Reconstruction of optical energy deposition for backward optoacoustic imaging

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Abstract. Visualizing optical properties, such as the optical absorption coefficient, helps us to obtain structural information of biological tissues. In this paper, we present an efficient reconstruction algorithm for optical energy deposition in backward optoacoustic imaging. Note that reconstruction of optical energy deposition is the first step to imaging the optical absorption coefficient distribution. This algorithm is derived from the optoacoustic wave equations with line focusing, in which the focusing techniques were utilized to reduce the reconstruction problem from three dimensions (3-D) to one dimension (1-D). Simulations and experiments were conducted to verify efficacy of this algorithm. In the simulations, optoacoustic signals were generated based on the solution of the optoacoustic wave equations. In the experiments, a 3-D backward mode optoacoustic imaging system was built. The system consisted of a Nd:YAG laser for optical irradiation and an acoustic detection system with a broadband hydrophone. A phantom was used to illustrate validity of the proposed algorithm. The results show that optical energy deposition can be efficiently reconstructed in both simulations and experiments.

Key words: absorption coefficient distribution, backward optoacoustic imaging, optical energy deposition, photoacoustics, reconstruction, ultrasound

1. Introduction

Optical properties, such as absorption and scattering, can be used to characterize biological tissues (Cheong *et al.* 1990; Tuchin 2000). Optoacoustic (OA) imaging has been used to measure tissue optical absorption *in vivo*. It takes advantage of high optical contrast and low acoustical scattering in tissue. Consider a short laser pulse irradiates a sample, absorption of the optical energy may produce thermal expansion and therefore generate acoustic waves (Gusev and Karabutov 1993; Tuchin 2000). The generated optoacoustic transients propagate outward and then can be detected by an acoustic transducer (e.g., a hydrophone). The detected optoacoustic signals can be used to reconstruct the optical energy deposition, which is related to the absorption coefficient distribution of the tissue (assuming temporal stress confinement) (Karabutov *et al.* 1996; Esenaliev *et al.* 1999). Two of the major scanning modes reported in the literature for optoacoustic imaging include the tomographic mode and the backward mode. In the tomographic mode, the acoustic transducer detects optoacoustic waves by surrounding

the sample on a scanning track which is perpendicular to the laser irradiation direction (Kruger *et al.* 1995; Wang *et al.* 2003a). Several reconstruction algorithms have been proposed for the tomographic mode and have been utilized for breast cancer detection (Kruger *et al.* 2002) and functional imaging of the rat brain (Wang *et al.* 2003b). In the backward mode, on the other hand, the transducer receives the optoacoustic waves at the same side as the laser beam (Karabutov *et al.* 2000). Under this condition, backward optoacoustic imaging is easier to implement and offers a wide scanning range. Therefore, it is a potentially useful mode for biomedical investigations in addition to the tomographic mode.

In recent years, reconstruction methods of the backward optoacoustic imaging have been proposed. They include the beam-forming method (i.e., synthetic aperture focusing) (Blouin *et al.* 1998; Hoelen *et al.* 1998, 2000), the Fourier transform method (Levesque *et al.* 2002), and the backprojection method (Kostli *et al.* 2001). However, success of these methods has been primarily demonstrated with layered structures and the ability of backward mode optoacoustic imaging in measuring optical energy disposition for heterogeneous tissue structures has been limited. In addition, most methods are computationally demanding. In this paper, an effective reconstruction algorithm derived from the solution of the optoacoustic wave equations is proposed. The solution of the optoacoustic wave equations for pressure in three dimensions (3-D) shows that the optoacoustic wave is determined by the geometric distribution of the optical absorber inside an optoacoustic radiation pattern (Kruger *et al.* 1995; Xu *et al.* 2003). The optoacoustic radiation pattern is defined as the overlap of the optical illumination pattern with the hydrophone's directivity pattern. It also determines the lateral resolution. In biological tissues, strong optical scattering broadens the optical illumination pattern thus degrading the lateral resolution in optoacoustic imaging. The concept of the proposed algorithm is to reduce the reconstruction problem from 3-D to 1-D by line focusing via synthetic aperture focusing technique (SAFT) and the adaptive weighting technique (i.e., SAFT-plus-CFW) (Liao *et al.* 2004). SAFT synthesizes a large aperture by properly delaying and summing the signals received at adjacent scan positions which increases both the signal-to-noise ratio (SNR) and improves the lateral resolution. In addition to SAFT, the focusing quality is further improved by utilizing the signal coherence, which has been proposed as coherence factor weighting (CFW). SAFT-plus-CFW creates a parallel optoacoustic radiation pattern that provides uniform lateral resolution through the depth. Under this condition, each scan position on the scan line receives only the pressure waves propagated from the sources located inside the narrowed radiation pattern. Therefore, the solution of the optoacoustic wave equation can be rewritten to a 1-D form. Moreover, the temporal profile of laser irradiation is a short Gaussian pulse with a

duration of 5–15 ns that can be regarded as a Dirac delta function in the 1-D form of the solution of the optoacoustic wave equation. Finally, the optical energy deposition can be achieved by integrating the well-focused pressure waves.

