Developing a stochastic model for acousto-optic tissue imaging

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ABSTRACT

Direct optical measurements in scattering media offer poor resolution due to the high scattering. Ultrasound is scattered orders of magnitude less in tissue compared with light and therefore offers good resolution. Photoacoustics and acousto-optics are both relatively new hybrid techniques that enable measurements of optical properties in scattering media by combining ultrasound and light. Quantified measurements of the fluence and absorption coefficient however are desired and can not be performed by these separate techniques. A new approach to achieve this goal is to combine both hybrid techniques. By combining photoacoustic and acousto-optic measurements there is sufficient information to calculate the absorption coefficient and fluence at the ultrasound focus used for the acousto-optics. We require knowledge on the interaction of light and sound inside tissue, so the size of the so called tagging volume can be determined. This tagging volume is defined by the size and shape of the ultrasound focus used in the acousto-optic measurements. A stochastic model for acousto-optics is under development that used existing knowledge on the in the interaction between light and sound. By separating light transport and the interactions of light and sound and writing this interaction as a probability density function it is possible to find the effective geometrical properties of the tagging volume. At the moment multiple interaction mechanisms of sound and light are added to this model. In the future this model will be validated in phantoms and biological tissue.

Keywords: Acousto-optics, photoacoustic, Monte-Carlo, phasor, labeling, tagging, model

1. INTRODUCTION

Imaging of light absorbing structures inside turbid media is challenging. Through a thick scattering layer the photon paths are randomized. These paths contain therefore no useful spatial information of objects under this layer of scatterers. In recent years several techniques were developed to visualize structures deep inside a scattering medium. Two of these combine optics and acoustics. The main advantage of using acoustics is the orders of magnitude less scattering of soundwaves than optical scattering. Photoacoustics combines the advantages of optics and acoustics. An object is illuminated, light absorbing structures inside will absorb this light and heat up. This causes a thermo-elastic expansion that causes a shockwave that is detected as ultrasound. The initial pressure

$$p_0 = \Gamma\Phi\mu_a \tag{1}$$

depends linear on the local fluence Φ, the optical absorption coefficient μ_a and a constant called the Grueneisen parameter Γ Even when the Grueneisen parameter can be predicted there are two unknowns, the fluence and the optical absorption coefficient. A map of the initial pressure distribution is therefore not a quantitative representation of the absorption coefficient. Quantitative measurements can tell more about the concentration of chromophores and not only its distribution. Examples of chomophores are, oxy- and deoxy-hemoglobine, nanoparticles and labeled medicine.

The second technique that combines optics and acoustics is acousto-optics. Here the object is also illuminated. In transmission mode the scattered light is collected at the far end where it forms a speckle pattern. In reflection mode the scattered light is detected at the injection aperture. On the point of interest inside the medium an ultrasound pulse is focused. The sound pulse interacts with the light in the so called tagging volume where light is tagged. The tagged photons modulate the intensity of the speckle with the ultrasound (US) frequency. Therefore detection of tagged photons gives information about the internal fluence.

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For both techniques there are efforts to make quantized measurements on the optical absorption coefficient. In the case of photoacoustics, the quantity that is reconstructed consist of the absorption coefficient distribution and the fluence distribution The fluence distribution can be calculated with the radiative transfer equation [1] but can also be measured. Wang for example used diffuse optical tomography (DOT) in combination with photoacoustics to achieve quantized measurements [2]. With DOT the fluence distribution is reconstructed using a light transport model is used. In both cases the acoustic signal is compensated for the fluence distribution. See [3] for more information on quantitative photoacoustics.

In the case of acousto-optics some also make an effort to obtain quantitative measurements on the optical absorption coefficient.[4] They used in these experiments a blank calibration phantom to compensate for the fluence distribution.

2. Soundlight theory

In a new approach presented by Steenbergen et al. [5], photoacoustics is combined with acousto-optics to form what we call soundlight. The more light reaches the focus of the ultrasound used in acousto-optics the more tagged photons will be detected. The more light at this point the stronger the photoacoustic signal originating from this point. In reflection mode one acousto-optic and one photoacoustic measurement is needed. In transmission mode two photoacoustic measurements are needed in combination with one acousto-optic measurement. In the acousto-optic measurement we can define 3 points:

1. The location of the injection aperture. Light with a long coherence length illuminates the object at this point.
2. At this point the light is tagged. We know the tagging of light does not take place in only one point, but rather in a small region with soft boundaries. This zone we call the tagging zone centered at point 2.
3. The position of the detection aperture. The light from this aperture forms a speckle pattern on a detector, such as a CCD camera. In reflection mode point 3 coincides with point 1.

