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On the viscoelastic characterization of thin tissues via surface-wave sensing

Marcin Białas [a,b], Bojan B. Guzina [a,*]

[a] Department of Civil Engineering, University of Minnesota, Minneapolis, MN 55455, USA
[b] Institute of Fundamental Technological Research, Pawińskiego 5B, 02-106 Warsaw, Poland

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ABSTRACT

This paper establishes a theoretical and computational framework for the development of a novel piezoelectric sensor array for the monitoring of surficial tissue motion that can be used as a basis for the reconstruction of layered viscoelastic skin properties. This is accomplished by the scale reduction of the so-called Multi-channel Analysis of Surface Waves (MASW), a methodology that is successfully used in engineering geophysics for the seismic-wave reconstruction of vertical geological profiles. The utility of the new sensor, containing an array of hair-like PVDF sensors that are sensitive to surficial tissue motion, is enhanced through a systematic solid-fiber interaction analysis that furnishes integral information, cumulative over the length of each fiber, about the attenuation and dispersion of surface waves. On employing such a predictive model as a lynchpin of the full waveform back-analysis used to interpret electric charges generated by the fibers, the methodology allows for an effective reconstruction and viscoelastic characterization of cutaneous and subcutaneous tissue sublayers on a millimeter scale. The performance of the proposed sensor array and data interpretation framework is illustrated through numerical simulations, which point to the feasibility of cost-effective, *in vivo* mechanical characterization of skin sublayers.

1. Introduction

Over the past decade, studies have demonstrated that quantitative medical imaging (targeting e.g. the spatial distribution of tissue's shear modulus) has a potential of identifying cancerous lesions in tissues that are otherwise visible, but indiscernible by anatomical imaging techniques such as X-ray, magnetic resonance, and computed tomography. In particular, results indicate (Ophir et al., 1991; Plewes et al., 2000) that the apparent shear modulus of certain types of cancer can be $5 \div 10$ times higher than that of the surrounding healthy tissue. Notwithstanding such critical advantage, at present there are no viable *in vivo* testing procedures nor analyses capable of quantitatively resolving the effective mechanical characteristics of multi-layered, small-scale tissue structures such as skin.

To enhance the fidelity of mechanical tissue characterization, growing number of studies have employed linear viscoelasticity to approximate the constitutive behavior of soft tissues (Kruse et al., 2000). While the latter are clearly non-linear at high strains and may exhibit complex features such as poromechanics (Thimus et al., 1998), anisotropy (Ventre et al., 2009) and mechanical adaptation (Lokshin and Lanir, 2009), studies have shown that linear viscoelastic models provide reasonable approximation of soft tissue's mechanical response in situations involving small strains and fast excitation with frequencies over 50 Hz, see e.g. Xydeas et al. (2005).

In most situations that entail the non-invasive use of elastic waves toward three-dimensional (3D) reconstruction and characterization of subsurface heterogeneities, one of the basic requirements is the prior knowledge of (visco-) elastic properties of the reference "background" medium. Such is the case for instance with *seismic migration* (Claerbout, 1976; Berkhout, 1981), as well as more recent 3D reconstruction techniques such as the *linear sampling method* (Baganas et al., 2006; Guzina and Madyarov, 2007) and the *topological sensitivity approach* (Guzina and Bonnet, 2004; Chikichev and Guzina, 2008) which commonly require the elastic layer properties (or seismic velocities) of the reference "defect-free" medium to be known beforehand. In the context of viscoelastic material characterization that is applicable to healthy (i.e. "background") skin and subcutaneous tissues, studies have largely focused on either one-dimensional testing of excised tissues (Catheline et al., 2004; Wu et al., 2006), or indentation testing (Suzuki and Nakayama, 1999; Dhar and Zu, 2007) that relies on the premise of local tissue homogeneity. More recently, Liu and Ebbini (2008) and Guzina et al. (2009) proposed a dynamic testing methodology for the viscoelastic characterization of homogeneous, millimeter-thin tissue constructs on rigid substrates that utilizes high-intensity ultrasound beam, modulated at frequencies on the order of $10^2 - 10^3$ Hz, as the source of mechanical vibrations.

* Corresponding author. Tel.: +1 612 626 0789; fax: +1 612 626 7750.
E-mail address: guzina@wave.ce.umn.edu (B.B. Guzina).

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