The relation between the far field optoacoustic signals and the optical energy deposition profile has also been reported in investigating layered structures without considering the broad optoacoustic radiation pattern (Paltauf and Schmidt-Kloiber 2000). In this method, the detected optoacoustic signals are integrated to obtain the profile of the optical energy deposition in a layer structure. Nevertheless, the strong optical scattering has to be considered in the biological tissue since the broadened optoacoustic radiation pattern affects the accuracy of the reconstruction. In this paper, we will provide a theoretical foundation and show that the optical energy deposition can be reconstructed with a broadened optoacoustic radiation pattern in the backward mode optoacoustic imaging. Based on the measured optical energy deposition, the ultimate goal of this study is to extend to reconstruction of optical absorption coefficient.

2. Reconstruction formulas

Figure 1 shows the schematic diagram of a backward optoacoustic imaging system with an optoacoustic probe. The probe laterally scans the tissue with a broad optoacoustic radiation pattern (defined as the product of the laser energy distribution and the acoustic beam).

The detected optoacoustic signals can be described by the optoacoustic theories which have been discussed in other articles (Gusev and Karabutov

Fig. 1. Focused radiation pattern in backward optoacoustic imaging.

1993; Tuchin 2000). When the laser pulse duration is much shorter than the thermal diffusion time, thermal diffusion can be neglected. It is also known as the thermal confinement. Under this condition, the physical interactions among laser energy, tissue characteristics, and the pressure wave propagation can be expressed by using the linear wave equation with a source term depending on space and time (Kostli *et al.* 2001; Xu *et al.* 2003). This linear wave equation in terms of the pressure waves describes the dispersing pressure field by

$$\nabla^2 p(r, t) - \frac{1}{V_s^2} \frac{\partial^2}{\partial t^2} p(r, t) = H \cdot E(r_0) \frac{d\eta(t_0)}{dt_0}, \quad (1)$$

where V_s is the sound velocity, and $H = \Gamma/V_s^2$ is assumed to be a constant in tissue. Γ denotes the Grüneisen coefficient, which represents the dimensionless conversion factor from deposited energy to pressure. $E(r)$ is the optical energy deposition, which is the product of the spatial distribution of laser energy $I(r)$ and optical absorption coefficients $A(r)$. η denotes the temporal profile of laser irradiation. The general solution of Equation (1) can be obtained by using the time-retarded solution to the wave equation (Walker 1970). By applying the Green's function, this equation can be rewritten in terms of optical energy deposition $E(r_0)$:

$$p(r, t) = \frac{H}{4\pi} \int \frac{E(r_0)}{|r - r_0|} \cdot \frac{d\eta(t_0)}{dt_0} \bigg|_{t_0=t-|r-r_0|} dr_0, \quad (2)$$

where the 3-D volume integral is carried out over the entire r_0 space inside the optoacoustic radiation pattern. The optoacoustic radiation pattern is defined as the overlap of optical illumination pattern with the ultrasound hydrophone's directivity pattern. This is the solution of the optoacoustic wave equation, in which the propagated pressure wave can be characterized. This also describes how the pressure signal conveys the spatial information about the optical absorption properties of the tissue. $p(r, t)$ represents the pressure wave that detected by a transducer located at a spatial position r .

The purpose of the proposed algorithm is to reduce the dimension of the optoacoustic radiation pattern in Equation (2) from 3-D to 1-D by using SAFT-plus-CFW. SAFT synthesizes a large aperture by properly delaying and summing the signals received at adjacent scanning positions. Although SAFT is effective, strong side lobes are present and affect. Therefore, an improved beam-forming technique with a higher focusing quality has been proposed by combining SAFT with CFW. SAFT-plus-CFW improves the focusing quality by using the array signal coherence. In this paper, we use the SAFT-plus-CFW technique in order to narrow the optoacoustic radiation pattern to approximate a 1-D line. In this condition, each scan

