Computers in Biology and Medicine 54 (2014) 100–108

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

Evaluation of robust wave image processing methods for magnetic resonance elastography

Bing Nan Li [a,*], Xiang Shan [a], Kui Xiang [b,**], Ning An [c], Jinzhang Xu [d], Weimin Huang [e], Etsuko Kobayashi [f]

[a] Department of Biomedical Engineering, Hefei University of Technology, P.O. Box 112, Tunxi Road 193, Hefei, China
[b] School of Automation, Wuhan University of Technology, Wuhan, China
[c] School of Computer and Information, Hefei University of Technology, Hefei, China
[d] School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, China
[e] Neural and Biomedical Image Lab, Institute for Infocomm Research, Singapore
[f] Department of Precision Engineering, University of Tokyo, Tokyo, Japan

ARTICLE INFO

Article history:
Received 30 November 2013
Accepted 22 August 2014

Keywords:
Directional filtering
Magnetic resonance elastography
Noise suppression
Phase unwrapping

ABSTRACT

Magnetic resonance elastography (MRE) is a promising modality for in vivo quantification and visualization of soft tissue elasticity. It involves three stages of processes for (1) external excitation, (2) wave imaging and (3) elasticity reconstruction. One of the important issues to be addressed in MRE is wave image processing and enhancement. In this study we approach it from three different ways including phase unwrapping, directional filtering and noise suppression. The relevant solutions were addressed briefly. Some of them were implemented and evaluated on both simulated and experimental MRE datasets. The results confirm that wave image enhancement is indispensable before carrying out MRE elasticity reconstruction.

1. Introduction

There is a long tradition of soft tissue palpation in clinic for health evaluation and disease diagnosis. Manual palpation is not only limited to surface organs such as throat, breast and prostate for cancer screening, but also of major importance when diagnosing possible infection of liver and spleen [1]. Other than functional diagnosis [2], elasticity is essential for many emerging biomedical applications. For example, tactile sensation is important during surgical operation but it is difficult for medical robotics [3]. However, the outcomes of anatomical imaging, including ultrasound, computed tomography (CT) and magnetic resonance imaging (MRI), do not have explicit connections with soft tissue elasticity, in particular at the early stage of physiological alterations [4]. It is thus attractive to develop novel modalities to measure and visualize soft tissue elasticity quantitatively. This information is contributive to health evaluation, disease diagnosis, and medical robotics as well. Magnetic resonance elastography (MRE) is a promising technology in this regard [5].

For noninvasive palpation, MRE employs low-frequency mechanical waves as a virtual probe. Once being imported into soft objects, mechanical waves propagate with various complicated phenomena of refraction and diffraction. The pattern of wave propagation varies according to local biomechanical properties. With specially-programmed pulse sequences, MRI is able to capture varying wave patterns, from which it is possible to reconstruct or estimate soft tissue elasticity. In other words, MRE involves not only wave image reconstruction but also elasticity estimation. The first part is indispensable in most phase-contrast imaging, but the latter one is a challenging inverse problem of wave equation [6,7].

There have been several very good reviews on MRE [8–11], including those from the perspectives of method, technique and applications, respectively. Nevertheless, there is a lack of inspective study on wave image processing for MRE. Here we firstly introduce some popular techniques for MRE wave imaging, and then concentrate on the solutions for MRE wave image processing and analysis. The remainder of this paper is organized as follows. The second section briefs how wave images come into being in MRE and why they are prone to noise and artifacts. The third one describes some useful techniques for wave image enhancement, and how they assist elasticity reconstruction is explained with examples in the fourth section. Concluding remarks are drawn in the last section.

* Corresponding author. Tel.: +86 139 6508 9390.
** Corresponding author.
E-mail addresses: bingoon@ieee.org (B.N. Li), xkarcher@126.com (K. Xiang).

http://dx.doi.org/10.1016/j.compbiomed.2014.08.024
0010-4825/

2. Magnetic resonance wave imaging

MRE is designed to quantify soft tissue elasticity by noninvasive imaging techniques. It usually comprises an actuator for motion excitation, a specially-programmed magnetic resonance modality for motion imaging, and the software for elasticity interpretation [12]. There are two kinds of distinct MRE paradigms, one is static and the other one is dynamic. The static or quasi-static solutions track the tissues before and after deformation by using displacement-encoding or tagging pulse sequences [13]. They have widespread applications in evaluating myocardial stain. Note that both tagging and displacement-encoding pulse sequences are sensitive to large deformation only. Nevertheless, most soft tissues are nearly incompressible; hence substantial deformation is not easy. In addition, it is difficult to derive out quantitative strain maps because there is no information of force distribution [14].

Both imaging pulse sequences of static and dynamic MRE paradigms make use of the Stejskal–Tanner bipolar gradient pairs (BGPs) that are commonly found in phase contrast imaging. The Stejskal–Tanner BGPs are a group of balanced preparatory dephasing and rephasing gradients. If the tissues of interest are stationary in the encoding direction, there would be no accumulated difference in phase. In contrast, if the tissues are moving or vibrating, the resultant phase difference might encode such motion information. However, BGP has to be synchronized with external vibration in dynamic solutions [8–10]. The subsequent discussion is then limited to dynamic MRE, where the patterns of wave propagation in different soft tissues are imaged and quantitative elasticity is derivable.

