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Ultrasound elastomicroscopy using water jet and osmosis loading: Potentials for assessment for articular cartilage

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Abstract

Research in elasticity imaging typically relies on 1–10 MHz ultrasound. Elasticity imaging at these frequencies can provide strain maps with a resolution in the order of millimeters, but this is not sufficient for applications to skin, articular cartilage, or other fine structures. In this paper, we introduced two methods of ultrasound elastomicroscopy using water jet and osmosis loading for imaging the elasticity of biological soft tissues with high resolutions. In the first system, the specimens were compressed using water jet compression. A water jet was used to couple a focused 20 MHz ultrasound beam into the specimen and meanwhile served as a "soft" indenter. Because there was no additional attenuation when propagating from the ultrasound transducer to the specimen, the ultrasound signal with high signal-to-noise ratio could be collected from the specimens simultaneously with compressing process. The compression was achieved by adjusting the water flow. The pressure measured inside the water pipe and that on the specimen surface was calibrated. This system was easily to apply C-scan over sample surfaces. Experiments on the phantoms showed that this water jet indentation method was reliable to map the tissue stiffness distribution. Results of 1D and 2D scanning on phantoms with different stiffness are reported. In the second system, we used osmotic pressure caused by the ion concentration change in the bathing solutions for the articular cartilage to deform them. When bovine articular cartilage specimens were immerged in solutions with different salt concentration, a 50 MHz focused ultrasound beam was used to monitor the dynamic swelling or shrinkage process. Results showed that the system could reliably map the strain distribution induced by the osmotic loading. We extract intrinsic layered material parameters of the articular cartilage using a triphasic model. In addition to biological tissues, these systems have potential applications for the assessment of bioengineered tissues, biomaterials with fine structures, or some engineering materials. Further studies are necessary to fully realize the potentials of these two new methods.

Keywords: Ultrasound; Biomicroscopy; Elasticity imaging; Elastomicroscopy; Water jet; Indentation; Ultrasound indentation; Osmotic pressure; Triphasic model; Articular cartilage

1. Introduction

Tissue elasticity is generally known to be associated with pathologic changes, such as sclerous cancer, edema, degeneration, fibrosis and pressure sore [1,2]. Current research in ultrasonic elasticity imaging of soft tissues typically relies on 1–10 MHz ultrasound which is the frequency range used for most medical imaging applications [3]. The spatial resolution obtained at these frequencies (on the order of millimeters) is not sufficient for the study of very fine structures in tissues such as skin layers or articular cartilage [4–7].

Nanoindentation [8] has recently been used for the microscopic mechanical assessment of biological tissues including bone [9], spinal fusion [10], and articular cartilage [11,12]. However, nanoindentation can not provide mechanical properties of tissues at different depths. The testing results are highly dependent on the surface condition of the specimen [10]. Elasticity imaging based on optical coherence tomography (OCT) has also been reported [13,14]. Optical beams are used to probe tissues at different

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depths, thus images of the scattering intensity from subsurface structures of soft tissues are obtained to construct strain images [15,16].

High-frequency (20–100 MHz) B-mode imaging (ultrasound biomicroscopy) has been widely used in recent years for the assessment of eye tissues, skin, blood vessel, and articular cartilage with an axial resolution of approximately 100–20 μm [4]. Elastography of artery walls has been reported using intravascular ultrasound backscattered signals (~30 MHz) obtained while cyclic blood pressure applied a temporally varying loading source on the vessel [17,18]. In other tissues, requiring an external compression source, attempts have been made to acquire high-frequency (50 MHz) ultrasound signals while squeezing tissue through a slit in a compressor [6]. However, the slit introduces uncertainties in the mechanical boundary conditions on the specimen and it's difficult to estimate the stress distribution. Fortin et al. [5] used two parallel plates to compress the two sides of cartilage specimens and to collect 50 MHz ultrasound from the open side. Using this configuration, the lateral tissue displacements in one direction were mapped under an axial compression. Based on the ultrasound indentation technique [19–22] using a probe with an in-series ultrasound transducer (frequency ranged from 5 to 15 MHz) and a load sensor, Zheng and coworkers have developed a number of systems for mapping one-dimensional mechanical properties of articular cartilage (AC) using high-frequency ultrasound (20–50 MHz) [23–25]. 2D high-frequency ultrasound elasticity imaging has been earlier described in theory or using computer simulation in the literature [26,27]. Recently, Mofid et al. reported a method to map skin elasticity in vivo using a 20 MHz ultrasound imaging system together with a stretching device, which has two stretching elements to hold the skin surrounding the imaging region using suction [28]. Vogt et al. used a specially designed 20 MHz ultrasound probe, which could provide a suction force in the cavity between the skin and the transducer [29]. When the probe was applied on the skin surface, the negative suction pressure could lift the skin towards the transducer so that the skin elasticity could be mapped. Gennisson et al. extended the transient elastography method [30] from low frequency to 50 MHz and used to map the skin elasticity in the depth direction [31]. A shear vibration was used to disturb the skin and propagation of the shear wave was monitored using the transient ultrasound imaging.

