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Rousseau, Guy; Blouin, Alain; Monchalin, Jean-Pierre

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Spatial resolution of ultrasound-modulated optical tomography used for the detection of absorbing and scattering objects in thick scattering media

Guy Rousseau,* Alain Blouin and Jean-Pierre Monchalain
Industrial Materials Institute, National Research Council Canada,
75 de Mortagne Blvd., Boucherville, Québec, Canada, J4B 6Y4

ABSTRACT

Ultrasound-modulated optical tomography (UOT) combines the spatial resolution of ultrasonic waves and the spectroscopic properties of light to detect optically absorbing and/or scattering objects in highly scattering media. In this work, a double-pass confocal Fabry-Perot interferometer is used as a bandpass filter to selectively detect the ultrasound-tagged photons. The limited etendue of the confocal Fabry-Perot interferometer is compensated by using a single-frequency laser emitting high-peak-power optical pulses. Compared to photoacoustic tomography, UOT is not only sensitive to optical absorption but also to scattering properties. In this paper, we consider the detection of absorbing and scattering objects embedded in thick (30 to 60 mm) tissue-mimicking phantoms and biological tissues. The experimental evaluation of the spatial resolution of the technique is compared to that expected from the ultrasonic beam intensity profile. Preliminary results indicate that the edge spread function is influenced by the level of absorption of the embedded object.

Keywords: biomedical imaging, ultrasound-modulated optical tomography, acousto-optical imaging, ultrasound-tagged photons, scattering media, confocal Fabry-Perot interferometer, pulsed single-frequency laser

1. INTRODUCTION

Ultrasound-modulated optical tomography (UOT) or acousto-optic imaging (AOI) combines the spatial resolution of ultrasonic waves and the optical contrast [1]. It has also been shown that UOT is sensitive to the scattering properties of embedded objects [2,4], which might represent a significant advantage over photoacoustic tomography (PAT) [1].

Improvement of the signal-to-noise ratio (SNR) is still a challenge in UOT. The detection of ultrasound-modulated photons has been performed with confocal Fabry-Perot interferometers (CFPIs) [5,6], photorefractive interferometers [7-10], parallel speckle imaging [11,12], and spectral hole-burning in cryogenically cooled crystals [13]. The use of pulsed laser source and tagged photons detection schemes now allows performing imaging with a sufficient SNR to perform a quantitative evaluation of the spatial resolution of this technique. In pulsed UOT, where short ultrasonic bursts are used, the spatial resolution along the axis of propagation of the ultrasonic beam is expected to be determined by the bursts duration. In the transverse plane of the ultrasonic beam, the beam diameter is expected to be the limiting factor. Consequently, the UOT image should be the result of a three-dimensional (3D) convolution between the 3D point spread function (PSF) given by the intensity distribution of the ultrasonic burst and the true distribution of the absorbing and/or scattering properties of the medium at the probing wavelength.

In this paper, we apply basic concepts of image analysis [14] to UOT images of absorbing and scattering objects. The detection of tagged photons is performed with a double-pass CFPI and a pulsed laser source [6]. Special attention is paid to the spatial resolution along the axis perpendicular to both the ultrasonic and the laser beams. The experimental resolution is compared to the resolution expected from the ultrasonic beam transverse profile. More specifically, the edge spread function (ESF) is measured and compared to that expected from the ultrasonic beam intensity profile. This experimental analysis is done in the neighborhood of absorbing and scattering objects.

* guy.rousseau@cnrc-nrc.gc.ca

2. EXPERIMENTAL SETUP

2.1 Laser source

The setup used for the acquisition of UOT images is a combination of a pulsed single-frequency laser source and a double-pass CFPI [6]. The layout of the Nd:YAG master oscillator power amplifier (MOPA) is shown in Fig. 1(a). Figure 1(b) presents a typical pulse temporal profile at the exit of the MOPA. A peak power of 1.3 kW is routinely obtained at a repetition rate of 25 Hz. A 20- μ s time window is typically used for the measurements. All measurements were carried out with a mean laser irradiance of 90 mW/cm².

