Ultrasonic Methods for Imaging the Elastic Properties of Tissue

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Abstract

Imaging the elastic properties of soft tissue using ultrasonic methods has been the focus of many international research efforts. The primary goal of these labors has been development of novel` imaging methodologies and techniques for estimating the elastic properties of soft tissue to differentiate normal from pathological states. In this paper, we focus on ultrasound-based tissue elasticity estimation strategies and imaging methods. More specifically, we will introduce and discuss the techniques known as compression elastography and vibration sonoelastography.

Introduction

For more than a decade, imaging the elastic properties of soft biological tissues using ultrasonic methods has become the focal point of many research efforts. The goal of these initiatives revolves around mapping some tissue mechanical property in an anatomically meaningful manner in order to provide useful clinical information. Since changes in tissue stiffness may be indicative of an abnormal pathological process, imaging parameters related to tissue elasticity may provide a suitable gateway for differentiating normal from abnormal tissue types.

It has been shown experimentally that there is in fact a difference in stiffness between abnormal and normal tissues types owing to the pathological state. As Krouskop et al. reported from their work with breast tissue samples, ductal carcinomas exhibited a stiffness contrast of approximately 23 dB whereas invasive and infiltrating carcinomas exhibited a 28 dB contrast relative to the softer subcutaneous adipose tissue [1]. Additionally, it was shown that cancers of the prostate exhibited a stiffness contrast in excess of 10 dB when compared to the normal prostate tissue [1]. This observation confirmed an earlier report by Parker et al. [2] albeit using a very limited set of tissue samples.

Palpation is a routine physical examination where the clinician qualitatively assesses low-frequency tissue stiffness. During palpation, lumps that are discrete and differ from the surrounding tissue are identified for further diagnosis. Though these lumps may dislocate or feel fixed within the tissue, subtle finding are much more difficult to interpret. Specifically, in many tumor cases and despite the difference in stiffness, the small size of a pathological lesion and/or its non-superficial location impedes detection and evaluation by palpation. Additionally, lesions may or may not possess echogenic properties that make it detectable ultrasonically. For example, tumors of the prostate or the breast can be isoechoic or barely visible in standard ultrasound examinations, yet be much harder than the embedding tissue. It is hypothesized that imaging parameters related to tissue stiffness will provide novel information that is associated with tissue structure and/or pathology.

Elasticity Imaging using Ultrasound

Within the context of elasticity imaging, research devoted to ultrasonic-based methods have received a lot of attention. Some of these methods have focused on quantitatively measuring physical parameters (e.g. shear modulus reconstruction) whereas others strive to provide an image that qualitatively relates to the tissue stiffness distribution (e.g., strain estimation and low frequency vibrational response). The fundamental goal of these efforts has been the development of novel imaging methodologies and techniques for estimating the elastic properties of soft tissue in order to differentiate normal from pathological tissue structures. Based on results that can be found in the literature, these efforts are slowly coming to fruition.

An important distinction of ultrasound-based elasticity imaging systems is that tissue echogenicity and stiffness, attributed to the Bulk and shear moduli distributions, respectively, are disjoint. Figure 1 illustrates the variation of the shear and bulk moduli for various materials and body tissues (adapted from [3]). Note that though the Bulk moduli exhibits limited dynamic range, the opposite is true for the shear moduli distribution, which spans several orders of magnitude for the various biological materials and tissues. From Fig. 1, it can be inferred that though there may exist a relatively limited spatial fluctuation in the underlying Bulk moduli (which determines ultrasonic wave propagation and scattering) for given tissue volume, the shear moduli (and thus the elastic properties) may exhibit considerably larger spatial fluctuations. It is this large dynamic range in the elastic properties that motivates clinicians to routinely use palpation for the physical inspection of tissues and drives research in the field of elasticity imaging.

Several groups have contributed to the growing field of ultrasound-based elasticity imaging. While considerable variations exist in how the details are implemented, all methods share the following basic elements:

(1) A mechanical force is applied to the tissue,
(2) Local tissue motion is measured,
(3) Some elasticity parameter is estimated.

Since no known modality is capable of imaging the elastic properties of tissue directly, the application of a mechanical force in order to induce tissue motion is a prerequisite to all elasticity imaging techniques. Additionally, the mechanical

sources can be grouped based on the spatial characteristics of the tissue excitation. External methods apply a compressive force on the skin in order to deform the underlying tissue structures. These external sources can be further classified by the temporal characteristics of the mechanical source: static (or quasistatic) methods and dynamic methods. In contrast, internal methods apply the mechanical force internally and directly on the tissue region of interest. These mechanical sources can either be biological in nature (such as cardiovascular pulsation) or manually induced using approaches such as the acoustic radiation force of a focused ultrasound beam.

