MEASURING THE MECHANICAL PROPERTIES OF SOFT BIOLOGICAL TISSUES

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INTRODUCTION

The mechanical characterization of soft biological tissues is essential to a number of medical applications, such as surgery planning, surgical training deploying virtual reality based simulators, or diagnosis. Quantitative data sets are available on the in-vivo mechanical properties of soft tissues in animal organs, but very limited data are available on the behavior of soft tissues associated with human organs. This deficiency is primarily due to the severe technical and ethical problems related to the experiments. In this work two new techniques are presented for soft tissue's mechanical testing, that were designed to fulfill the requirements for in-vivo measurements on human organs during open surgery: the aspiration test and the dynamic torsion test.

In the aspiration test relatively large local tissue deformations are imposed and the time dependent behavior of the tissue can be observed. The experiment is characterized by well defined kinematic and static boundary conditions and the time required for each measurement is very short (of the order of 20 seconds). This device has been used already for the in-vivo characterization of the mechanical behavior of human organs during open surgery.

In the dynamic torsion test the soft tissue is made part of a vibrating system. The complex shear modulus of the soft tissue is determined from the transfer function of the system. Measurements are performed at frequencies ranging from 1 to 10 kHz. This non-destructive technique can be applied for in-vivo measurements.

The goal of the quasi-static and dynamic experiments is to derive a constitutive model of the soft tissue. Typically a large number of material constants need to be determined for model formulations that account for viscoelastic or viscoplastic behavior at large deformations. Numerical methods are used for the solution of the inverse problem. From the quasi-static and the dynamic experiments different types of constitutive model are evaluated in their capability of describing the soft tissue response.

EXPERIMENTAL PROCEDURES

Aspiration test

The aspiration test has been designed for in-vivo applications addressing issues associated with: safety, sterilization, space limitation and a short data acquisition cycle time. The device consists of a tube in which the internal pressure can be controlled according to a desired pressure law. The experiment is performed by (i) gently pushing the tube against the tissue to ensure a good initial contact, (ii) creating a (time variable) vacuum inside the tube so that the tissue is sucked in through the aspiration hole (diameter of 10 mm).

Assuming the tissue to be isotropic and homogeneous in the small portion under deformation, a complete description of the deformed tissue can be given by monitoring the side-view profile of the tissue during its deformation. The profile is extracted from the images reflected by a mirror and are captured by a digital camera.

With a pressure control system a predefined pressure law can be obtained inside the tube. Typically the pressure is decreased to a certain vacuum level (in the order of 700 mbar absolute pressure, deemed insufficient to cause tissue damage), is kept constant for a couple of seconds and is than increased back to atmospheric pressure. Each such cycles lasts for about 20 seconds and can be repeated several times, in order to study tissue's preconditioning, [1]. Time histories of measured pressure and deformation profiles are the input data used to evaluate the mechanical properties and to determine the constitutive model.

Dynamic Torsion test

The experimental set-up consists of a cylindrical rod which is excited at its torsional eigenfrequencies (from 1 kHz to 10 kHz) by an electromagnetic transducer (with actuator and sensor function). One extremity of the rod is in contact with the soft tissue. Perfect adherence is ensured by vacuum clamping. The damping characteristics and the resonance frequency of the vibrating system are inferred from the control variables of a phase stabilization loop. Due to the contact with the soft tissue, changes occur in the Q-Factor and in the resonance frequency of the system. These changes are quantified from the differences between a calibration run (without soft tissue contact) and a measurement with soft tissue contact. Based on an analytical model, the mechanical impedance of the material in contact is determined from these data and the complex shear modulus G* is evaluated for each resonance frequency. The dependency of the complex shear modulus on contact force, vibration amplitude, frequency, and number of loading cycles can be studied with this experiment.

CONSTITUTIVE MODELING AND DETERMINATION OF MATERIAL PARAMETERS

Aspiration test

Large deformations occur in the aspiration test, up to stretches in the order of $\lambda=1.3$. According to the model proposed by Fung, [1], a common approach to modeling large deformations in soft tissues is by "quasi-linear viscoelsticity". The tissue's hyperelastic response is described in terms of a strain energy function U (we use the so called "reduced polynomial form"); viscoelasticity is taken into account by applying time dependent (relaxation) coefficients to the constants that define the energy function (we express these coefficients in terms of Prony series).

Our quasi-linear viscoelastic model contains 13 parameters, which are determined from the experiments by finite element calculations: (i) the experiment is simulated by a finite element model in which the (time dependent) aspiration pressure is imposed as kinetic boundary condition; (ii) the material constants are determined iteratively from the comparison of calculated and measured soft tissue deformation. With our refined optimization procedure and the current hardware implementation the time required for the definition of the best-fit parameter set is approximately two hours.

