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Journal Title: Optics Letters
Volume: Volume 45, Number 7
Publisher: (publisher) | 2020-04-01, Pages 1810-1813
Type of Work: Article
Publisher DOI: 10.1364/OL.383932
Permanent URL: https://pid.emory.edu/ark:/25593/vvn9s

Final published version: http://dx.doi.org/10.1364/OL.383932
Accessed November 7, 2022 10:50 AM EST
Ultrafast ultrasound imaging of surface acoustic waves induced by laser excitation compared with acoustic radiation force

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Abstract

Two generation mechanisms—optical perturbation and acoustic radiation force (ARF)—were investigated where high frame rate ultrasound imaging was used to track the propagation of induced SAWs. We compared ARF-induced SAWs with laser-induced SAWs generated by laser beam irradiation of the uniformly absorbing tissue-like viscoelastic phantom, where light was preferentially absorbed at the surface. We also compared the frequency content of SAWs generated by ARF versus pulsed laser light, using the same duration of excitation. Differences in the SAW bandwidth were expected because, in general, laser light can be focused into a smaller area. Finally, we compared wave generation and propagation when the wave’s origin was below the surface. We also investigated the relationship between shear wave amplitude and optical fluence. The investigation reported here can potentially extend the applications of laser-induced SAW generation and imaging in life sciences and other applications.

Utilization of a pulsed laser beam to generate SAWs based on thermoelastic effects has been previously introduced to study mechanical properties of thin metal films and plates [1–3]. This approach typically uses a laser pulse to generate SAWs on the surface of the material and detects the subtle surface displacement with piezoelectric or capacitance transducers [3], or by using interferometers [4]. Laser-induced SAW imaging has also been applied to biological tissues [5–7]. For example, to evaluate corneal ectasia, laser irradiation was used to induce displacement at the corneal surface, and optical coherence tomography (OCT) was employed to detect the laser-induced displacement [8–10]. These studies have shown that imaging of laser-induced SAWs can be used to measure the stiffness of superficial tissue.

Disclosures. The authors declare no conflicts of interest.
Another way to remotely excite SAWs in soft tissue is to apply acoustic radiation force (ARF) using low frequency focused ultrasound (US) [11–13]. The SAWs generated by ARF can then be observed by OCT with an imaging depth of 2 mm or by ultrafast US imaging with an imaging depth of several centimeters. Ultrafast US imaging utilizes transmission of plane or diverging waves to attain a frame rate typically higher than 1,000 frames per second over a large field of view. This frame rate enables recording of transient, subtle movements of tissue and visualization of SAW propagation.

Laser-induced SAWs and ARF-induced SAWs may have different characteristics due to the difference in excitation mechanisms. With laser excitation, SAWs are generated by thermoelastic effects or ablation effects [14]. With ARF excitation, SAWs are generated mainly due to a transfer of momentum from the propagating acoustic waves to the medium through attenuation or reflection of the ultrasonic wave [15]. Here we investigate the differences in propagation velocity and frequency spectrum between SAWs induced by laser excitation and SAWs induced by ARF excitation. In addition, we also investigate the relationship between the shear wave amplitude and the optical fluence. Ultrafast US imaging was used to measure the propagation of the SAWs for both laser-generated and ARF-generated cases.

In the first experiment, we compared the velocity of SAWs induced by two methods. Phantoms of three different degrees of stiffness were prepared by dissolving gelatin powder (gelatin, Type A; MP Biomedicals, LLC., Santa Ana, CA, U.S.) in distilled water (6%, 9%, and 12% w/v concentrations). To mimic optical absorption, 0.5% (w/v) graphite powder (Graphite 282863; Sigma-Aldrich, Inc., St. Louis, MO, U.S.) was added to solutions. To provide US scattering, 2% (w/v) 60–120 μm silica particles (silica gel 236772; Sigma-Aldrich, Inc., St. Louis, MO, U.S.) were also added. Each phantom had the same dimensions: 6.2 cm × 5.1 cm × 5.1 cm (L × W × H).

A previously developed US, photoacoustic (PA), and elasticity imaging platform, which was implemented on a programmable US research scanner (Vantage 256; Verasonics, Inc., Kirkland, WA, U.S.), was used to carry out all of the imaging experiments [16]. A pulsed Nd:YAG laser (Vibrant 532 I; Opotek Inc., Carlsbad, CA, U.S.) operating at 1,064 nm wavelength was interfaced with the imaging platform to irradiate the phantom and to excite both PA transients and photothermal SAWs. The duration of the laser pulse was about 5 ns. The laser light was delivered by an optical fiber with a diameter of 1.5 mm. A linear array US transducer (CL15–7; Philips Healthcare, Andover, MA, U.S.) was used to acquire photoacoustic (PA) and US signals, as well as to emit the ARF push pulse. The gap between the transducer and phantom surface was filled with water to provide acoustic coupling.