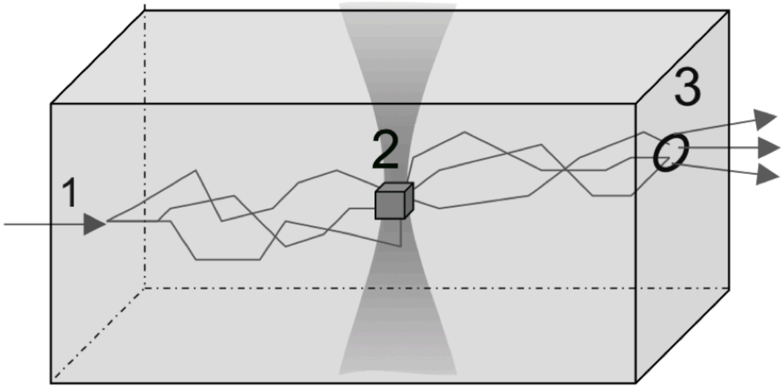

Figure 1. Schematic of a transmission mode acousto-optics, light is injected at 1, the photons travel random paths, some of the photons arrive at 2 where tagging takes place in the US focus, while at 3 a selection of tagged and untagged photons are detected.

Light injected at point 1 has a certain probability to travel to point 2, the tagging zone. Here we assume a small fraction of the light is absorbed at point 2. The normalized absorbed energy $E^*_{a,12}$ resulting in a photoacoustic signal originating from point 2 is proportional to this probability Pr_{12}. A certain fraction of the light is tagged at point 2. This tagged light has some probability to reach point 3, Pr_{23}. This probability is equal to the probability for light injected at point 3 to reach point 2. When light is injected at point 3 is the result a photoacoustic signal from point 2 by the normalized absorbed energy $E^*_{a,32}$. The tagged light detected at point 3, $P^*_{L,3}$ is proportional with the area of the aperture at point 3, A_3 and the solid opening angle of this aperture Ω_3.

As mentioned before an experiment to measure the local absorption coefficient at point 2 consists of 2 photoacoustic measurements and one acousto-optic measurement. It is important that the same aperture sizes are used for the acousto-optic and photoacoustic measurements so that the light distribution in the medium is the same. By combining the 3 experiments the optical absorption coefficient is a function of measured quantities and experimental settings.

$$\mu_{a,2} = \sqrt{\frac{A_3 A_2 \Omega_3 E^*_{a,12} E^*_{a,32}}{4\pi V_2^2 P^*_{L,3}}} \tag{2}$$

In this equation only the average frontal area A_2 and the effective volume V_2 of the tagging zone are unknown. We expect that these quantities depend on the size and power of the acoustic beam used in the acousto-optic part of the experiment. However in addition to the acoustic properties of the setup the effective geometry may also depend on the optic and acoustic properties of the object investigated. Is tagging a local phenomena or will properties of the object outside point 2 affect the effective properties of the tagging zone?

We assume light is tagged in point 2 what can be seen as a source of labeled photons. In simplified acousto-optic Monte Carlo simulations a photon travels a random path through the object. When it encounters the tagging zone it is simply tagged. An easy shape for the tagging zone is a hard boundary sphere. All photons entering this sphere are labeled. In real experiments this view does not hold. When the ultrasound pressure is nearing its limit to zero, no tagged photons are expected. However in the simplified Monte Carlo simulations the same number of photons are tagged. The second difference between a real experiment and the simulation is hard and soft boundaries. In the experiment the ultrasound focus has no hard boundaries. The ultrasound pressure is gradually smaller the further from the center of the focus. From experiments however we know that when for example 5 MHz ultrasound is used for the tagging, the injected monochromatic light gets two sidebands. These bands are located 5 MHz from the central laser frequency. Therefore we can speak about -5 and 5 MHz tagged light. However when high ultrasound pressures are applied in an acousto-optic experiment higher harmonics are present in the ultrasound. These higher harmonics can cause to some extent tagging at multiples of the fundamental frequency. When the ultrasound is pulsed the spectrum must consist of more frequencies then the fundamental frequency. This leads to tagged photons at a multitude of frequencies.