Mechanical wave propagation is refractory and difficult to control [15]. In heterogeneous viscoelastic soft tissues, propagation has to confront attenuation, reflection and refraction [16]. MRE encodes wave propagation into phase; hence imaging parameters including BGP duration and strength have to be appropriate [17]. As shown in Fig. 1(a) through (d), if too small, signals would be too weak; if too big, they are prone to being wrapped. Also, in MRE wave images, there are other noise and outliers from wave interference [18], electromagnetic turbulence [19] or chemical phase shifts.

One of the biggest challenges in MRE wave imaging lies in low signal-to-noise ratio (SNR). There has been an intrinsic mechanism since the beginning [5], namely, employing multiple synchronized BGPs to amplify weak elastic vibrations inside heterogeneous soft tissues. As shown in Fig. 1(e) through (h), SNR usually increases with more pairs of Stejskal–Tanner gradients. Nevertheless, the pairs of BGPs are limited to other imaging parameters including repetition time (TR) and echo time (TE). In particular, the more pairs of Stejskal–Tanner gradients, the more demanding to MRI hardware. As a consequence, a scanning with multiple BGPs is often subjected to field inhomogeneity, electromagnetic noise and phase wrapping. In other words, it might be more effective to enhance tissue motion directly. Usually, low-frequency shear waves penetrate deeper into soft tissues, while high-frequency shear waves have higher spatial resolution. Then, there is another dilemma between penetration and resolution [20]. It is yet an open issue on efficiently delivering shear waves to a specific region of interest (ROI) [19].

Imaging speed is another big issue in MRE that involves multiple steps of phase delay for wave field reconstruction. In some cases, it has to capture the information of wave propagation in all three directions. Therefore, for a dedicated low-field MRE system [21], it is not surprising to take about 80 min for wave imaging. Although MRE is theoretically insensitive to unsynchronized motion, it inevitably results in low SNR [22] and, in particular, is not reasonable to keep objects static for such a long time. It is thus attractive to speed up MRE wave imaging. Ultrafast pulse sequences including [17] and [23] are helpful, but their outcomes often suffer from low SNR. Murphy et al. [32] found that, for relatively low spatial frequency content and low amplitude of the shear waves in the brain, it is possible to significantly reduce acquisition time by subsampling *k*-space while maintaining a mean error of elasticity reconstruction less than 10%.

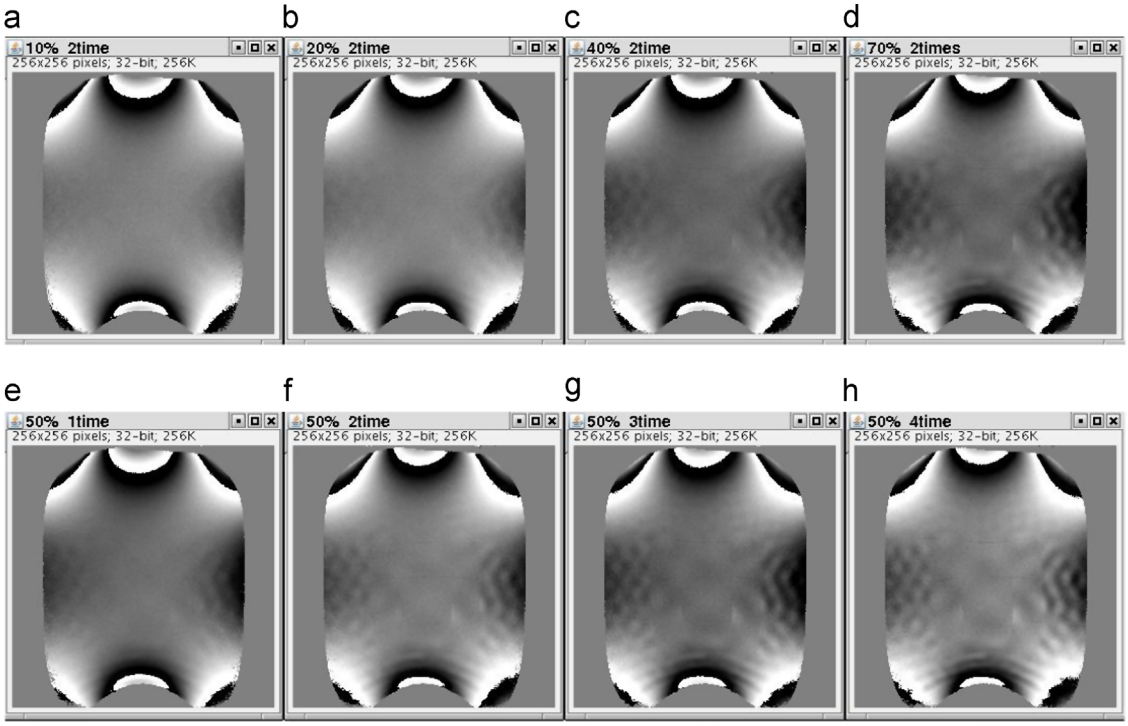

Fig. 1. Influence of controlling parameters of a MRE imaging pulse sequence: (a)-(d) varying BGP strength, (e)–(h) varying numbers of BGPs.