During the experiments, PA imaging was performed first, followed by ultrafast US imaging to track the laser-induced displacement induced within and on the surface of the phantom. In other words, the same laser pulse was used to generate the PA response and to induce tissue motion, both due to thermal expansion. The SAW propagation was recorded using ultrafast US imaging where 30 ultrafast US images at a frame rate of 3.3 kHz were captured starting 300 μs after the laser pulse. Next, instead of a laser pulse, a 300 μs ARF pulse was applied, and another set of 30 ultrafast US images at the same frame rate was recorded immediately.
after the ARF push pulse. The ARF push beam was focused 2 mm below the surface of the phantom.

SAW velocity was measured for both laser-based excitation and ARF-based excitation. We calculated the displacement maps by correlating adjacent ultrafast US imaging frames along the axial direction. Two points 0.2 mm below the phantom surface and 0.86 mm apart were selected to calculate SAW propagation velocities. These two points were about 3.57 and 4.43 mm away from the center of the excitation region to allow SAWs to develop (thus avoiding transient artifacts caused by the push pulse), yet close enough to make sure that the SAWs were strong enough to provide an adequate signal-to-noise ratio (SNR) in displacement measurements. The time-displacement curves at these two locations were evaluated from displacement maps at different time points. After interpolation with a time interval of 3 μs and normalization of shear wave amplitude, we calculated the time delay of the shear wave traveling from one point to another using a correlation-based approach. Finally, SAW velocities were estimated by dividing the physical distance between two points (0.86 mm) by the estimated time delay.

Due to the solid-fluid interface between the phantom and water, SAWs generated in our experiments are essentially Scholte waves that travel at 84% of the shear wave speed [17]. Therefore, a correction factor of 1.19 was applied to calculate the shear wave speed. For each phantom, the laser/ARF SAW imaging process was repeated four times. A two-sample two-sided student t-test (MathWorks, Natick, MA, U.S.) was used to calculate the statistical significance in shear wave velocity (SWV) values obtained by the laser-induced SAW imaging method versus the ARF-based SAW imaging method.

In the second experiment, we compared the frequency content of ARF-induced SAWs and laser-induced SAWs. A phantom with a size of 4.9 cm × 4.9 cm × 3.7 cm (L × W × H) made out of synthetic gel (Gelatin #5, Humimic Medical, SC, U.S.) was used. Similar to before, 0.5% (w/v) graphite powder (Graphite 282863; Sigma-Aldrich, Inc., St. Louis, MO, U.S.) was added to provide photoabsorption, and 2% (w/v) 60–120 μm silica particles were added to provide US scatterers. In this experiment, we employed a different laser system (Quanta Ray; Spectra-Physics, Santa Clara, CA, U.S.) which could generate a 100 μs laser pulse at 1064 nm so that the optical excitation duration would match the ARF pulse duration. A 300 μm diameter fiber was attached on the edge of the transducer to deliver light. The full width at half-maximum (FWHM) beam width was 400μm at the phantom surface. The optical fluence was 3.9 mJ/mm²; this is below the ANSI limit for a 100 μs pulse at 1064 nm, which is 5.5 mJ/mm² [18]. The FWHM of the ARF excitation beam was 1.34 mm.

A 100 μs laser pulse and a 100 μs ARF pulse were used to excite SAWs at the same location separately, with ultrafast US imaging at 3.3 kHz frame rate following immediately after the excitation pulse. Displacement-time curves for two regions spaced 2.5 and 3.3 mm laterally away from the excitation region were calculated and then analyzed with fast Fourier transform. Similar to the first experiment, these two locations were chosen far away enough to ensure that the SAWs took enough time to reach the regions of interest to allow decay of artifacts due to the excitation, yet close enough to provide adequate SNR in displacement measurements.
In the third experiment, we explored the difference in SAW phenomenon when the excitation location is below the surface. A 4.9 cm × 4.9 cm × 3.7 cm (L × W × H) phantom was made out of synthetic gel (Gelatin #5, Humimic Medical, SC, U.S.) mixed with 2% (w/v) 60–120 μm silica particles acting as US scatterers. A 0.8 mm diameter metal needle was placed 3.3 mm below the phantom surface to serve as a photoabsorber, because metal is generally highly absorbing [19]. To generate SAWs from the optical absorber inside the phantom, the tip of the optical fiber was adjusted to irradiate the needle.