Fig. 1 (color online) (a) Layout of the MOPA. MO: continuous-wave master oscillator, OI1-2: optical isolators, LR1-2: Nd:YAG laser rods, FL: flashlamp, HW: half-wave plate, QW: quarter-wave plate, TFP: thin film polarizer. Other components are dielectric mirrors. (b) Pulse temporal profile. The useful part is enclosed between the red dotted lines.

2.2 Imaging system

In this study, a double-pass CFPI is used as a bandpass filter for the detection of photons tagged by a frequency shift equal to the ultrasound frequency. The experimental setup is schematically shown in Fig. 2. In Fig. 2(a), the single-frequency laser pulses emitted by the MOPA are brought to the imaging setup by the illumination multimode optical fiber (IMF). The beam exiting the IMF is collimated and directed to the plexiglas cell containing the scattering medium (SM). The SM is insonified with a focused ultrasonic transducer (UT: 19 mm diameter, 45 mm focal length) fed by 10-cycle bursts at 5 MHz, creating a peak pressure at focus of 1.9 MPa. At the rear face of the SM, photons are injected into a detection multimode optical fiber (DMF: 1 mm core diameter, 0.36 NA) with a lens or the DMF is directly butted against the surface of the plexiglas cell. In Fig. 2(b), the beam exiting the DMF is first collimated and transmitted through a polarizing beamsplitter (PBS). The beam is then coupled in the CFPI for a first pass. The 1-m-long CFPI is characterized by a free spectral range (FSR) of 75 MHz and a finesse $F = 28$ (mirrors' reflectivity: 95%). The beam exiting the CFPI is reflected back by a plane mirror (PM), a quarter-wave plate (QW) being used to rotate the polarization of the reflected beam by 90°. After the second pass in the CFPI, the beam is redirected by the PBS toward an InGaAs PIN photodiode (PD: 0.5 mm active diameter, 400 kHz bandwidth). The optical etendue of the CFPI (0.38 mm² sr) is approximately equal to that of the DMF (0.33 mm² sr). In the double-pass configuration, the CFPI is equivalent to a bandpass spectral filter having a FWHM of about 2.4 MHz. Such a filter is sufficiently narrow to efficiently reject untagged photons while keeping tagged photons. The CFPI is actively stabilized at the tagged-photon frequency with a stabilization unit (SU) using an error signal obtained from the single-pass transmission of a frequency-shifted sample of the master oscillator beam [6].

Fig. 2 (color online) Schematic diagrams of (a) the imaging setup and (b) the double-pass confocal Fabry-Pérot interferometer. Abbreviations are defined in the text. The black sphere in the SM represents the typical position of the absorbing and/or scattering object.

3. RESULTS

3.1 ESF of the ultrasonic beam

The radial intensity profile of the ultrasonic beam was measured in the focal plane of the transducer using a heterodyne interferometer [9]. This profile was used to generate the PSF by assuming a perfect cylindrical symmetry of the ultrasonic beam. The ESF and the modulation transfer function (MTF) have been evaluated numerically from the PSF. The same quantities were evaluated for a diffraction-limited ultrasonic beam using the Airy intensity distribution expected from the nominal diameter and focal length of the transducer. Figure 3 compares the diffraction limit (blue curves) and the experimental results (red dashed curves). The results are in very good agreement considering that nominal values of the transducer were used.

Fig. 3 (color online) (a) PSF, (b) ESF, and (c) MTF of the calculated diffraction-limited ultrasonic beam (blue curves) and the measured intensity profile of the ultrasonic beam (red dashed curves) emitted by the 5 MHz UT.

