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Theoretical Modelling of Modulation Depth of Acoustic Optical Imaging at Varying Mechanical Properties

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Abstract: The signal from acousto-optical imaging is affected by the mechanical properties of a sample. A theoretical model showed that speed of sound, density, peizooptical coefficient, and acoustic amplitude affect modulation depth.

1. Introduction

Acousto-optical imaging (AOI) combines optical imaging with ultrasound (US). AOI shows great potential as a translatable imaging modality, providing high molecular sensitivity with the resolution of US. AOI works by sending light through a diffuse media that is undergoing US. Some of the light travels through the US focus and becomes 'tagged'. Essentially, the frequency of the light is shifted the same frequency as the US frequency ($\nu_{Tagged} = \nu_{Laser}+\nu_{US}$). The tagged light is then detected by using one of various techniques such as speckle contrast, heterodyne holography, spectral hole burning methods, etc. [1]. The mechanisms that lead to some of the light being tagged has been theorized[2]. There are two main mechanisms. First, light scatters from particles that are in motion and moving at a particular velocity. Therefore, there is a phenomenon similar to the Doppler Effect. The second effect is due to localized changes in the index of refraction, which causes light to refract as it travels through the medium.

However AOI still faces several key challenges. One such challenge is understanding how the mechanical properties of the medium affect the results of an imaged sample. US propagation is affected by the mechanical properties of the material that it travels through, therefore, the resulting AOI signal can also be affected. To test this, we programmed and utilized a theoretical model developed by Lihong V.Wang [2]. Mechanical properties (i.e. density) of the model were varied in order to observe the changes on the modulation depth or signal from the AOI. This is the first step to understanding how the signal can change depending on the mechanical properties of the medium.

2. Methods

The theoretical model was based on the Wang's work, and briefly described here. For the full description of the model please refer to reference [2]. The modulation depth (M) is calculated using the ratio of the intensity of the tagged light (I_1) over the untagged light (I_0), $M = I_1/I_0$. The intensity can be calculated based on the Wiener-Khinchin theorem:

$$I_m = \frac{1}{T_a}\int_0^{T_a} \cos(m\omega_a\tau)\, G_1(\tau)d\tau. \tag{1}$$

where m is the mth harmonic, T_a is the acoustic period, ω_a is the acoustic angular frequency, and G_1 is the Green's function. The Green's function is a function of ϕ_n and ϕ_d, which are the phase variation due to the index of refraction of the medium and the displacement of particles, respectively.

$$\phi_{nj}(t) = 2n_0\eta k_0 A \sin\left(\boldsymbol{k_a}\cdot\boldsymbol{r_{j-1}} + \frac{k_a l_j cos\theta_j}{2} - \omega_a t\right) \times \frac{\sin(k_a l_j cos\theta_j)}{cos\theta_j}, \tag{2}$$

$$\phi_{dj}(t) = -n_0 k_0(\hat{\boldsymbol{k}}_{j+1} + \hat{\boldsymbol{k}}_j)\cdot \boldsymbol{A}\sin(\boldsymbol{k_a}\cdot\boldsymbol{r}_j - \omega_a t). \tag{3}$$

where j is the jth scattering event, n_0 is the background index of refraction, k_0 is the optical wave vector, $\mathbf{k_a}$ and k_a are the acoustic wave vector and its amplitude, respectively, A is the acoustic amplitude, l_j is the length of jth free path, θ_j is the angle between the optical wave and the jth free path, r_j is the location of the jth scatterer, and t is time. The last undefined parameter, η, is defined as:

$$\eta = \frac{\partial n}{\partial p}\rho v_a^2. \tag{4}$$

where $\partial n/\partial p$ is the piezooptical coefficient, ρ is the density, and v_a is the acoustic velocity. The model was setup to simulate a 785 nm laser with a 1 MHz US transducer. The medium was setup to mimic gel phantoms that have similar density (ρ = 1000 kg/m^3) and properties (v_a=1480 m/s, n_0=1.33) as water, but with scattering (μ_s =2500 m^{-1}) added. The length of the medium was 1cm, had an anisotropic factor of 0.9, and a piezooptical coefficient of

1.466E10 m^2/N. The acoustic amplitude was 0.1 nm. The mechanical parameters A, v_a, ρ, and $\partial n/\partial p$ were varied over a range (while the others remained the same) to observe the effects on the modulation depth.

