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Light and Sound: Integrating Photonics with Ultrasonics

Matthew O'Donnell[1], Geng-Shi Jeng[1], MinWoo Kim[1], Soon Joon Yoon[1], John J. Pitre Jr[1], David S. Li[1], Mitchell A. Kirby[1], Hong-Cin Liou[1], Tueng T. Shen[1], Ruikang Wang[1], and Ivan Pelivanov[1]

[1]Department of Bioengineering, University of Washington, Seattle, Washington 98105, USA

1. Introduction

Coherent light and sound have become essential tools in modern medicine. Lasers are routinely used for both therapeutic and diagnostic applications, and real-time ultrasound scanning has become the dominant biomedical imaging modality in the world. Starting over thirty years ago, scientists and engineers have combined these modalities for applications ranging from non-contact sensing to novel molecular imaging techniques. In this paper, we explore integrated photonic-ultrasonic systems, focusing on examples where light generates sound, light detects sound, and sound "tickles" light. We also present specific applications of integrated photonic-ultrasonic techniques, including photoacoustics for molecular imaging, non-contact laser ultrasound systems for medical and non-medical applications, and optical coherence elastography (OCE) in which air-coupled ultrasound stimulates propagating shear waves in the eye and skin tracked with real-time, 3-D optical coherence tomography (OCT).

2. Photoacoustic Imaging

Nearly every object has a unique optical signature based on its molecular constituents. As a result, optical spectroscopy is one of the most important tools in all of science and technology. For biomedical applications, it can help quantify molecular components within complex structures based on each constituent's optical absorption spectra. Spatially resolved optical spectroscopy is not used routinely in vivo, however, because high tissue scattering typically limits ballistic photon penetration to a millimeter or less. Photoacoustics (PA) has been proposed to overcome this barrier.

For over two decades, photoacoustic imaging has been tested clinically, but successful human trials have been limited. To enable quantitative clinical spectroscopy, the fundamental issues of wavelength-dependent fluence variations and inter-wavelength motion (see **Fig. 1**) must be overcome.

Our group has developed a real-time, spectroscopic photoacoustic/ultrasound (PAUS) imaging system including a compact, 1-kHz rep-rate wavelength-tunable laser[1]. Instead of illuminating tissue over a large area, a narrow laser beam is scanned sequentially using a fiber-optic delivery system, with partial PA image reconstruction for each laser pulse. The final image is then formed by coherently summing partial images. This scheme enables (i) spectroscopic PA imaging with automatic compensation of wavelength-dependent fluence variations and (ii) motion correction of spectroscopic PA frames using US speckle tracking in real-time systems.

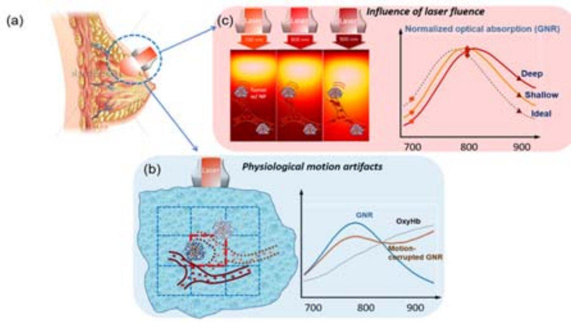

Fig. 1 (a) Issues in spectroscopic photoacoustic imaging; (b) motion artifacts; (c) wavelength dependent laser fluence variations.

3. Laser Ultrasound

For over thirty years, laser ultrasound (LU) has been used as an alternative to conventional ultrasound scanning for a range of applications. Among its many advantages, two stand out. First, laser-generated US transients are ultra-wideband, providing at least 3 times better resolution compared to conventional US transducers with the same characteristic frequency. Second, the system is fundamentally non-contact and removes all issues related to US coupling. However, it has remained a specialty technique primaruly because of its disadvantages, including low sensitivity, instability, low pulse repetition rate and high cost.

We have recently overcome these limitations with a new kHz-rate fiber-optic LU scanner [2-4]. We have used this system for a range of applications in non-destrutive testing of materials. The basic experimental configuration for non-contact inspection of composite materials used in the aerospace industry is illustrated in **Fig. 2**. A high repetition rate solid state laser acts as the source of ultrasound through photoacoustic excitation of mechanical waves at the suface of the material. Ultrasound waves reflected from heterogeneities within the material are detected at the same surface using a novel interferometer based on a Sagnac design. This approach overcomes all of the significant disadvantages of current laser ultrasound systems and forms the basis of a compact, portable, cost-effective, and highly sensitive non-contact ultrasound inspection system.

