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● *Original Contribution*

OPTIMIZATION OF A PIXEL-TO-PIXEL CURVE-FITTING METHOD FOR POROELASTOGRAPHY IMAGING

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Abstract—Ultrasound poroelastography is an imaging modality used to characterize the temporal behavior of soft tissue that can be modeled as a solid permeated by interconnected pores filled with liquid (poroelastic medium). It could be useful in the stage classification of lymphedema. Generally, time-constant models are applied to strain images, and precision of the fitting process, computational cost and versatility in response to changes in tissues properties are crucial aspects of clinical applications. In the work described here, we performed creep experiments on poroelastic phantoms and used rheologic models to visualize the changes in viscoelastic response associated with fluid mobility. We used the Levenberg–Marquardt algorithm as a fitting tool and performed parametric studies to improve its performance. On the basis of these studies, we proposed an optimization schema for the pixel-to-pixel curve-fitting process. We determined that the bimodal Kelvin–Voigt model describes efficiently the temporal evolution of the strain images in heterogeneous phantoms. (E-mail: belfor.galaz@usach.cl or bgalazd@gmail.com)

Key Words: **Ultrasound elastography, Poroelastography, Viscoelasticity imaging, Rheologic models, Creep test.**

INTRODUCTION

Ultrasound (US) elastography (Ophir et al. 1991) is a well-established imaging technique that allows the detection of pathologic defects in soft tissues through visualization of some mechanical features. In clinical practice, the standard elastography usually refers to axial strain elastograms (ASEs), which are images of the strain tensor component along the axis of insonification (Ophir et al. 1999). ASE images are computed from the signals by tracking the axial displacement induced on the tissue when a small quasi-static compression is generated using generally the ultrasound probe itself. This small compression and the assumption that the tissues behave as linearly elastic solids are crucial to relate the local changes in the ASE images to tissue stiffness distribution (Srinivasan et al. 2004a, 2004b). However, the mechanical behavior of the tissues is more complex, and therefore, novel elastographic techniques have been proposed to image additional mechanical properties of tissues related to their temporal behavior.

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The viscoelastic response of soft tissues can be visualized by subjecting them to a dynamic or quasi-static stimulus and using a specific model to characterize their spatial–temporal dependence (Fatemi and Greenleaf 1998; Greenleaf et al. 2003; Lerner et al. 1990). Quasi-static methods like stress relaxation and creep allow visualization of the viscoelastic tissue's properties through the characterization of time-varying ASE images obtained when a sudden (speed >2 s) step compression is applied and held for a specific time (Insana et al. 2004; Sridhar and Insana 2007). The impact of these viscoelastic imaging techniques may be relevant in tumor classification (Thomas et al. 2006, 2007; Zhi et al. 2007). In fact, *in vivo* studies have indicated that viscoelasticity imaging could be effective in the early detection of non-palpable breast lesions (Qiu et al. 2008). In this context, the application of viscoelastic models to soft tissues has been extensively studied using numerical simulations, *in vitro* phantom experiments and *in vivo* studies (Insana et al. 2004; Sridhar and Insana 2007; Sridhar et al. 2007a, 2007b; Qiu et al. 2008).

On the other hand, the viscoelastic response of tissues may be modified by the mobility of the interstitial fluid as a consequence of the stress distribution (Kalyanam et al. 2009). Considering this mechanism, the tissues behave as a poro-viscoelastic material, where

the dependence between fluid movement, pore pressure and the viscoelastic tissue response is a function of the applied stimulus and boundary conditions. The incorporation of this behavior may have important implications in tumor classification because of its fluid content and mobility. In addition, this poro-viscoelastic mechanism may also be relevant in diseases like lymphedema, where a malfunction of the lymphatic system induces a gradual accumulation of interstitial fluid.