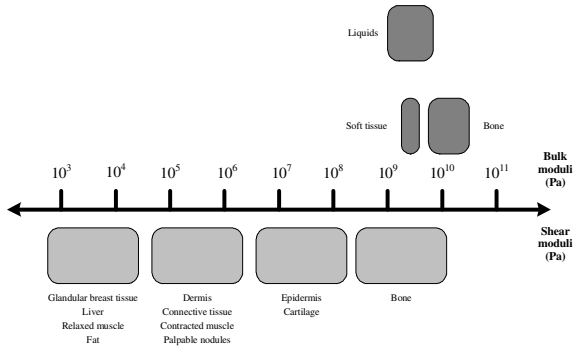

Figure 1 *Summary of the relative shear and bulk moduli variation for several materials and biological tissue types (adapted from Sarvazyan et al. 1998).*

Static Elastography

In 1991, Ophir and coworkers introduced an ultrasound-based technique termed elastography for imaging soft tissue strain profiles (i.e., relative deformation) owing to a quasistatic compressive force [4]. In this particular method, tissue strain is used as a surrogate for stiffness; low tissue strain regions implies high stiffness and vice versa. In elastography, axial tissue motion is typically estimated (numerically) as the peak position of a cross-correlation function applied to congruent pre- and post-compressed radio-frequency (RF) echo data segments [4,5]. By shifting the data windows, displacement estimates are obtained as a function of tissue depth and repeated until all pre- and post-compressed A-line pairs are processed. Finally, strain images (termed elastograms) are obtained by taking the gradient of the axial displacement estimates. For elastograms produced using internally applied compressive forces, natural tissue motion (such as vessel wall displacement) is tracked using the same cross-correlation based techniques as described above [6]. A representative ultrasound B-mode image and matched elastogram from a tissue-mimicking phantom are illustrated in Figure 2. Note that the B-mode image is nearly isoechoic with no discernible lesion whereas the elastogram clearly depicts a stiff circular mass within the image plane.

In contrast to the temporal based elastographic methods discussed above, Fourier-analysis based strain estimation techniques have been introduced [7,8]. In general, the spectral techniques are premised on the Fourier scaling principle that states a scale change in the time-domain corresponds to an inversely related scale change in the frequency-domain. Specifically, compression of a gated temporal RF echo sequence produces an expansion of the signal spectrum. Local values of tissue strain are then estimated as the relative shift between sets of pre- and post-compressed power spectra and imaged (termed a spectral elastogram). A representative ultrasound B-mode image and matched spectral elastogram from a tissue-mimicking phantom are illustrated in Figure 3. Notice that the spectral elastogram shows a high contrast stiff circular mass within the image plane.

The advantage of spectral-based elastographic methods is that they are direct estimators of tissue strain. Hence, these estimators are devoid of any noise amplifying gradient operations that are characteristic of temporal-based elastographic approaches but are more computationally demanding in application.

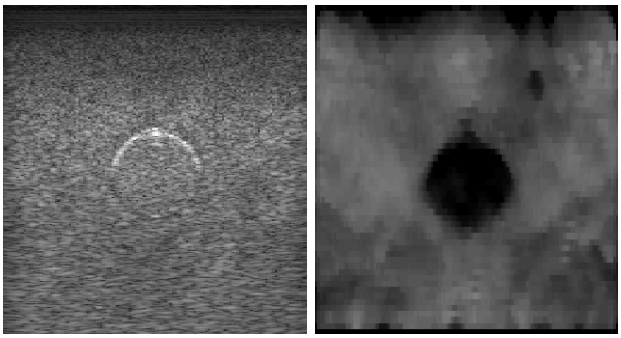

Figure 2 *Matched (a) Ultrasound B-mode image and (b) Elastogram of tissue-mimicking phantom containing a stiff focal mass. Regarding the elastogram, high intensity colormap values denote high strain (soft tissue) and dark values denote low strain (hard tissue).*