In addition to a wide range of applications in materials testing, this same approach has been used for biomedical applications such as scatter-free spectrophotometry [5] and label free flow cytometry.

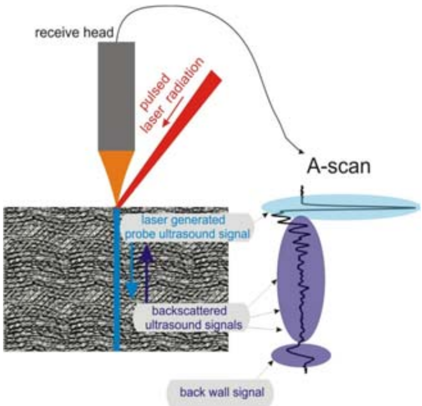

Fig. 2 Basic principle of non-contact inspection with laser ultrasound.

4. Optical Coherence Elastography

Elastography is a key player in characterizing soft media such as biological tissue. Although it is widely used in both clinical diagnostics and basic science research, nearly all methods require direct physical contact with the object of interest and can even be invasive. For a range of applications, including diagnostic measurements on the anterior segment of the eye and evaluating donor tissue elasticity for skin grafts, physical contact is not desired and may even be prohibited.

Recently, our group developed a fundamentally new approach to dynamic elastography using non-contact mechanical stimulation of soft media with precise spatial and temporal shaping [6-7]. We call it acoustic micro-tapping (AμT) because it employs focused, air-coupled ultrasound to induce mechanical displacement at the boundary of a soft material using *reflection-based* radiation force. Combining it with high-speed, four-dimensional (three space dimensions plus time) phase-sensitive optical coherence tomography (OCT) creates a non-contact tool for high-resolution and quantitative dynamic elastography (OCE) of soft tissue at near real-time imaging rates. An example of a robotic AμT-OCE system we are currently developing to monitor the elastic properties of skin is illustrated in **Fig. 3**.

We have used AμT-OCE to characterize the anisotropic elasticity of cornea and skin. Starting with a transverse isotropic model of material elastic characteristics, we have developed a nearly-incompressible TI model we call the NITI model to describe deformations in these tissues. Using real-time measurements of elastic wave propagation in cornea and skin, we have successfully extracted elastic moduli that have been confirmed in animal models using conventional destructive mechanical measurements. Future work is directed toward clinical systems for corneal diagnostics and management of skin grafts.

odonnel@uw.edu

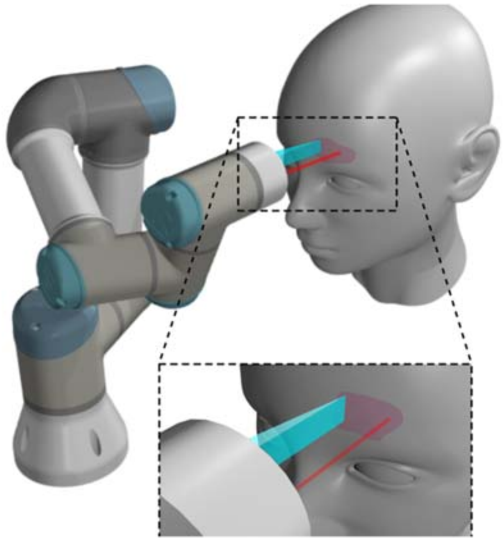

Fig. 3 Non-contact dynamic elastography combining optical coherence tomography (red) for imaging with air-coupled ultrasound (blue) for mechanical stimulation.

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References
1. G-S Jiang et al: Nat. Commun. **12(1)** (2021) 716.
2. I. Pelivanov et al: J. Appl. Phys. **115(11)** (2014) 113105-1.
3. I. Pelivanov et al: Photoacoustics **2(2)** (2014), 63.
4. I Pelivanov et al: IEEE Tran. UFFC **62(9)** (2015) 1696.
5. I. Pelivanov et al: Scientific Reports **8** (2018) 14425.
6. Ł. Ambroziński et al: Applied Physics Letters **109** (2016) 043701.
7. Ł. Ambroziński et al: Sci. Rep. **6** (2016) 38967.