3. Acousto-optic modeling and tagging

In recent years several models are presented that give some insight in the interaction of light and sound in the object. Wang [6] identified several mechanisms that tag light inside the medium. The two major mechanisms are the modulation of the refractive index and the periodical displacement of scatterers inside the medium.

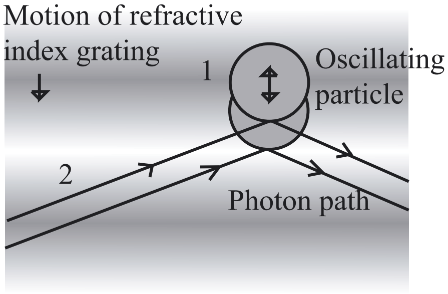

Figure 2. Coherent modulation mechanisms: oscillation of scattering particles modulate the photon optical path length (1) and the optical path length variaties due to refractive index changes (2).

Several models are developed in recent years. Mahan et al.[7] investigated the fraction of photons that is tagged by the influence of refractive index modulation. This fraction was only calculated for homogeneously distributed ultrasound fields. Most other models are based on the temporal autocorrelation function of the intensity or electric field [8]. The result of this function is transformed into a power spectrum of the speckle pattern using the Wiener-Khinchin theorem that is related to the Fourier transform. This approach allows us to calculate the power spectrum of the tagged photons created inside the medium. However the position of the creation of tagged photons is not known and therefore information on the geometry of the tagging zone is lost. This theory only works for a single frequency of the ultrasound. Therefore it is not directly applicable to acousto-optic techniques where two or more ultrasound frequencies are used, i.e [9]. The early autocorrelation based models only incorporate scatter displacement modulation. Wang combined this model with the refractive index modulation tagging mechanism. [10] Later Sakadžić improved on this model [11] so localized ultrasound beams could be used. To date this is the most advanced acousto-optic model. However we where not able to calculate and predict an effective volume for the tagging zone using this model.

We need a model describing the physics of tagging in acousto-optics with several capabilities and parameters.

1. Defining an effective geometry for the tagging zone, with effective aperture and volume.
2. Using multiple acoustic beams with different frequencies, power, direction, pulse duration and higher harmonics.
3. Several acoustic material properties such as speed of sound and acoustic impedance.
4. Using different optical parameters as absorption coefficient, scattering coefficient, refractive index, anisotropy factor, wavelength and adiabatic piezo-optical coefficient.

It is preferable to keep the model close to the Monte-Carlo photon picture because of the intuitive concept and the nature of existing proof of equation 2. The easiest way to include photon tagging in the Monte-Carlo simulation is by defining a hard boundary sphere or tagging zone. Every photon that enters this sphere is tagged. As mentioned before, the number of tagged photons must depend on the ultrasound pressure. Therefore we like to treat photon tagging just as photon absorption. The tagging probability per unit volume or unit length is a function of ultrasound pressure. With simulations as k-wave [12] is it possible to define the ultrasound pressure as function of time and place. These pressures lead to the displacement of scatterers and refractive index variations, both of these mechanisms lead to tagging of light. There is a whole range of frequency shifts that a photon might get. When a fundamental frequency of 5 MHz for the ultrasound is used, the most probable labels or frequency shifts are +5 and -5 MHz.

A +5 MHz labeled photon might return to, or stay in the tagging zone. In this zone the photon might interact again with the sound and get a -5 MHz tag with a certain probability. In this case both tags cancel each other and we are left with an untagged photon. There is an equal probability that this photon receives another +5 MHz tag. In this case the photon is tagged with a +10 MHz tag.

4. The probability of tagging

In the tagging zone light is tagged due to the interaction with sound. The two major tagging mechanisms have the highest probability of tagging light and the first version of our model will incorporate both of them. By treating the tagging as a probabilistic event it is possible to extent our model in future with additional mechanisms when necessary.

Tagged light has a slightly different frequency compared with the untagged light. See figure 3 the two side peaks in this figure depict the tagged light and the central peak is the untagged light.

