Irradiation source profile dependence of optoacoustic signals generated in layered absorbers

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We address the numerical simulation of optoacoustic (OA) signals generated in a single-layered absorber and assess the sensitivity of the resulting OA excess pressure profiles on the subtleties of a custom irradiation source profile, geared towards actual “in-house” experiments.

1 Introduction

Optoacoustics can be considered a two-part phenomenon, based on two distinct processes that occur on different time-scales: (P.1) *Optical absorption* of electromagnetic waves by media followed by photothermal heating of the absorber (i.e. a fast process), and, (P.2) *emission of acoustic pressure waves*, triggered by thermoelastic expansion induced by the heating (i.e. a comparatively slow process). During the course of their propagation, the initial acoustic stress profiles experience a diffraction induced shape transformation [1]. The particular features of the resulting OA signals are sensitive to the details of the irradiation source and detector setup.

We here report on numerical experiments that where carried out to better understand the features of OA signals resulting from measurements on melanin enriched absorbing structures, i.e. melanoma, within tissue. In the remainder we focus on the subtle dependence of OA signals on the characteristic features of a custom irradiation source profile used in our combined experimental and numerical study [2].

2 Optoacoustic signal generation

In *stress confinement*, i.e. if the temporal duration of the irradiation source is short enough to be represented by a delta-function on the scale of typical acoustic propagation times, photothermal heating can be accounted for by a heating function $H(\vec{r},t)$ that factors in space and time coordinates according to

$$H(\vec{r},t) = W(\vec{r})\,\delta(t). \tag{1}$$

Considering pure absorbers, a proper Ansatz for the volumetric energy density reads

$$W(\vec{r}) = f(\vec{r}_\perp)\,\mu_a(z)\,\exp\Big\{-\int_0^z \mu_a(z')\,dz'\Big\}, \tag{2}$$

where the axial absorption depth profile is in accordance with Beer-Lamberts law for a depth-dependent absorption coefficient μ_a, and where we consider the custom flat-top irradiation source profile

$$f(\vec{r}_\perp) = \begin{cases} 1, & \text{if } |\vec{r}_\perp| \leq a \\ \exp\{-(|\vec{r}_\perp|-a)^2/d^2\}, & \text{if } |\vec{r}_\perp| > a \end{cases} \tag{3}$$

consistent with beam profiling measurements for our in-house OA detection setup.

In *thermal confinement*, i.e. when the laser pulse duration is significantly shorter than the thermal relaxation time, the propagation of acoustic stress profiles $p_0(\vec{r})$ is governed by the scalar OA wave equation

$$\left[\partial_t^2 - c^2\Delta\right]\,p(\vec{r},t) = \partial_t\,p_0(\vec{r})\,\delta(t), \tag{4}$$

which yields the excess pressure field $p(\vec{r},t)$ at time t and field point $\vec{r}$ [1, 3].

An analytical solution for the excess pressure profile $p_D(\tau) \equiv p(\vec{r}_D,t)|_{\vec{r}_D=(0,0,z_D),\tau=t-|z_D|c}$ as function of the retarded time τ at the field point $\vec{r}_D$ is possible in terms of the OA Poisson integral

$$p(\vec{r},t) = \frac{\Gamma}{4\pi c}\partial_t \int_V \frac{W(\vec{r}')}{|\vec{r}-\vec{r}'|}\delta(|\vec{r}-\vec{r}'|-ct)\,d\vec{r}', \tag{5}$$

where the “source volume” V signifies the part of the computational domain wherein $W(\vec{r}) \neq 0$, and $\delta(\cdot)$ limiting the integration to a time-dependent surface constraint by $|\vec{r}-\vec{r}'| = ct$. Considering layered absorbing media, the formulation of the Poisson integral in cylindrical coordinates paves the way for an efficient numerical algorithm for the calculation of optoacoustic signals [2].

3 Beam profile dependence of the OA signal

While the characteristic features of OA signals for a variety of detector positions are discussed in Ref. [2], we here report on the sensitivity of OA signals on a variation of the beam shape parameters a and d, see Eq. (3). In this regard, Fig. 1(a) illustrates a 2D slice of the volumetric energy density $W(\vec{r})$ deposited by the irradiation source within the source volume, parallel to the beam axis for beam shape parameters $a = 0.1\,\text{cm}$, $d = a/4$ and absorption coefficient $\mu_a = 20\,\text{cm}^{-1}$ within the range $z = 0 \ldots 0.1\,\text{cm}$.