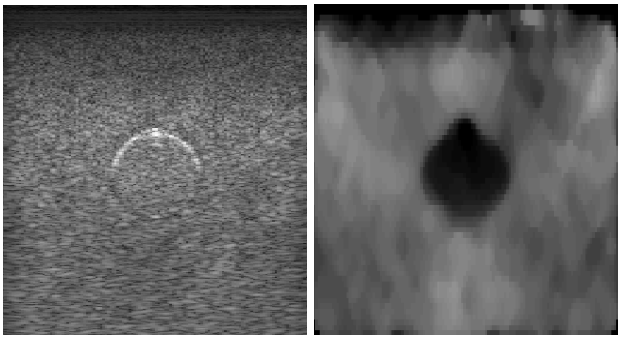

Figure 3 *Matched (a) Ultrasound B-mode image and (b) Spectral elastogram of tissue-mimicking phantom containing a stiff focal mass. Regarding the spectral elastogram, high intensity colormap values denote high strain (soft tissue) and dark values denote low strain (hard tissue).*

Dynamic Elastography

Foregoing its introduction in the late eighties, an ultrasound-based technique now known as sonoelastography was conceived at the University of Rochester for measuring soft tissue elasticity [9]. In general, a low frequency (less than 1 kHz) and low amplitude (20 to 100 μm) mechanical excitation is utilized to propagate shear waves in tissue. Note the low frequency requisite reduces shear wave attenuation whereas low amplitudes ensure patient safety. Due to the tissue response from propagating shear waves, elasticity information can be estimated in depth using Doppler ultrasonic techniques. Consequently, the Doppler shift of an ultrasonic wave scattered from a spatially oscillating object (tissue volume) is given by a Fourier-Bessel series of equally spaced harmonics above and below the Doppler carrier frequency [10]. It has been shown that the vibrational amplitude of tissue scatterers in sinusoidal motion alters the power spectrum of an insonifying ultrasound beam in a predictable manner. Specifically, there exists a linear relationship between vibrational amplitude and the standard deviation of the power spectrum, forming the basis of sonoelastography imaging. Using a modified pulsed Doppler ultrasound system, local estimates of tissue elasticity can be estimated and imaged (termed a sonoelastogram) in real-time to reflect changes in deep tissue stiffness. In practice, when a region of tissue contains a stiff lesion or mass, a local decrease in peak vibrational amplitude results [11]. Figure 4 illustrates a typical ultrasound B-mode image and matched sonoelastogram from a tissue-mimicking prostate phantom. Notice that the B-mode image is isoechoic with no detectable mass whereas the sonoelastogram clearly depicts a stiff focal lesion.

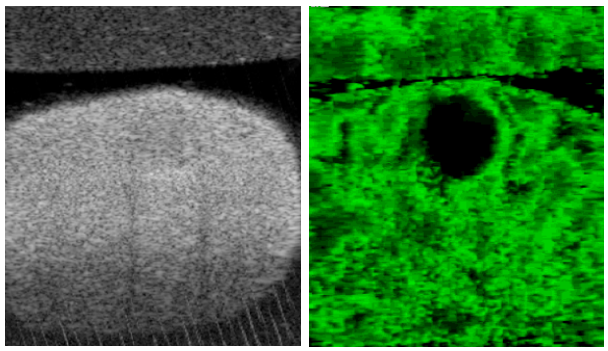

Figure 4 *Matched (a) Ultrasound B-mode image and (b) Sonoelastogram of tissue-mimicking prostate phantom containing a stiff focal mass. Regarding the sonoelastogram, high intensity colormap values denote high vibrational amplitude (soft tissue) and dark values denote low vibrational amplitude (hard tissue).*

Conclusions

Since changes in tissue stiffness may be indicative of an abnormal pathological process, imaging parameters related to tissue elasticity may provide a suitable gateway for differentiating normal from abnormal tissue types. In this paper, we introduced and discussed the principles and practices of two ultrasound-based tissue elasticity imaging techniques: compression elastography and vibration sonoelastography. Results illustrate that high contrast images can be obtained using various mechanical excitation sources and estimation strategies to represent important diagnostic information relating to soft tissue elasticity.

References

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Author Biography

Kenneth Hoyt received his B.S. and Ph.D. degrees from Drexel University, Philadelphia, PA in 2001 and 2005, respectively. His doctoral dissertation describes novel spectral-based methods for estimating and imaging soft tissue elasticity using ultrasound. Since 2005, he has been with the Department of Electrical and Computer Engineering at the University of Rochester as a post-doctoral fellow working on various ultrasound-based techniques for soft tissue elasticity imaging.