3.2 ESFs of absorbing and scattering objects

In UOT, it is generally assumed that resolution in the transverse plane of the ultrasonic beam is limited by the spatial extent of the beam. In pulsed UOT, the resolution along the axis of propagation of the ultrasonic beam is assumed to be limited by the ultrasonic burst duration. Recent results [6] have shown that the edges' sharpness could also be dependent on the type of object detected. Figure 4 shows images obtained in a 30-mm-thick SM composed of titanium dioxide particles dispersed in sunflower oil (reduced scattering coefficient: $\mu_s' = 6.3 \text{ cm}^{-1}$). Figure 4(a) shows the image of a piece of jellified India ink ($3 \times 3 \times 3 \text{ mm}^3$). In this case, the acousto-optic interaction is blocked by the high optical absorption of the photons in India ink. Figure 4(b) shows the image of a piece of white putty ($4 \times 5 \times 5 \text{ mm}^3$). In this case, the acousto-optic interaction is blocked by the strong optical diffuse reflection on the surface of the piece of white putty. Moreover, the strong ultrasonic attenuation in white putty results in a shadow on the opposite side of the incoming ultrasonic beam. The horizontal and vertical UOT signal profiles passing through the center of each object are also shown in Fig. 4.

Fig. 4 (color online) Images of objects in the central plane of a 30-mm-thick SM. (a) Piece of jellified India ink ($3 \times 3 \times 3 \text{ mm}^3$). (b) Piece of white putty ($4 \times 5 \times 5 \text{ mm}^3$). Horizontal and vertical profiles passing through the center of the object are shown on the top and right-hand side of each image. Curves enclosed in red dotted rectangles are considered to be representative of the ESF in both cases.

In principle, the ESF is obtained by imaging a sharp semi-infinite object equivalent to a unit step function. Here, it is assumed that the embedded objects were sufficiently large to be considered as semi-infinite. The rising edge on the right-hand side of each object in Fig. 4 (within the red dotted rectangles) was considered to be representative of the ESF, the flat bottom being identified as the null level and the maximum signal level being identified as the maximum irradiance by a vertical linear rescaling. Figure 5(a) shows the ESF of the diffraction-limited ultrasonic beam (blue curve) and the measured ESF of the ultrasonic beam (red dashed curve) already shown in Fig. 3(b). Horizontal scales have been shifted to ease the comparison of all the curves. The experimental horizontal profiles at the edge of both objects are also shown as data points. It is clearly seen that the ESF measured at the edge of the piece of white putty (green solid squares obtained from Fig. 4(b)) is essentially identical to that expected from the diffraction limit (blue curve) and the ultrasonic beam (red dashed curve). However, the ESF measured at the edge of the piece of jellified India ink (black solid circles obtained from Fig. 4(a)) is significantly wider. Table 1 gives the rise distances of the ESFs presented in Fig. 5(a). It is clearly seen that rise distances associated with the diffraction limit, the ultrasonic beam and the UOT signal in the neighborhood of an optically scattering object (white putty) are practically equal whereas the rise distances of the UOT signal in the neighborhood of an optically absorbing object (jellified India ink) are longer by about a factor 3. This significant difference can be understood qualitatively in the following way. Photons propagating in the neighborhood of the highly absorbing object can be tagged but their “survival” is afterward hindered by their diffuse propagation. Indeed, by propagating in a strongly scattering medium, photon tagged in the immediate vicinity of the absorbing object have a higher probability of being “killed” before exiting its immediate neighborhood. On the contrary, photons tagged in the vicinity of a highly scattering object such as white putty will be diffusely reflected by it until they exit its neighborhood, thus “surviving” until their detection and providing the optimum resolution.

A linear fit (central black solid line in Fig. 5(a)) can be used to evaluate approximately the MTF when imaging an absorbing object. Assuming that the ESF can be approximated by three linear segments, the MTF is given by $|\sin(\pi Ws)/(\pi Ws)|$ where $W = 2.77$ mm and s is the spatial frequency. This MTF (black curve in Fig. 5(b)) is characterized by a 3 dB bandwidth of 0.22 mm^{-1} compared to 0.60 mm^{-1} , the value expected from the ultrasonic beam (red dashed curve in Fig. 5(b)).