In this paper, we introduce two ultrasound elastomicroscopy systems, which utilize a mechanical loading using a water jet indentation device and an osmotic loading induced by changing the ion concentration of the bathing solution for the tissue, respectively. In both systems, water served as a coupling medium, so that high-frequency focused ultrasound beam could be used to monitor the tissue deformation at a microscopic level. Using our ultrasound elastomicroscopy systems, the strain images at both ultrasound propagation direction and orthogonal direction could be obtained. Furthermore, with the estimated stress distribution, modulus images could also be derived. The system architectures were described. Experimental results on both gel phantoms and bovine articular cartilage were provided and discussed.

2. Methods

2.1. Ultrasound biomicroscopy for water indentation and osmosis loading

A biomicroscopy system with a frequency range of 10–80 MHz was developed. It was comprised of a pulser/receiver (Model 5601A, Panametrics, Waltham, MA, USA), 3D translating device (Parker Hannifin Corporation, Irvine, CA, USA), 500 MHz A/D converter (Model CompuScope 8500PCI, Gage, Canada), PC and custom-developed software. For the water jet indentation system, a bubbler was used to eject a water jet by controlling the water flow (Fig. 1). The diameter of the water ejecting nozzle was 1.94 mm. A 20 MHz focused ultrasound transducer with a focal length of 12.7 mm (GE Panametrics, Inc., OH, USA) was fixed with the water ejector and the focused ultrasound beam could propagate through the bubbler when it was full of water as the coupling medium. The transducer and the bubbler were installed to a 3D translating device which was used to adjust the distance from the nozzle to the specimen surface and to perform 2D scanning over the tissue. During experiment, specimens were placed on a rigid platform within a water container. A pressure sensor (EPB-C12, Entran Devices, Inc., Fairfield, NJ, USA) was used to measure the water pressure within the water pipe. A load cell (ELFS-T3 mol/L, Entran Devices, Inc., Fairfield, NJ, USA) located under the platform could monitor the overall force applied on the specimen. Both of them were calibrated. The program was used to control the

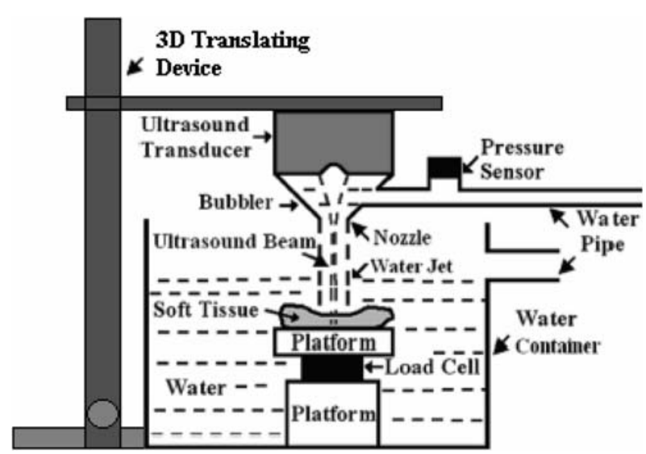

Fig. 1. Diagram of the ultrasound water jet indentation system. The water jet was used as an indenter and focused high-frequency ultrasound was employed to monitor the deformation of the soft tissue. The 3D translating device facilitated the system to easily apply C-scan for the soft tissue. By applied different pressure during C-scan sequences, the modulus image was obtained with the recorded pressure, deformation and thickness.