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Acoustic radiation force optical coherence elastography using vibro-acoustography

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ABSTRACT

High-resolution elasticity mapping of tissue biomechanical properties is crucial in early detection of many diseases. We report a method of acoustic radiation force optical coherence elastography (ARF-OCE) based on the methods of vibro-acoustography, which uses a dual-ring ultrasonic transducer in order to excite a highly localized 3-D field. The single element transducer introduced previously in our ARF imaging has low depth resolution because the ARF is difficult to discriminate along the entire ultrasound propagation path. The novel dual-ring approach takes advantage of two overlapping acoustic fields and a few-hundred-Hertz difference in the signal frequencies of the two unmodulated confocal ring transducers in order to confine the acoustic stress field within a smaller volume. This frequency difference is the resulting "beating" frequency of the system. The frequency modulation of the transducers has been validated by comparing the dual ring ARF-OCE measurement to that of the single ring using a homogeneous silicone phantom. We have compared and analyzed the phantom resonance frequency to show the feasibility of our approach. We also show phantom images of the ARF-OCE based vibro-acoustography method and map out its acoustic stress region. We concluded that the dual-ring transducer is able to better localize the excitation to a smaller region to induce a focused force, which allows for highly selective excitation of small regions. The beat-frequency elastography method has great potential to achieve high-resolution elastography for ophthalmology and cardiovascular applications.

Keywords: Optical coherence tomography, elastography, acoustic radiation force, ultrasound
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1. INTRODUCTION

Mechanical elasticity of tissue is a major indicator for diseased tissue compared to normal ones. Elastography, which quantifies the tissue mechanical properties in response to force, has gained attention over the last decade. Elasticity imaging methods including ultrasound, magnetic resonance imaging (MRI), and tactile imaging have been used to classify abnormal tissues, such as cancerous lesions and nodules, fibrosis, and atherosclerotic plaques[1]. Optical coherence elastography (OCE), which is based on optical coherence tomography (OCT), is an emerging field that holds three major advantages over other modalities: high resolution, high speed, and high sensitivity[2-3]. It has capabilities to image elasticity changes in the early stages of disease, as well as detect the subtle progression of disease.

We previously reported on a dynamic phase-resolved acoustic radiation force (ARF-OCE) method to achieve high resolution and high speed imaging on tissue-mimicking phantoms and human coronary artery tissues[4]. Using ARF as dynamic excitation, and Doppler OCE as detection, relative values of strain and Young's module could be imaged. In order to obtain absolute values of the mechanical properties, we also developed a method of resonant ARF-OCE technique, which sweeps over a range of modulation frequencies to determine the resonant frequency of the sample[5]. In both methods, the acoustic pressure field of the transducer focused at approximately a lateral region of 500 um, and a depth region of 10 mm. The excitation signal is greatly diminished by the energy dispersion caused by such a large focal volume. In order to better distinguish small regions and zooming into tissue areas of interest, a method that enables reduced region of excitation is essential.

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In this paper, we propose an ARF-OCE method using a confocal dual-ring transducer to generate a "beating" frequency excitation on the sample. By applying a continuous wave to both transducers with a small frequency difference, we observe a modulated signal at the overlapping focal region of the two transducer elements, similar to vibro-acoustography[6-7]. This resulting stress field where the signals overlap is confined to a smaller three-dimensional region depending on the amount of overlap in the two acoustic fields, thus preventing dispersion and energy loss. This vibro-acoustic ARF-OCE method has the potential to finely focus onto small regions as well as distinguish tissues features with high resolution.

2. METHODOLOGY

2.1 Tissue-Mimicking Phantom and Tissue Preparation

A uniform silicone tissue-mimicking phantom was fabricated, with 0.04% (by weight) of silicone activator. The sample, 5.5 cm total in diameter, was placed on top of a holder, and then sectioned for OCE imaging.

A two-layer silicone phantom was also fabricated to imitate layer discrimination in tissue. The top layer is a 0.04% silicone phantom, with a thickness of approximately 200 um, while the bottom layer is composed of 0.05% silicone activator, with a thickness of 1 cm.