The imaging system and the pulsed laser system employed in the third experiment were the same as in the first experiment. During the imaging process, 14 ultrafast US images at a frame rate of 2.78 kHz were first captured 60 μs after the laser pulse. Then a 60 μs ARF pulse with a US beam focused 1.3 mm above the photoabsorber was used to generate SAWs, followed by another set of 14 ultrafast US imaging frames.

With the setup in the third experiment, we also investigated the relationship between the displacement amplitude and the optical fluence by applying three different optical fluences (46, 69, 92 mJ/cm²). The maximum amplitude of displacement was calculated 0.78 ms after the laser excitation in a region located at the same depth as the photoabsorber, 3.3 mm below the phantom surface. For each fluence, the imaging process was repeated three times. Because a local maximum of displacement amplitude exists on both the left side and the right side of the photoabsorber, six measurements of the displacement amplitude were performed for each laser fluence.

The co-registered US/PA image [Fig. 1] of the 9% gelatin phantom indicates the location where the laser beam irradiated the surface of the phantom. The PA signal is strongest at the surface and quickly decays with depth. Furthermore, the PA signal at the surface also corresponds to the origin of SAWs created by photothermal expansion of the material.

Laser-induced SAWs can be clearly seen in the displacement maps calculated from the ultrafast US image set [Fig. 2(a)]. For comparison, displacement maps from ARF excitation are shown in Fig. 2(b). The displacement maps represent SAW displacement estimated at 1.5, 2.1, 2.7, and 3.3 ms after the laser/ARF excitation pulse. Once the laser/ARF excitation is applied, the surface wave propagates away from the excitation region. Generally, the displacement profiles are spatially correlated (Fig. 2). However, several differences exist. First, with laser excitation, the displacement at the excitation point is directed towards the imaging transducer. In comparison, ARF excitation induces displacement directed away from imaging transducer, i.e., the polarity of laser-generated SAWs is opposite that of ARF-generated SAWs. Secondly, the SAW amplitude in laser-induced SAW imaging is on the order of tens of nanometers, while the displacement amplitude in ARF-based SAW imaging is generally several micrometers.

The results of SWV measurements in different gelatin phantoms are shown in Fig. 3, where SAWs were produced by a laser or ARF. P values of the t test between the two methods were 0.13, 0.79, and 0.19 for 6%, 9%, and 12% gelatin phantoms, respectively. There is no evidence to reject the null hypothesis that the mean values of the two measurement methods are equal. The results presented in Fig. 3 demonstrate that laser-induced SAWs are capable...
of quantifying SWVs and, therefore, the shear modulus of materials such as biological soft tissues with accuracy on par with ARF-induced SAWs.

The temporal behavior of the SAW displacements at two locations is shown in Figs. 4(a) and 4(b). Each displacement curve represents an average of five acquisitions, each repeated with the same imaging and excitation parameters. The center frequency and 3 dB bandwidth of the displacement produced by the laser pulse were 920 and 1310 Hz at the first location, which was 2.5 mm away from the excitation region. The center frequency and bandwidth reduced to 767 and 1062 Hz, respectively, by the time the SAW propagated to the second location, 3.3 mm away from the center of the laser beam. The center frequency and 3 dB frequency bandwidth of the displacement excited with ARF were 452 and 790 Hz at the first location, and 410 and 655 Hz at the second location. In both methods, there is a slight drop of bandwidth due to the attenuation of higher frequency components of the waves, as SAWs propagate further. Nevertheless, laser-induced SAWs have a broader bandwidth than SAWs induced by ARF excitation given that the laser excitation region (FWHM of laser excitation beam: 400 μm) is smaller than the ARF excitation region (FWHM of ARF excitation beam: 1.34 mm). These results are in agreement with the theoretical relationship between the bandwidth and the spatial extent of the displacement [20]. The broader bandwidth of SAWs induced by laser excitation may potentially provide better spatial resolution if SAW velocity is measured to infer the stiffness of the material. Theoretically, the beam width for both the ARF- and laser-induced cases is determined by wavelength and numerical aperture of the transducer or objective lens used in the experiment. Since the optical wavelength can be much shorter than the US wavelength for the same numerical aperture, the excitation beam width can be much smaller for the laser-based method.

