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Simulation and experimental investigation of turbid medium in frequency-domain photoacoustic response induced by modulated laser

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ABSTRACT

In this work, a one-dimensional (1D) photoacoustic mathematic model of turbid medium in frequency domain is presented, and it is derived from the theories of optical absorption and radiation transfer, thermal-wave diffusion and mechanical fluctuant effect. The theoretical simulations are carried out to analyze the effects of absorption coefficient, the relative position of the absorber on the amplitude and phase of the photoacoustic signal. A frequency – domain photoacoustic imaging system is developed to carry out the position scanning inspection experiments. At the fixed laser modulation frequency, the absorption property of the medium is detected according to the positive correlation between the amplitude of the photoacoustic signal and the absorption coefficient. Based on the relationship between the relative phase of the photoacoustic signal and the relative position of the medium, the depth of the optical absorber inside the turbid medium is quantitatively detected. The experiment results indicate that the amplitude and phase of the photoacoustic signal have high sensitivity to the optical absorption coefficient and structural characteristic parameters of the turbid medium.

1. Introduction

Due to the mean free path of photon propagation in biological tissue is limited, the traditional optical methods have difficulties in detecting the deep-seated tissue lesions. In recent years, photoacoustic detection methods, which inherit the advantages of high contrast and large probing depth respectively from optical and acoustical methods, have been deeply studied and gradually applied in the field of biomedical imaging. With non-ionizing radiation and non-invasion, photoacoustic methods can reliably detect the internal structure as well as the function of the biological tissue [1,2], which can substantially benefit the diagnosis and treatment of the tissue lesion [3,4].

Frequency-domain photoacoustic methods [5] were found to be eminent alternatives to traditional time-domain ones [6]. The continuous laser source which is generally implemented in the frequency-domain photoacoustic detection system, compared with pulsed excitation, is more stable and economical and has the capability of utilizing the correlation algorithm to improve the signal-to-noise ratio in signal detection and processing [7]. In frequency-domain methodologies, the excitation laser is intensity modulated, accordingly, the frequency characteristics (amplitude and phase) of the photoacoustic signal are extracted to manifest optical and structural characteristics based on the theoretical model. Fan et al. [8] established a single-layer frequency-domain photoacoustic model to study the effect of medium thickness on the amplitude and phase of the photoacoustic signal based on the theory of diffusion photon density field, and carried out tomographic imaging of turbid medium, the feasibility and effectiveness of modulated frequency-swept laser excitation and heterodyne detection methods for biological tissue were studied [9]. Telenkov et al. carried out three-dimensionally imaging of absorbers in turbid medium and biological tissues using matched filtering method [10,11], compared the maximum detectable depth in the time-domain and frequency-domain methods [12]. Lashkari et al. established a two-layer medium model, studied the dual-mode imaging method of time and frequency domain, [13,14] and significantly improved the imaging signal-to-noise ratio by optimizing the scanning bandwidth. By adopting dual-mode imaging method, bone mineral density distribution was reliably measured [15]. Dovlo et al. [16] applied array acoustic sensor to the frequency-domain photoacoustic radar imaging system to improve the imaging speed.

The current researches show that the frequency-domain characteristic parameters of photoacoustic signals are closely related to the characteristic parameters of the turbid medium. However, there are few studies on the influence of the relative depth of the absorber in the

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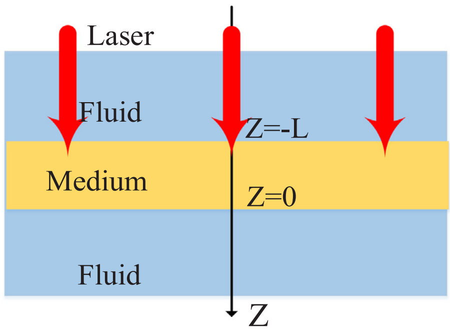

Fig. 1. Fluid coupling structure.

turbid medium on the phase of the photoacoustic signal. In this paper, a 1 D mathematical model for laser induced acoustic pressure in turbid medium and the quantitative relationship between the phase of the photoacoustic signal and the relative position of the absorber were established. Frequency-domain photoacoustic signals were theoretically simulated with the absorbers of different absorption coefficient and relative position. The position scanning imaging experiments on the turbid medium were performed using the developed frequency-domain photoacoustic imaging system, the relation between the phase of the signal and the relative position of the absorber was verified, furthermore, the depth of the absorber inside turbid medium was quantitatively detected.

2. Mathematical model

2.1. Laser induced acoustic pressure in turbid medium

For analyzing the generation and propagation of the photoacoustic signal in the turbid medium, a 1D liquid coupled structure is established (as shown in Fig. 1). The top and bottom layers are composed of fluids and the middle layer is composed of turbid media. The top layer occupies the spatial region $z \in (-\infty, -L]$ with density ρ_f and sound velocity c_f. The middle layer occupies the spatial region $z \in (-L, 0)$, with a thickness of L, a density of ρ_s and a sound velocity of c_s, Optical absorption coefficient μ_a and optical scattering coefficient μ_s. The bottom fluid occupies the region $z \in [0, \infty)$.

The photoacoustic effect includes the energy conversion process of photo-thermal-acoustic. For analyzing the process of photoacoustic effect in frequency-domain, corresponding time-domain equation can be established and transformed into frequency-domain using Fourier transform [17,18].