2.2 ARF-OCE System

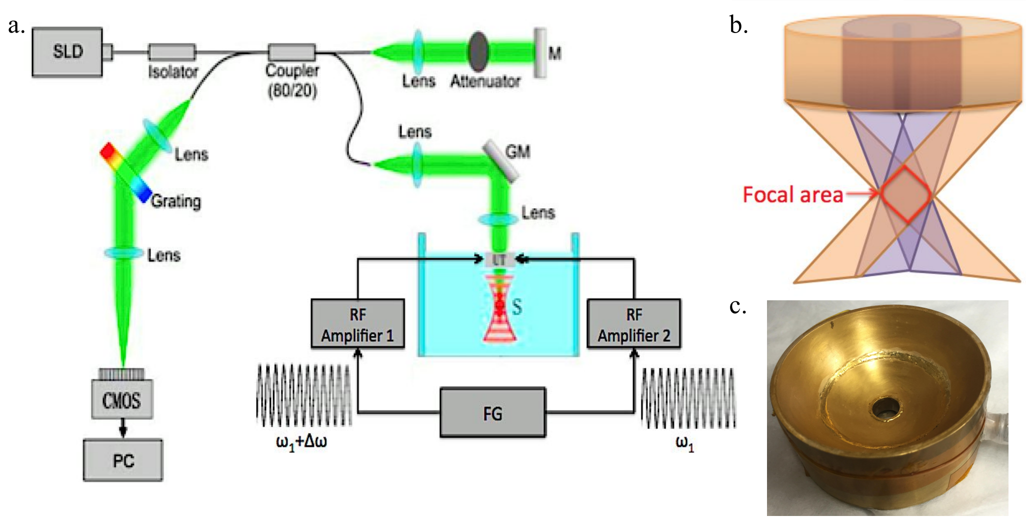

Figure 1. ARF-OCE System; a. Schematic diagram of ultrasound excitation and OCE detection: SLD-superluminescent diode, M-mirror, GM-Galvo mirror, UT-dual ring ultrasound transducer, S-sample, RF-radiofrequency, FG-function generator, CMOS-complementary metal oxide semiconductor. b. Schematic diagram of dual-ring ultrasonic transducer with focal region outlined in red. c. Image of dual-ring ultrasonic transducer.

The OCE system involves an OCT system for detection, ultrasound system for excitation, and computer for image processing. The basic design is shown in figure 1a. The system resolution is approximately 2.5 um axially and 15 um laterally. The function generator feeds two separate continuous-wave signals into two amplifiers. The resonant frequencies of the dual-ring focused ultrasonic transducer are 2.1 MHz, and will generate an acoustic radiation force (ARF) excitation on the sample. The frequency of one of the transducers is manipulated to differ from the other by a small amount less than 1% of the center frequency in order to generate a modulated wave at the focal zone[6-7]. The focal zone is the region where the inner and outer transducers completely overlap, which is shown in the red outlined region of figure 1b. An image of the dual-ring transducer is shown in figure 1c.

On the detector side, we use a superluminescent diode source with a central wavelength of 890 nm, and a bandwidth of 150 nm. The light enters an 80/20 coupler, with 20% of the light traveling to the sample arm and 80% to the reference arm. The light from the reference arm gets reflected back via a mirror, while the light from the sample arm interacts with the sample, and the scattering is detected. The light of the sample arm travels through the small hollow ring in the ultrasound transducer, so that the light and acoustic waves are confocal on the sample. Both arms travel back via the same fiber into the camera arm, which houses a collimator to guide the light, a diffraction grating to separate the wavelengths, a narrowing lens to focus the beam, and a CMOS camera, which generates an interference signal. Finally, the interference signal is fed into the computer, where Fourier Transforms are performed to generate raw OCT images. The data are processed using Doppler methods and the phase shifts are determined. The phase information is calculated based on the changes between axial scans or A-lines[4]. Intuitively, a greater phase change means more sample displacement, which means a softer sample.

3. RESULTS AND DISCUSSION

The feasibility of the beating frequency approach was first tested on a homogeneous silicone phantom. In order to generate a comparison between the single ring modulation and dual ring beating frequency, we imaged a section of the same uniform silicone phantom. In the single ring experiment, we used a function generator to directly apply a modulated pulse that varies from 100Hz to 5000Hz. In the dual ring experiment, we used the function generator to apply two continuous wave signals, with a "beating" frequency difference of 100Hz to 5000Hz, mimicking the same modulation frequency at the focal region. We applied a similar pre-amplified voltage in both cases, 200mvpp to one transducer for the single ring case, and 100mvpp to each of two transducers in the dual ring experiment. The displacement differences are likely due to the differences in amplification of the two transducer inputs. Using the principles of Doppler, we were able to obtain the average maximum vibrational displacement of the phantom under each excitation condition for both the single and dual ring case, shown in figure 2. Because the displacement values represent relative vibrational response, we wanted to verify the feasibility of the dual ring modulation by comparing the resonance frequency. As shown in figure 2, for both cases, the signal increased when the modulation is below 2000Hz, then peaks at 2000 Hz, which is the resonance frequency of the silicone phantom, and finally decreases when frequency is greater than 2000 Hz.