3. Results and Discussion

Figure 1 shows the modulation depth for various mechanical properties. When the acoustic amplitude (Fig 1a) increases the modulation depth increases as well. Here, the acoustic amplitude is the distance a particle in the medium travels when undergoing ultrasound. This acoustic amplitude could possibly change depending on the mechanical properties of the medium. For example, if there is a stiffer material, then an US pulse with the same power may not be able to move a particle the same distance as for a material of less stiffness. Therefore, one could expect that the greater the stiffness, the less modulation depth that might be measured. For the density versus modulation depth (Fig 1b), as the density increased so did the modulation depth. The speed of sound also showed an increase in modulation depth as it increased (Fig 1c). This may give a means of contrast using AOI, in which different tissues have different speeds of sound. For example, breast tumors have a speed of sound of 1548 m/s, while fat has a speed of sound of 1478 m/s [3]. The difference in speed of sound would result in difference in modulation depth and could provide potential tissue differentiation. Last, the piezooptical coefficient showed a similar trend in which an increase in the coefficient led to an increase in the modulation depth. The piezooptical coefficient is how much the index of refraction changes within in the medium undergoing a change in pressure due to the ultrasound pulse. Here the optical and mechanical properties are directly related.

We demonstrated that the mechanical properties have an effect on the AOI signal or modulation depth. Understanding these effects is important for future studies of AOI in order to properly assess how the signal is being generated. As of now, determining optical properties using AOI is difficult and adding the mechanical influence makes image processing even more complex[1]. Future research will consist of an updated model for pulsed and focused ultrasound [4]. Additionally, phantoms studies are necessary in order to verify the theoretical models.

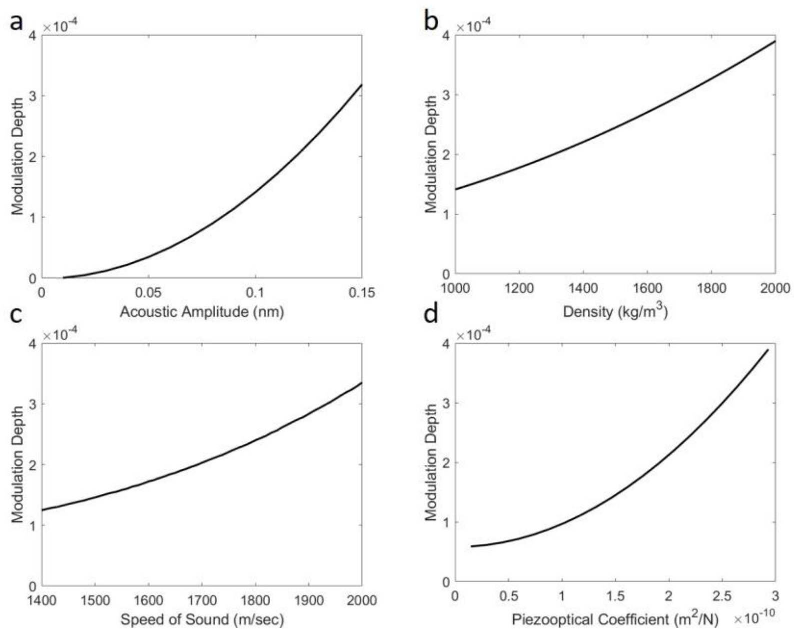

Fig. 1. The acoustic amplitude (a), density (b), speed of sound (c), and the piezooptical coefficient (d) versus the modulation depth using acousto-optical imaging techniques.

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