We next compared the generation mechanism when the excitation region is below the surface. The co-registered US/PA image [Fig. 5(a)] shows the location of the photoabsorber embedded 3.3 mm below the phantom surface. Displacement maps [Fig. 5(b)] at three different time points after the laser pulse indicate that both SAWs and shear waves were successfully induced by the laser pulse. From the displacement map at 1.5 ms, it can be observed that the shear waves and SAWs began to propagate separately. This observation indicates that the applications of laser-induced SAW imaging may be extended from superficial measurements of mechanical properties of materials to measuring mechanical properties of materials at depth. Furthermore, SWV measurements are usually more desirable than SAW velocity measurements due to its straightforward relationship with the shear modulus of the measured material [21]. For ARF-based excitation, because the energy mainly remained within the surface region due to the shallow excitation depth, only SAWs were generated [Fig. 5(d)], limiting the elastography analysis to just the surface layer.

With the optical fluence increasing from 46 to 92 mJ/cm², a linear relationship ($R^2 = 0.93$) between the shear wave amplitude and the optical fluence was observed [Fig. 5(c)], indicating that higher optical fluence results in larger shear wave amplitude. The energy we used here is within maximum permissible exposure for skin (100 mJ/cm² for 1064 nm wavelength) according to the American National Standard Institute [18]. Based on a previous study [14], laser-induced shear waves can be caused by two regimes: the thermoelastic regime and the ablative regime. In the ablative regime, displacement can reach
several micrometers and is quadratically dependent on energy. In the thermoelastic regime, displacements can only reach tens of nanometers and are linearly dependent on energy, which is in agreement with our observations [Figs. 5(b) and 5(c)]. Therefore, the shear waves generated in [Fig. 5(b)] were induced by the thermoelastic regime, rather than ablative regime.

In conclusion, we have demonstrated several differences in laser-induced SAWs and ARF-induced SAWs. First, the polarities of SAWs induced by the two excitation methods are opposite. Second, the amplitude of laser-induced SAWs is one to two orders of magnitude less than amplitude of ARF-induced SAWs. To create SAWs in biological tissue that does not efficiently absorb optical energy, an acoustically friendly external photoabsorber can be placed at the tissue surface to generate SAWs while protecting other tissues from laser irradiation hazard [6]. Third, with laser excitation, perturbation within a much smaller region (hundreds of micrometers) is feasible. As a result, SAWs with higher bandwidths can be generated, which could potentially increase the spatial resolution of the velocity maps. Finally, for superficial regions, laser excitation can generate both shear waves and SAWs.

Acknowledgment.

The authors would like to thank Dr. Yiying Zhu of the Georgia Institute of Technology for her assistance in signal processing and Dr. Andrei Karpiov, Dr. Kelsey Kubelick, and Dr. Kristina Hallam of the Georgia Institute of Technology for their guidance in optical system design.

Funding. National Institutes of Health (EB008101, HL130804); Breast Cancer Research Foundation (BCRF-18-043); Ministry of Science and Technology of the People’s Republic of China (2017YFE0104200); China Scholarship Council (201806010304); Friends of Bobby Jones Fund.

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Fig. 1.
Combined US (grayscale map) and PA image of the tissue-mimicking gelatin phantom.
Fig. 2.
Displacement maps at four different time points obtained using ultrafast US imaging for (a) laser-induced SAWs and (b) ARF-based SAWs.
Fig. 3.
SWV measurements ($n = 4$) in gelatin phantoms of different gelatin concentrations and, therefore, different degrees of stiffness. Measurements were obtained using laser-induced SAWs and ARF-based SAWs. The mean SWV value is shown as a vertical bar, and 95% confidential interval is shown as an error bar.
Fig. 4.
Temporal profile of the displacement of SAWs measured at locations (a) 2.5 and (b) 3.3 mm away from laser/ARF excitation region. The excitation occurred at time zero.
Fig. 5.
(a) Combined US (grayscale map) and PA image of the phantom with a photoabsorber located 3.3 mm below the surface. (b) Laser-induced shear wave displacement maps in the phantom at three different time points. (c) Scatter plot of mean value of shear wave displacement amplitude, measured 0.78 ms after the laser pulse, as a function of optical fluence. The error bars show standard deviation ($n = 6$). (d) ARF-induced shear wave displacement maps in the synthetic phantom at three different time points.