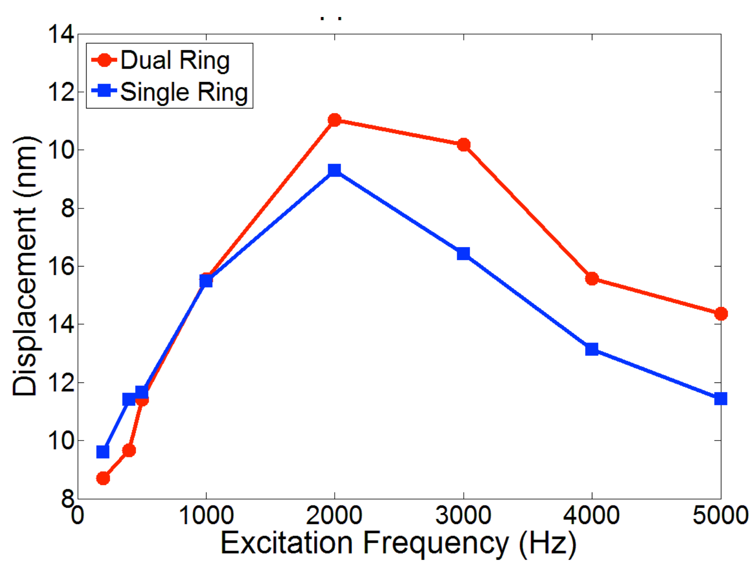

Figure 2. Comparison of displacement of tissue when using single ring vs. dual ring excitation. Resonance frequency of phantom is 2000Hz.

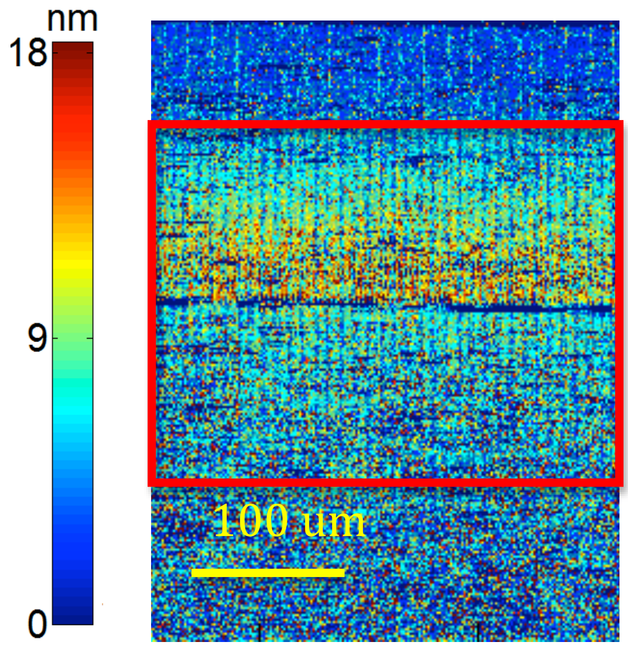

Figure 3. OCE image using dual ring vibro-acoustography approach showing displacement shift of dual-layered silicone phantom at resonance frequency excitation of 2000Hz. Red box represents focal zone.

Next we imaged a section of a dual-layered silicone phantom using the dual ring approach, shown in figure 3. Our aim was to focus the acoustic stress field to an area near the boundary of the two phantoms for better distinction. The resulting focal area is boxed in red, and shows a boundary between the signal region and the non-signal region, especially on the upper boundary. It is important to note that the top area above the red box shows the phantom with no modulated signal. This means that the dual-ring transducer was able to penetrate through the top of the phantom to focus on the intended region of interest, which is where the layers overlap. This is a phenomenon that was not observed in the single ring transducer, with a less focused axial focal region.

4. CONCLUSION

We have developed a method of ARF-OCE using the beating frequency of two ultrasonic transducers to generate a highly concentrated 3-dimensional focal region. The feasibility of this method was initially tested on uniform tissue-mimicking phantoms, where we confirmed that the signal is more highly focused on a smaller zone. We also confirmed that the resonance frequency of the sample measured from the dual ring beating frequency approach is consistent with the resonance frequency obtained from the single ring transducer method. We have performed imaging of a two-layered silicon phantom with the beat frequency ARF-OCE. We were able to focus the concentrated signal onto the region where the boundary between the two phantoms are, and generate images to show the two layers. The acoustic radiation force was able to penetrate the top of the phantom and focus directly on the region of interest. These results show that our beating frequency ARF-OCE method can generate a highly confined 3-D ARF excitation region. This method has great potential to produce high-resolution images of tissue samples and quantitatively characterize mechanical properties of these samples using the resonance frequency.

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