position on the scan line receives only the pressure waves propagated from the sources inside the narrowed 1-D radiation pattern, which is perpendicular to the scan line in backward optoacoustic imaging, as shown in Fig. 1. Consider the four optoacoustic point sources denoted as 'a', 'b', 'c' (points located inside the broad radiation pattern) and 'd' (located outside the radiation pattern). Each channel detects the signals coming from the sources inside its radiation pattern, thus the received signal consists of the pressure waves that are produced by points 'a', 'b', and 'c'. After applying SAFT-plus-CFW, the radiation pattern can be formed as a line along the depth direction with uniform width through the depth. Therefore, only the signals from point 'b' are detected and the pressure waves detected at each scan position x (i.e. each channel) can be rewritten:

$$p(t)|_x = \frac{H}{4\pi} \int \frac{E(z)|_x}{z} \cdot \frac{d\eta(t_0)}{dt_0} \bigg|_{t_0=t-\frac{z}{V_s}} dz, \quad (3)$$

where the $p(t)|_x$ is the result of the focusing technique at the scan position x . $E(z)|_x$ denotes the 1-D optical energy deposition profile along the depth at the scan position x . Note that the depth $z=r-r_0$. The focused pressure waves at each scan position are then integrated with respect to t_0 from $-\infty$ to t , which gives

$$\hat{p}(t)|_x = \int_{-\infty}^t p(\tau)|_x d\tau = \frac{H}{4\pi} \int \frac{E(z)|_x}{z} \cdot \int_{-\infty}^t \frac{d\eta(t_0)}{dt_0} \bigg|_{t_0=\tau-\frac{z}{V_s}} d\tau \cdot dz, \quad (4)$$

where $d\tau = dt_0$ and

$$\hat{p}(t)|_x = \frac{H}{4\pi} \int \frac{E(z)|_x}{z} \cdot \eta\left(t - \frac{z}{V_s}\right) dz. \quad (5)$$

The above equation can be rewritten as a convolution sum of the 1-D optical energy deposition with the temporal profile of laser irradiation.

$$\hat{p}(t)|_x = \frac{H}{4\pi} \cdot \text{conv} \left\{ \frac{E(z)|_x}{z}, \eta(t \cdot V_s) \right\}. \quad (6)$$

Therefore, the optical energy deposition along the depth can be calculated.

$$E(z)|_x = \frac{4\pi \cdot z}{H} \cdot \text{deconv} \left\{ \hat{p}(t)|_x, \eta(t \cdot V_s) \right\}, \quad (7)$$

As previously mentioned, the temporal profile of the laser irradiation is a short pulse since it is in the regime of thermal confinement. Therefore, it

can be regarded as a Dirac delta function $\eta(t \cdot V_s) = \delta(t \cdot V_s)$. Subsequently, Equation (7) can be rewritten as

$$E(z)|_x = \frac{4\pi \cdot z}{H} \cdot \hat{p}(t)|_x. \quad (8)$$

Finally, the image of optical energy deposition can be reconstructed by applying this algorithm with all scan lines.

3. Numerical simulations

To demonstrate the validity of the proposed reconstruction algorithm for backward mode optoacoustic imaging, simulations have been performed. The simulations were based on the scanning setup shown in Fig. 1. The solution of the optoacoustic wave equations was used to produce the optoacoustic signals that were detected by a wideband acoustic transducer. A rectangular optical absorber, with a size of 3.5 mm in width and 2.5 mm in thickness, was located at a depth of 1 mm below the scan surface. Laser energy was irradiated from the top of the phantom. The optical energy was absorbed exponentially from the top to the bottom of the phantom in accordance with the Beer–Lambert law (Tuchin 2000) that can be expressed as

$$\Phi(z) = \Phi_0 \cdot \exp(-\mu_a(z) \cdot z), \quad (9)$$

where $\Phi(z)$ denotes the remained optical energy at the depth of z , Φ_0 and μ_a represent the incident optical energy and the absorption coefficient, respectively. The transducer was scanned with a step of 20 μm , and the signal sampling frequency was 150 MHz. The laser temporal profile was set to be a Gaussian pulse with a duration of 25 ns. The sound velocity was 1500 ms^{-1} .

Thermal noise was then added to the received signals to result in a signal-to-noise (SNR) of 17 dB, as shown in Fig. 2(b). The optoacoustic radiation pattern was set to be a sector shape with a wide beam divergence of 65° to simulate a strong optical scattering in tissue. According to this broad optoacoustic radiation pattern, the detector received the optoacoustic waves propagated from almost entire region of the predefined absorber at each position on the scan line. Figure 2(b) shows the image of the absorber using the conventional backward imaging method (i.e., direct display of the detected pressure wave). It is not possible to distinguish the shape of the target and to measure the optical energy distribution.