When the light is scattered by the turbid medium, the photon density field ψ_t formed inside the medium can be expressed as:

$$\psi_t = \psi_d + \psi_c \tag{1}$$

where ψ_d is the diffuse photon density field, ψ_c is the coherent photon density field, ψ_c can be expressed as:

$$\psi_c = I_0 e^{-\mu_t(z+L)} \tag{2}$$

where $\mu_t = \mu_a + \mu_s$ is the attenuation coefficient of the turbid medium, I_0 is the laser fluence.

The distribution of scattered photons in a medium can be described by a photon diffusion equation which is approximated by the first-order spherical harmonics of the radiation transport equation [19]. The distribution of photons in the turbid medium emitted by modulated source can be expressed by diffuse photon density wave (DPDW) [20]. The frequency-domain form of the diffuse photon density field ψ_d satisfies the equation [21]:

$$\frac{\partial^2}{\partial z^2}\psi_d(z,\omega) - \sigma_p^2\psi_d(z,\omega) = -\frac{S(z,\omega)}{D},\ z \in [-L, 0] \tag{3}$$

where $\sigma_p{}^2 = (1 - i\omega\tau)/c\tau Dw$ is the diffuse photon wave number, $\tau = (c\mu_a)^{-1}$ is the lifetime of photon diffusion from generation to absorption, $D = c/3(\mu_a + \mu_s')$ is the photon diffusion coefficient, $\mu_s' = \mu_s(1 - g)$ is the reduced scattering coefficient, g is the scattering anisotropy factor, $S(z,\omega) = I_0\exp[-\mu_t(z + L)]\mu_s c(\mu_t + g\mu_a)/(\mu_t - g\mu_s)$ is the source function [22]. The boundary conditions of the diffuse photon density field can be written as:

$$\psi_d(-L,\omega) - A\frac{\partial}{\partial z}\psi_d(z,\omega)|_{z=-L} = -3\mu_s gAI_0 \tag{4a}$$

$$\psi_d(0,\omega) + A\frac{\partial}{\partial z}\psi_d(z,\omega)|_{z=0} = 3\mu_s gAI_0 e^{-\mu_t(z+L)} \tag{4b}$$

where $A = 2D(1 + r)/(1 - r)$, r is the reflection coefficient of the solid-fluid interface. According Eqs. (3) and (4), diffuse photon density field can be solved.

The photothermal energy conversion occurs when the medium absorbs photons, and the heat source term $q(z,\omega)$ of the frequency-domain heat transfer differential equation can be expressed as a function of the photon density field ψ_t. The frequency-domain thermal transfer equation in the medium layer can be expressed as:

$$\frac{\partial^2}{\partial z^2}T_s(z,\omega) - \left(\frac{i\omega}{\alpha_s}\right)T_s(z,\omega) = -\frac{q(z,\omega)}{k_s},\ z \in [-L, 0]$$

$$q(z,\omega) = \eta_{NR}\mu_a\psi_t(z,\omega) \tag{5}$$

where $T_s(z,\omega)$ is the temperature rise above ambient in the solid medium, α_s is the thermal diffusivity of the solid and k_s is the thermal conductivity of the solid, η_{NR} is the photo-thermal transfer efficiency. The frequency-domain thermal transfer equation in the top and bottom fluid layers can be expressed as:

$$\frac{\partial^2}{\partial z^2}T_f(z,\omega) - \left(\frac{i\omega}{k_f}\right)T_f(z,\omega) = 0,\ z \in (-\infty, -L] \cup [0, +\infty) \tag{6}$$

where $T_f(z,\omega)$ is the temperature rise in the fluid, α_f is the thermal diffusivity of the fluid and k_f is the thermal conductivity of the fluid. The continuity conditions for temperature and heat flux at the fluid-solid interfaces can be written as:

$$T_f(-L,\omega) = T_s(-L,\omega) \tag{7a}$$

$$k_f\frac{\partial}{\partial z}T_f(z,\omega)|_{z=-L} = k_s\frac{\partial}{\partial z}T_s(z,\omega)|_{z=-L} \tag{7b}$$

$$T_f(0,\omega) = T_s(0,\omega) \tag{7c}$$

$$k_f\frac{\partial}{\partial z}T_f(z,\omega)|_{z=0} = k_s\frac{\partial}{\partial z}T_s(z,\omega)|_{z=0} \tag{7d}$$

$T_s(z,\omega)$ can be solved by using Eqs. (5)–(7). Assuming that only longitudinal waves propagate in the isotropic solid medium, the displacement potential $\phi(z,\omega)$ satisfies the Helmholtz equation [23]:

$$\frac{\partial^2}{\partial z^2}\phi(z,\omega) + \frac{\omega^2}{c_s^2}\phi(z,\omega) = \left(\frac{K\beta}{\rho_s c_s^2}\right)T_s(z,\omega),\ z \in [-L, 0] \tag{8}$$

where K is the bulk modulus, β is the isobaric volumetric expansion coefficient, and the displacement potential $\phi(z,\omega)$ is related to the displacement vector of solid particles $u(z,\omega)$ and $u(z,\omega) = \text{grad}\ \phi(z,\omega)$. In the top and bottom fluid layers, assume that the fluid is non-viscous and slightly fluctuating, the velocity potential satisfies the wave equation according to the hydrodynamics principle:

$$\frac{\partial^2}{\partial z^2}\xi(z,\omega) + \frac{\omega^2}{c_f^2}\xi(z,\omega) = 0 \tag{9}$$

where the velocity potential $\xi(z,\omega)$ in the formula is the potential function of the vibration velocity $v(z,\omega)$ of the fluid. The relation between them is: $v(z,\omega) = \text{grad}\ \xi(z,\omega)$. According to Eq. (9), velocity