Elastography
General Principles and Clinical Applications

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KEYWORDS

• Elastography • Ultrasonic imaging • Ultrasonic elastography • MRI

KEY POINTS

- Like conventional medical imaging modalities, forward and the inverse problems are encountered in elastography.
- Quasistatic elastography visualizes the strain induced within tissue using either an external or internal source.
- Direct and iterative inversion schemes have been developed to make quasistatic elastograms more quantitative.
- Soft tissues display several biomechanical properties, including viscosity and nonlinearity, which may improve the diagnostic value of elastography when visualized alone or in combination with shear modulus. Elastography can characterize the nonlinear behavior of soft tissues and may be used to differentiate between benign and malignant tumors.

INTRODUCTION

Elastography visualizes differences in the biomechanical properties of normal and diseased tissues.[1–4] Elastography was developed in the late 1980s to early 1990s to improve ultrasonic imaging,[5–7] but the success of ultrasonic elastography has inspired investigators to develop analogs based on MRI[8–11] and optical coherence tomography.[12–14] This article focuses on ultrasonic techniques with a brief reference to approaches based on MRI.

The general principles of elastography can be summarized as follows: (1) perturb the tissue using a quasistatic, harmonic, or transient mechanical source; (2) measure the resulting mechanical response (displacement, strain or amplitude, and phase of vibration); and (3) infer the biomechanical properties of the underlying tissue by applying either a simplified or continuum mechanical model to the measured mechanical response.[2,15–18] This article describes (1) the general principles of quasistatic, harmonic, and transient elastography (**Fig. 1**)—the most popular approaches to elastography—and (2) the physics of elastography—the underlying equations of motion that govern the motion in each approach. Examples of clinical applications of each approach are provided.

THE PHYSICS OF ELASTOGRAPHY

Like conventional medical imaging modalities, forward and the inverse problems are encountered in elastography. The former problems are concerned with predicting the mechanical response of a material with known biomechanical properties and external boundary conditions. Understanding these problems and devising accurate theoretical models to solve them have been an effective strategy in developing and optimizing the performance of ultrasound displacement estimation methods. The latter problems are concerned with estimating biomechanical properties noninvasively using the forward model and knowledge of the mechanical response and external boundary conditions. A comprehensive review of methods developed to

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Ultrasound Clin 9 (2014) 1–11
http://dx.doi.org/10.1016/j.cult.2013.09.006
1556-858X/14/$ – see front matter Published by Elsevier Inc.

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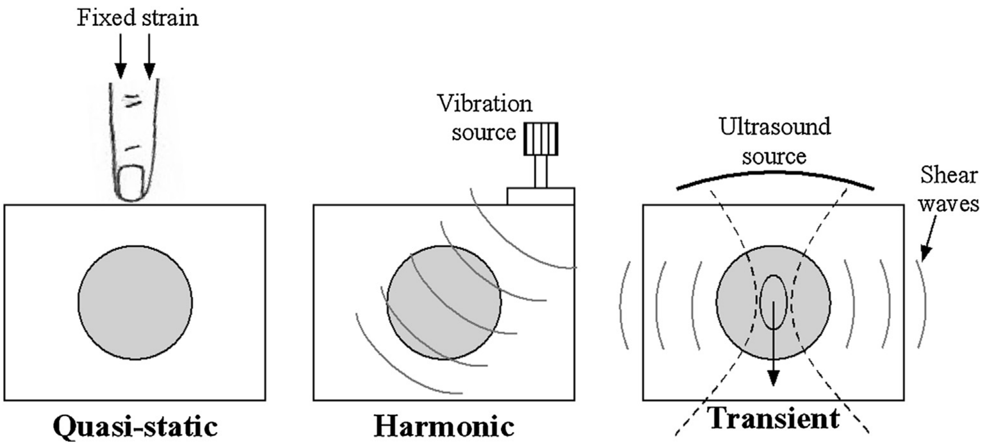

Fig. 1. Schematic representation of current approaches to elastographic imaging: quasistatic elastography (*left*), harmonic elastography (*middle*), and transient elastography (*right*).

solve inverse problems is given in the article by Doyley[19]; therefore, this section focuses only on the forward problem.

The forward elastography problem can be described by a system of partial differential equations (PDEs) given in compact form[20,21]:

$$\nabla \times [\sigma_{ij}] = \beta_i \quad \textbf{(1)}$$

where σ_{ij} is the 3-D stress tensor (ie, a vector of vectors), β_i is the deforming force, and ∇ is the del operator. Using the assumption that soft tissues exhibit linear elastic behavior, then the strain tensor (ε) maybe related to the stress tensor (σ) as follows[22]:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \quad \textbf{(2)}$$

where the tensor (C) is a rank-four tensor consisting of 21 independent elastic constants.[16,20,23] Under the assumption that soft tissues exhibit isotropic mechanical behavior, however, then only 2 independent constants, λ and μ (lambda and shear modulus), are required. The relationship between stress and strain for linear isotropic elastic materials is given by:

$$\sigma_{ij} = 2\mu\varepsilon_{ij} + \lambda\delta_{ij}\Theta \quad \textbf{(3)}$$

where $\Theta = \nabla \cdot \mathbf{u} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$ is the compressibility relation, δ is the Kronecker delta, and the components of the strain tensor are defined as:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial j} + \frac{\partial u_j}{\partial x_i}\right) \quad \textbf{(4)}$$

Lamé constants (ie, λ and μ) are related to Young modulus (E) and Poisson ratio (v), as follows[20,21]:

$$\mu = \frac{E}{2(1+v)}, \quad \lambda = \frac{vE}{(1+v)(1-2v)} \quad \textbf{(5)}$$

The stress tensor is eliminated from the equilibrium equations (ie, Equation 2) using Equation 3. The strain components are then expressed in terms of displacements using Equation 4. The resulting equations (ie, the Navier-Stokes equations) are given by:

$$\nabla \cdot \mu \nabla \mathbf{u} + \nabla(\lambda+\mu)\nabla \cdot \mathbf{u} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \quad \textbf{(6)}$$

where ρ the is density of the material, $\boldsymbol{u}$ is the displacement vector, and t is time. For quasistatic deformations, Equation 6 reduces to:

$$\nabla \cdot \mu \nabla \mathbf{u} + \nabla(\lambda+\mu)\nabla \cdot \mathbf{u} = 0 \quad \textbf{(7)}$$

For harmonic deformations, the time-independent (steady-state) equations in the frequency domain give[10,24]:

$$\nabla \cdot \mu \nabla \mathbf{u} + \nabla(\lambda+\mu)\nabla \cdot u = \rho\omega^2 \mathbf{u} \quad \textbf{(8)}$$

where ω is the angular frequency of the sinusoidal excitation. For transient deformations, the wave equation is derived by differentiating Equation 6 with respect to *x, y,* and *z,* which gives[21]:

$$\nabla^2 \Delta = \frac{1}{c_1^2}\frac{\partial^2 \Delta}{\partial t^2} \quad \textbf{(9)}$$

where $\nabla \cdot \mathbf{u} = \Delta$, and the velocity of the propagating compressional wave, c_1, is given by:

$$c_1 = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad \textbf{(10)}$$

The wave equation for the propagating shear wave is given by:

$$\nabla^2 \zeta = \frac{1}{c_2^2}\frac{\partial^2 \zeta}{\partial t^2} \quad \textbf{(11)}$$

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