By applying the proposed algorithm, an optical energy deposition image is shown in Fig. 3(a) on a linear scale. The reconstructed image shows a rectangle with the same size and position as the predefined phantom. The

Fig. 2. (a) The distribution of optical energy deposition on a linear scale, and (b) received optoacoustic signals on a log scale with a 30-dB dynamic range.

Fig. 3. (a) Reconstructed image of optical energy deposition, (b) spectrum of 1-D axial profile, (c) the weighting map, and (d) the final reconstructed image after weighing.

focusing technique also produced a higher SNR and better spatial resolution. The SNR was increased via summing the properly delayed signals, and it was further improved by applying CFW. On the other hand, Fig. 3(a) also shows a tail artifact and elevated side lobes. These are due to the increased low frequency signal amplitude via de-convolution. In order

to reduce such artifacts, a weighting map was used. Figure 3(b) shows the spectrum of a 1-D signal on the axial direction in the reconstructed image. The weighting map was produced by de-modulating the high-frequency components and taking envelopes of all the axial profiles in the reconstructed image in which the resultant frequency components are indicated by the dashed rectangle. Because of the narrowed spectrum, weighting map presents a blurred pattern. However, it indicates the position of the object without the influence from the low-frequency errors (i.e., the tail artifacts and the side lobes), as shown in Fig. 3(c). Finally, the optical energy deposition image can be obtained by weighting the reconstructed image by this map, as shown in Fig. 3(d). The spectrum of Fig. 3(d) can be regarded as a convolution form of the filtered region with the original spectrum in the axial direction. Therefore, the image shown in Fig. 3(d) maintains clear boundaries due to the maintenance of the complete spectrum in Fig. 3(a).

The reconstructed images using the conventional method and the proposed algorithm are shown in Fig. 4(a) and (b), respectively. These images are displayed over a 30-dB dynamic range. The vertical axis is the depth and the horizontal axis is the lateral position (both in millimeters). The results of the conventional method show that the image consists of only two straight lines corresponding to the phantom boundaries. Details inside the phantom are missing, which agree with the relation between the far field optoacoustic signal and the optical energy deposition profile (Paltauf and Schmidt-Kloiber 2000). The results of the proposed algorithm in Fig. 4(b) show not only edges but also the optical energy deposition inside of the phantom. The image shows a rectangular shape, which is in good agreement with the predefined phantom.

Fig. 4. Images of the optoacoustic phantom. (a) the conventional method and (b) the reconstructed image using the proposed algorithm. The images are displayed over a 30-dB dynamic range.

Figure 5 shows 1-D signals on the axial direction at the 10-mm scanning position. The dashed line is the predefined optical energy deposition (i.e., the theoretical profile), the dashed-dotted line and the solid line represent the reconstructed results of the conventional method and the propose algorithm, respectively. According to the Beer's law, the theoretical profile shows an exponential decay from top (1 mm) to bottom (3.5 mm) of the phantom. Using the conventional method, strong signals only occurred at the edges of the phantom. By applying the proposed algorithm, the 1-D result shows good agreement with the theoretical profile. It presents not only the boundaries but also the internal optical energy deposition, which demonstrates that the phantom was irradiated by the optical energy from the top and decayed through the depth inside the phantom.

4. Experimental methods

In order to further demonstrate performance of the proposed algorithm, a 3-D backward mode optoacoustic scanning system was built. Figure 6 shows the schematic diagram of the scanning system which mainly consists of a Q-switch Nd:YAG laser, a wideband acoustic receiving system, and a 2-D precision translation stage. The Q-switch Nd:YAG laser (LS-2132U, LOTIS TII) operating at 1064 nm infrared light with a pulse duration of 8 ns was employed for optical illumination. The laser energy was focused by lenses onto a 1000- μm fiber (FT-1.0-UMT, Thorlabs) with an optical energy of 21 mJ and a 15-Hz pulse repetition rate. An ultrasonic needle hydrophone (MHA9-150, Force) PVDF hydrophone with a frequency response from 0.1 to 80 MHz was used to detect the generated optoacoustic signals. The

Fig. 5. Simulation results represented in A-lines at 10-mm scanning position, including the theory (dashed), the proposed method (solid), and the conventional method (dashed-dotted).

