by the comparison of the measurements at different locations and is in line with findings from other studies [3,7]. Figure 10 shows the time evolution of the measurements performed at one single location. The TRD technique is capable of detecting tissue alterations due to dehydration and oxidation, with high sensitivity.

Experiments with bovine liver were performed at different eigenfrequencies of the resonator, in order to show the frequency dependence of the material be-

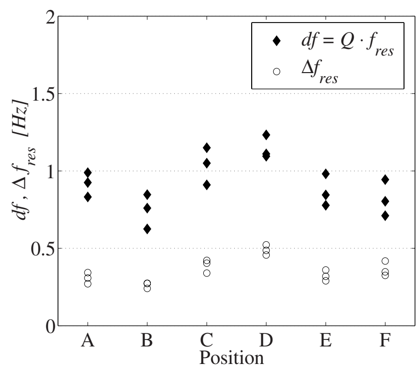

Fig. 9. Repeatability of the measurements on bovine liver capsula

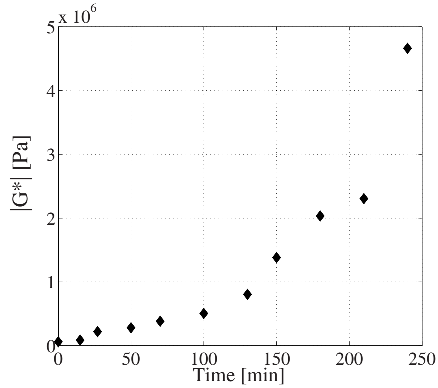

Fig. 10. Time evolution of $|G^*|$ on bovine liver capsula

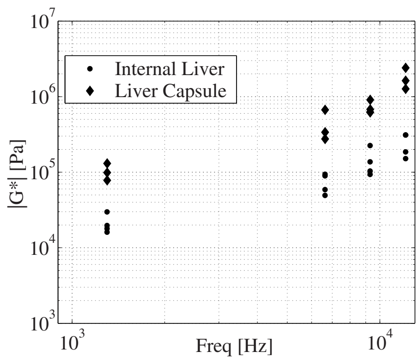

Fig. 11. Frequency dependence of the shear modulus $|G^*|$

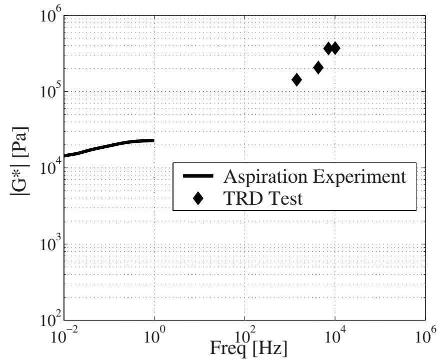

Fig. 12. Results from quasi-static experiments [7] and TRD tests

havior. Measurements were taken at one single location. Results are reported for the first, the third, the fourth and the fifth eigenfrequencies. The resulting values of the shear modulus amplitude $|G^*|$ are shown in figure 11, which includes for comparison the results obtained from measurements at the external surface of the liver (contact with the capsule) and at an internal section of liver. Different material responses are obtained from external and internal measurements, acting the capsule as a stiffening membrane. These data show that the shear modulus increases at higher frequencies. The combination of the quasi-static aspiration test [7] and the TRD test yields a characterization of the material response over a wide range of frequencies. Figure 12 shows the results of quasi-static and dynamic experiments on the same bovine liver: in contrast with other studies [2], a significant frequency dependence of $|G^*|$ is demonstrated by these measurements.

4 Conclusions

A new technique has been proposed for dynamic testing of soft biological tissues. The procedure for viscoelastic material properties measurement is fast (results for one frequency are obtained in approximately 20 seconds) and local (a tissue volume of approximately $100mm^3$ is tested). An analytical model allows determining the complex shear modulus of the tissue from the experimental data. Tests on bovine liver have shown the repeatability ($\pm 10\%$ and $\pm 5\%$ for the target parameters Q and f_{res}) of the experimental technique. The TRD measurements are sensitive enough to detect the influence of the capsule in the mechanical response of the liver as well as the changes in material properties due to dehydration and oxidation. Experiments are ongoing for validation of the reliability of the material properties measurements with TRD: for this purpose, silicone phantoms are used, whose viscoelastic properties are determined with independent wave propagation experiments.

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