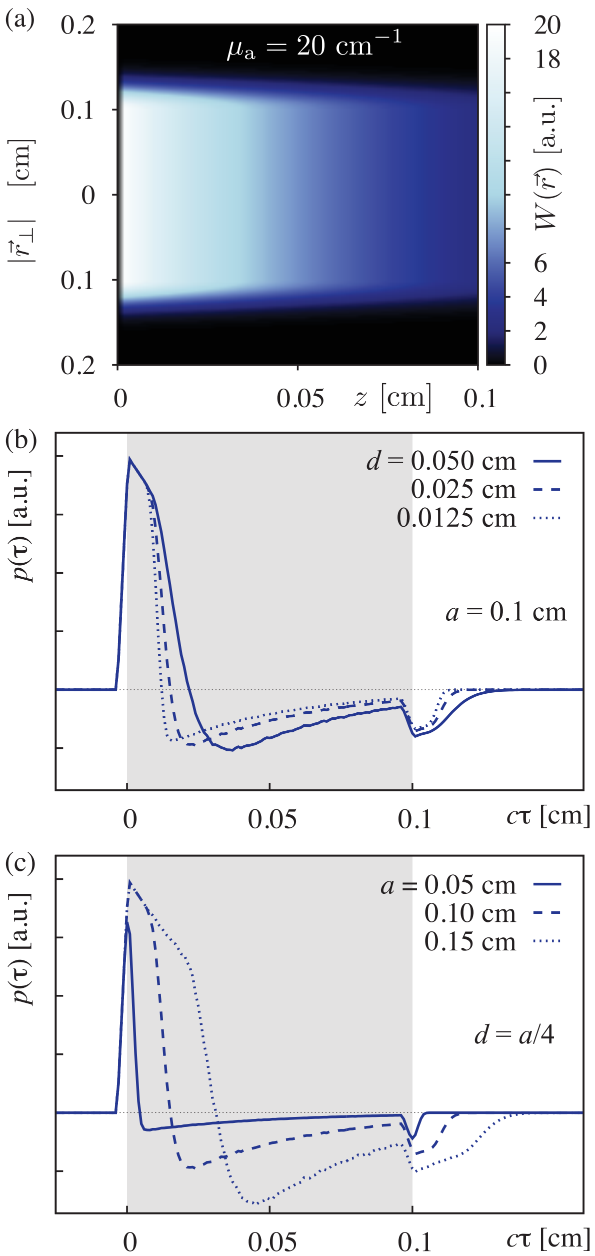

Fig. 1 *Dependence of the OA excess pressure profile p_D as function of the signal depth $c\tau$ on the subtleties of the transverse irradiation source profile $f(\vec{r}_\perp)$ [seed Eq. (3)]. (a) axial 2D slice through the source volume illustrating the distribution of volumetric energy density within the absorbing layer for beam parameters $a = 0.1$ cm and $d = a/4$, (b) sensitivity of the OA signal to a variation of the decay-width parameter d of the beam profile, and, (c) sensitivity to a variation of the top-hat width a.*

Therein, the color gradient indicates the flat-top beam profile along the abscissa and the Beer-Lambert decay along the ordinate. As evident from Fig. 1(b), an increasingly narrow decay width d of the Gaussian profile, while keeping the width a of the flat-top profile fixed, leads to an increasingly narrow compression peak and rarefaction dip. Further, as can be seen from Fig. 1(c), decreasing the width a of the flat-top profile, while maintaining the Gaussian decay width $d = a/4$, results in increasingly narrow compression and rarefaction features as well.

In either case, note that the extended rarefaction phase caused by the initial diffraction stress-wave appears more shallow if the irradiation source decreases in extend. To facilitate intuition, note that decreasing the extension of the irradiation source profile effectively shifts the detection point further towards the far field, in accordance with the observed effects. Also, note that the principal shape of the observed OA signals is characteristic for a flat-top irradiation source profile.

Note that a `Python` implementation of our code for the solution of the Poisson integral Eq. (5) (detailed in Ref. [2]) can be found at Ref. [4].

4 Summary and Conclusions

We considered the process of OA signal generation and complemented the combined numerical and experimental study reported in Ref. [2] by clarifying the influence of the beam parameters of the employed irradiation source profile on the signal features. The qualitative change of the simulated OA signals highlights the expected intuitive relation between far field characteristics and system parameters.

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