Fig. 6. Schematic diagram of the experiment optoacoustic system.

active area of the hydrophone had a diameter of $150\text{ }\mu\text{m}$. We incorporated the fiber and the needle hydrophone on a single holder as an optoacoustic probe. This probe was affixed on the 2-D translation stage (CSR200, Control System in Motion) and mechanically scanned with a $100\text{ }\mu\text{m}$ step size. The scan range was 10 mm in both the X and Y directions. A rectangular sample, which was made from a dyed polyvinyl alcohol (PVA), with a size of 2.5, 2.5, and 3.5 mm respectively in the width (Y-direction), thickness (Z-direction), and length (X-direction) was immersed in milk solution contained in a water tank to be the target under investigation. The phantom optical absorption coefficient was 4.1 cm^{-1} and the milk solution had a scattering coefficient of 3.69 cm^{-1} , which was measured by a double integrating sphere system. This top edge of the rectangle phantom was 3 mm below the hydrophone tip. The detected optoacoustic signals were amplified by an acoustic amplifier (5800PR, Panametrics). These waveforms were digitized and stored in a personal computer with a data acquisition card (CompuScope 12100, Gage) at a 100-MHz sampling rate.

Although the hydrophone provides high performance in detecting wide-band optoacoustic signals, the proposed algorithm required higher sensitivities in the low frequency range in order to reduce the artifacts. Laser-induced optical breakdown (LIOB) is a useful technique to calibrate the hydrophone sensitivities especially those components near DC (Hollman 2001). It instantaneously creates a single micro-bubble in de-ionized water by irradiating high power laser energy inside the water with a tiny focused spot. This micro-bubble quickly expands into the surrounding material (i.e., the water) with a velocity exceeding the speed of sound. The acoustic transient is a short and positive pressure wave. Thus, it has a wide bandwidth

from DC to 10 MHz or higher frequencies (depends on the bubble size). An LIOB experiment was conducted to obtain the acoustic transient by using focused laser energy with a duration of 5 ns. The acoustic transient was detected by using the same system as the one used in optoacoustic experiments, as shown in Fig. 7(a). The spectrum of this acoustic transient has been shown in Fig. 7(b). The frequency response was calibrated by using the results of the LIOB.

5. Experimental results

The experimental results are shown in Fig. 8. These images are the cross-sectional images of the reconstructed 3-D object including the Z-direction, X-direction, and Y-direction views. Figure 8(a)–(c) are the 2-D images using the conventional method. The Z-view image shows the top of the phantom with a rectangular shape since only the top and bottom edges can be exhibited by using conventional method. Figure 8(b) and (c) present the images with only two straight lines on the boundaries of the phantom and some contents between the lines that also appeared in the simulation results. The results show inadequate information of optical energy deposition. The results of the proposed reconstruction algorithm are shown in the bottom figures (Fig. 8(d)–(g)). Distributions of the energy depositions are clearly presented visible. The object is more similar to a rectangular structure especially in the X-view and Y-view images. The energy decay from the top to the bottom is easier to observe, which indicates that the laser energy was exposed from the top of the phantom, and decayed due to the energy absorption of the phantom.

Fig. 7. The LIOB signal detected by the hydrophone (a), and its spectrum (b).

Fig. 8. 2-D cross-sectional images of the reconstruction results including Z-view, X-view, and Y-view images from left to right, respectively. (a)–(c) show the results of conventional reconstruction method and (d)–(f) show the results of proposed algorithm. The dynamic range is 30 dB. The vertical axis is the depth, and the horizontal axis is the lateral direction.

6. Conclusions

In this research, we reconstructed the optical energy deposition as the first step to reconstruction of the optical absorption coefficient in optoacoustic imaging using both numerical simulations and experiments. This algorithm was developed from the 3-D optoacoustic wave equations in combination with the SAFT-plus-CFW focusing technique. The focusing technique provides good image quality. We have demonstrated that the proposed algorithm effectively reconstructed the optical energy deposition in both the simulations and the experimental results in the backward mode optoacoustic imaging. In the experiments, the hydrophone was calibrated by using the LIQB method thus the influences of hydrophone were reduced. Furthermore, a weighting map was produced to eliminate the tail artifacts and the side lobes. The proposed method performs a complete imaging of the optical energy deposition without assuming the homogeneous absorption coefficient. The integration of the focused pressure wave in this algorithm, as shown in Equation (4), can be regarded as the gain of the spectrum and the gain increases as the frequency decreases. Under this condition, the proposed algorithm is applicable even in the presence of optical absorption inhomogeneities. Nonetheless, efficacy of this algorithm in an inhomogeneous medium will be tested using *in vivo* data.

The future work of this study will be to obtain the absorption coefficient distribution by using the detected optical energy depositions.

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