Poroelastography imaging is an elastography modality that uses quasi-static techniques to characterize the temporal behavior of tissues that can be modeled as poroelastic media (Berry et al. 2006a; Konofagou et al. 2001; Righetti et al. 2004, 2005a). Similar to viscoelasticity imaging, a fast step compression is applied to the tissues, but it is held for a longer time (>500 s) to allow lateral fluid diffusion (Ammann et al. 2006; Konofagou et al. 2001; Nair et al. 2011). It allows the generation of new types of elastograms, which include the effective Poisson ratio (EPR) elastogram, the axial strain time constant (TC) elastogram, the effective Poisson ratio TC elastogram and the permeability elastogram (Righetti et al. 2004, 2005b, 2007b). These elastograms have the potential to provide new information, which may be clinically relevant in the diagnosis and staging of lymphedema. Indeed, the feasibility of using the temporal evolution of EPR elastograms to differentiate between normal and lymphedematous tissues has been determined by *in vivo* studies (Righetti et al. 2007a). The use of poroelastic models in a simulation study has indicated that the effect of "permeability contrast" can be a relevant aspect in the detection of inhomogeneity (Chaudhry et al. 2013).

In poroelastography imaging, the application of a mechanical model to the temporal sequence of EPR or ASE images permits the generation of the respective TC elastograms by using curve-fitting techniques on pixel-to-pixel temporal data (Nair et al. 2011; Righetti et al. 2005b, 2007a). Theoretical poroelastic models have been proposed (Armstrong et al. 1984; Berry et al. 2006b; Fung 1981; Leiderman et al. 2006; Samarin 1974); however, these models are unsuitable for *in vivo* applications. In particular, Kuei–Lai–Mow (KLM) biphasic poroelastic linear theory (Armstrong et al. 1984) predicts very well the time dependence of radial or axial strain of poroelastic materials in unconfined compression (Berry et al. 2006b). However, its complexity makes it difficult to use to describe elastographic *in vivo* data. Single exponential models have been proposed to estimate TC elastograms in clinical conditions (Nair et al. 2011; Righetti et al. 2005b). Performance analysis in terms of accuracy, precision, sensitivity, signal-to-noise ratio (SNR) and computation speed has revealed that these models can produce highly accurate and sensitive TC elastograms in real time at high SNRs (Nair et al. 2011).

In the work described here, we used rheologic models to capture the temporal behavior of poroelastic phantoms (water-saturated polyurethane foam) under unconfined creep compression. These models are formed by specific configurations of springs and dampers that define a viscoelastic cell, which is characterized by a time constant proportional to the ratio between viscosity and stiffness. Because of the biphasic nature of poroelastic phantoms, we believe that rheologic models formed by two viscoelastic cells (bimodal) should be more appropriate. In fact, the feasibility of using bimodal rheologic models was reported before the use of single-element transducers (Ammann et al. 2006). In creep-test configuration, the ASE images evolve in time as a consequence of the sustained axial stress, and its viscoelastic response is modified by the lateral diffusion of liquids. Thus, our long-term goal is to visualize these viscoelastic changes to improve the diagnosis of lymphedema. It is expected that its poroelastic nature should be more relevant in the lateral direction (Kalyanam et al. 2009), an aspect used by some poroelastograms (Righetti et al. 2004, 2005b, 2007b). However, the low lateral resolution of US imaging systems reduces the sensitivity of these techniques. Improvements in lateral resolution like dynamic focusing may help to overcome this disadvantage. However, the rheologic models required become more complex because of the coupling between axial and lateral strain (Kobelev et al. 2005). In this context, we believe that the use of ASE images with appropriate rheologic models may be useful in visualizing changes in the viscoelastic behavior of lymphomatous tissues associated with the interstitial fluid mobility. However, to achieve this, we need models capable of fitting the temporal ASE images with high precision and a computational time in accordance with the duration of the medical exam. In this work, our immediate goal was to propose a method of curve-fitting optimization and find an appropriate rheologic model to generate viscoelastic images (time constants) of high precision with minimal computational cost. We used the Levenberg-Marquardt (LM) algorithm (Madsen et al. 1999) as a fitting tool, and we compared the performance of different rheologic models in terms of their fitting precision, processing time and robustness to LM algorithm parameters. We evaluated the versatility of the proposed rheologic model in response to drastic changes in material properties by using an inhomogeneous phantom.