Experiments with repeated aspiration cycles were performed to study soft tissue's preconditioning: the internal structure of the material changes due to mechanical loading and eventually reaches a steady state in repeated cycling. The initial response and the changes of the response in early loading cycles is more important for a number of medical applications than the stabilized (preconditioned) mechanical behavior. With the multiple cycle aspiration experiments the history dependence of the mechanical response can be studied. As clearly shown by the tests on animal organs, the evolving cyclic response cannot be described by a quasi-linear viscoelastic model. The elastic-viscoplastic model proposed by Rubin and Bodner [2] is able to describe the relevant physical features of the soft tissue response, including preconditioning, recovery and anisotropy. We have implemented this model in the finite element code and use it for characterizing the soft tissue response in multiple cycle experiments.

Dynamic torsion test

Due to the high sensitivity of the sensor for vibration detection, the vibration amplitude of the dynamic torsion test can be kept very small, so that a linear viscoelastic material model represent a valid approximation for the evaluation of this experiment. In the current implementation, the soft tissue is modeled as a semi-infinite, homogenous, isotropic medium. A kinematic boundary condition is applied for the points in contact with the vibrating rod. The elastodynamic wave equation is solved for the specified torsional excitation. Depending on the soft tissue properties, shear waves (SH waves) propagate mainly in the radial direction or in the vertical direction, toward the tissue interior. From the analytical model, the mechanical impedance of the medium can be expressed as function of the complex shear modulus G^* of the tissue. In this way, Q-factor and resonance frequency can be mapped to real and imaginary part of G^*.

RESULTS AND CONCLUSIONS

The experimental techniques were applied on animal and human organs. From these experiments the reliability of the measurements has been evaluated. The results obtained from post-mortem aspiration experiments on human liver and kidney, [3], show that the method can describe the differences in the mechanical response of two types of organs and can distinguish between the mechanical behavior of a normal and a diseased liver. These results seem to indicate that the application of this technique can lead to the identification of objective parameters for diagnostic purposes.

A series of tests were performed on adult bovine liver using both aspiration test and dynamic torsion test. From the dynamic torsion test the complex modulus $G^*(\omega)$ is determined in the range of 1 kHz to 10 kHz. There is an appreciable difference in G* values obtained from measurements at the external skin (liver capsule) and in the liver interior. Based on the non-linear constitutive model determined in the aspiration test, a small strain shear relaxation module G(t) is calculated, from which the frequency dependant complex modulus $G^*(\omega)$ is readily derived. In this way the results from the quasi-static and dynamic experiments can be compared in the frequency domain. The constitutive behavior is characterized over a wide frequency range from the combination of the results of the two tests. In contrast with common assumptions, [1], a significant frequency dependency of ¦G*¦ is demonstrated by our measurements, Figure 1.
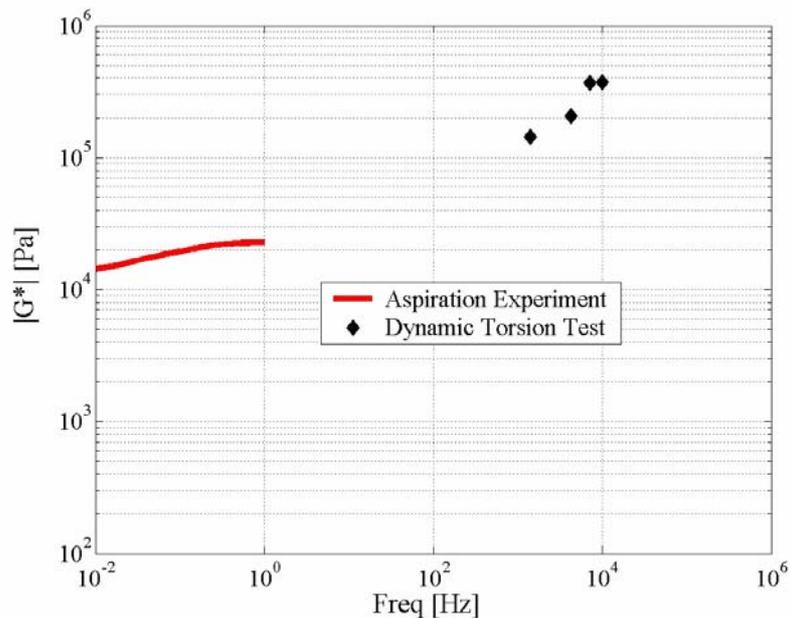

Figure 1: frequency dependence of the complex shear modulus (bovine liver)

References

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