Fig. 5 (color online) (a) Comparison of the diffraction limited ESF (solid blue curve) and the measured ultrasonic ESF (red dashed curve superimposed on the blue curve) with the ESF of the UOT signal obtained in the neighborhood of a piece of jellified India ink (black solid circles) and in the neighborhood of a piece of white putty (green solid squares). The three segments (black lines) are associated with the black solid circles. (b) Corresponding MTFs (same color code).

Table 1 Comparison of the rise distances (in mm) obtained from the ESFs shown in Fig. 5(a).

Rise distance	Diffraction limit	Ultrasonic beam	Optically scattering	Optically absorbing
10%-90%	0.86	0.86	~0.84	~2.2
25%-75%	0.43	0.42	~0.40	~1.4

4.3 ESF in 60-mm-thick biological tissue

The detection of a piece of jellified India ink ($3 \times 3 \times 3 \text{ mm}^3$) embedded in the central plane of a 60-mm-thick sample of chicken breast has also been performed. In this case, a 2.25 MHz UT was used (38 mm diameter, 51 mm focal length) with 5-cycle bursts. The peak pressure in the focal plane was equal to 2.9 MPa. The resulting image is shown in Fig. 6.

Fig. 6 (color online) Image of a piece of jellified India ink ($3 \times 3 \times 3 \text{ mm}^3$) in the central plane of a 60-mm-thick sample of chicken breast. Horizontal and vertical profiles passing through the center of the object are shown on the top and right-hand side of the image. The curve enclosed in the red dotted rectangle is considered to be representative of the ESF.

The radial intensity profile of the ultrasonic beam in the focal plane of the 2.25 MHz UT has been measured using a heterodyne interferometer. Figure 7(a) compare the experimental PSF (red dashed curve) with the Airy intensity distribution expected from the nominal diameter and focal length of the transducer (blue solid curve). The slight discrepancy between both curves can be attributed to the large numerical aperture of this transducer (0.38), which is somewhat too high to apply the Airy intensity distribution obtained in the Fraunhofer approximation. The corresponding ESF and MTF are respectively shown in Figs. 7(b) and 7(c) using the same color code. Following an analysis similar to that made in Sec. 3.2, the experimental ESF of the UOT signal has been extracted from the horizontal profile over the image in Fig. 6. Again, the ESF has been modeled by three linear segments (black solid lines in Fig. 7(b)) where the central part has been obtained by a linear fit with the relevant experimental points (black solid circles for positions between -1.4 mm and 1.4 mm in Fig. 7(b)). The corresponding MTF is shown in Fig. 7(c). The rise distances of all ESFs shown in Fig. 7(b) are given in Table 2. Again, a significant difference is observed for the ESF derived from the UOT image of the absorbing object. This difference can also be observed in the spatial frequency domain where the 3 dB bandwidth of the MTFs shown in Fig. 7(c) are equal to 0.22 mm^{-1} (black solid curve), 0.36 mm^{-1} (red dashed curve), and 0.48 mm^{-1} (blue solid curve).

Fig. 7 (color online) (a) PSF, (b) ESF, and (c) MTF of the calculated diffraction-limited ultrasonic beam (blue curves) and the measured ultrasonic beam (red dashed curves).

Table 2 Comparison of the rise distances (in mm) obtained from the ESFs shown in Fig. 7(b).

Rise distance	Diffraction limit	Ultrasonic beam	Optically absorbing
10%-90%	1.1	1.4	~2.2
25%-75%	0.54	0.64	~1.4

4. CONCLUSIONS

The results presented here show that the spatial resolution in UOT depends on the type of embedded object. This study has focused on the resolution along the axis perpendicular to both the ultrasonic and the laser beams, but a quantitative evaluation of the 3D point spread function might reveal other effects. The case where the embedded object has different scattering properties while being acoustically transparent still needs to be investigated.

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