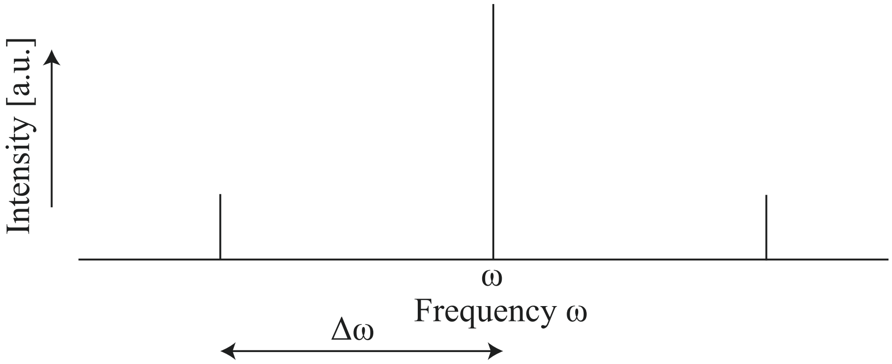

Figure. 3 Schematic spectrum of tagged and untagged light where the peak at frequency ω_0 is the untagged light and the two side peaks at Δω distance from this peak are the tagged light.

If we for now approximate the spectrum only consisting of 3 frequencies then we can calculate the oscillation of the electric field. A tool to calculate the oscillation of a multitude of waves is a phasor diagram. In this diagram the electric fields are added together as complex numbers or vectors. Each phasor is the electric field oscillating at a certain frequency which corresponds to a rotation of a phasor in the complex plane. The length of this vector is proportional with the square root of the intensity. To make addition easy we rotate the complex plane with the frequency ω. This way the phasor corresponding with the untagged light is stationary in the phasor diagram. The phasors corresponding with the tagged light rotate with a frequency of Δω, one rotates clockwise the other anti clockwise. The sum of the three phasors is the resulting electric field with a frequency of ω and an oscillating phase. The phase oscillates with frequency Δω which is equal to the used ultrasound frequency. Then amount of this phase modulation depends on the fraction of tagged light. This fraction is proportional to the probability to tag light. When we can calculate the phase modulation of the light by the interaction with the ultrasound we can calculate the probability to tag light.

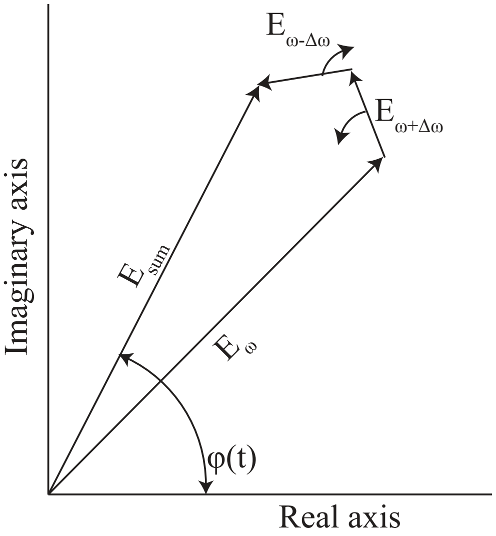

Figure 4. Phasor diagram. The phasors representing tagged light, $E_{\omega-\Delta\omega}$ and $E_{\omega+\Delta\omega}$ are added to the phasor representing the untagged light E_{ω} to form E_{sum} with time dependent phase φ(t). The curved arrows show the rotation direction of the tagged light phasors.

We calculate for each infinitesimal volume dV the tagging probabilities, this way the total tagging by the tagging zone is calculated even when there is spatial variation of optical and acoustic properties. This means that focused ultrasound beams can be used but also multiple beams. A probability density function is formed from the tagging probability for volume dV at position r. This function contains the geometry of the tagging zone and can provide us with the effective volume needed in equation 2. The effective volume for tagging at frequency ω is approximately

$$V_{eff,\omega} \approx \int_V \mathrm{Pr}_\omega(\bar{r})dV \qquad (5)$$

where $\mathrm{Pr}_\omega(r)$ is the tagging probability density function. In this equation it is assumed that the fluence distribution is homogenous in the tagging zone and the probability $\mathrm{Pr}_\omega(r)$ is small.

5. Discussion

The approach of defining a tagging probability function makes it possible to calculate the amount of tagged of light by a focused ultrasound beam. It also makes it relatively easy to use inhomogeneous distributions of various optical and acoustical properties. When the fluence distribution is inhomogeneous in the tagging zone equation 5 must be rewritten in a more complicated form. In future we will validate our approach together with the implementations of both major tagging mechanisms.

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