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Modified delay-and-sum reconstruction algorithm to improve tangential resolution in photoacoustic tomography

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ABSTRACT

In photoacoustic/optoacoustic tomography (PAT/OAT) for a circular scanning geometry, the axial/radial resolution is not variant spatially and also do not depend on the ultrasound transducer (UST) aperture. But the tangential resolution is affected by the size of the detector aperture and is spatially variant. To counter this problem many techniques such as attaching a negative lens to the transducer surface, or using virtual detectors were proposed. However these techniques have difficulties. Therefore, a modified delay-and-sum reconstruction algorithm was proposed which can be used with the normal UST to improve the tangential resolution. In this work, we demonstrate the improvement of tangential resolution using the modified delay-and-sum reconstruction algorithm with experimental data. We have obtained more than twofold improvement of resolution in the tangential direction using non-focused and cylindrically focused USTs in a circular scanning geometry. We also observe that shape of the target object can also be preserved which is helpful for diagnosis and treatment purposes.

Keywords: image reconstruction, tangential resolution, photoacoustic tomography, thermoacoustic tomography.

1. INTRODUCTION

Photoacoustic imaging is an upcoming biomedical imaging modality which is based on photoacoustic (PA) effect.¹⁻³ PA waves are generated from any biological tissue when it is irradiated with a laser source. When a laser beam hits the target object, due to thermoelastic expansion of the illuminated region there is an initial pressure rise. This initial pressure rise results in generation of pressure waves in the ultrasonic frequencies. This phenomenon is termed as photoacoustic effect. The generated ultrasound waves are detected using an ultrasound transducer (UST). These pressure waves give the structural information of the biological tissue (target object). The PAT imaging modality finds vast applications in brain imaging,⁴ molecular imaging,⁵ tumor angiogenesis,⁶ breast cancer imaging,⁷ sentinel lymph node imaging,⁸ monitoring of temperature,⁹ tissue engineering¹⁰ and so on.¹¹⁻¹³

The photoacoustic tomography (PAT) scanner acquires the photoacoustic waves in a circular geometry around the target object. Various reconstruction algorithms can be used for mapping the initial pressure rise distribution from the boundary data,¹⁴⁻²⁴ In any circular PAT scanning system, the spatial resolution depends on transducer bandwidth and the detector aperture. The axial resolution (along radial direction) is dependent on transducer bandwidth and is spatially invariant whereas the tangential resolution (along tangential direction) is dependent both on transducer bandwidth and detector aperture and is spatially variant.^{25, 26} The tangential resolution of a larger aperture detector is poorer for the target objects that are away from the scanning center (nearer to the transducer detection area). To improve the tangential resolution, the transducer can be rotated around the specimen in a larger scanning radius i.e. away from the scanning center. However, this results in increase in occupying of space. Also the sensitivity of the detector decreases as it

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moves away from the center. Alternate way to improve the tangential resolution is by using a negative acoustic lens attached to the detector surface. This increases the acceptance angle of the detector and thereby improves tangential resolution.²⁷ But there is a difficulty in attaching the custom made acoustic lens to the transducer as it may result in formation of air bubbles between the lens and the detector. This induces artifacts in the reconstructed images. Also, the impedance mismatch between the lens and the water medium (acoustic coupling medium) results in loss of signal. It is also very difficult to design custom made in house negative lens for cylindrically focused transducers with curved detection surface. A custom made detector with negative lens attached to the piezo surface inside transducer can be used to overcome this problem. But this increases cost. To avoid such difficulties, a modified delay-and-sum reconstruction algorithm was proposed to improve the tangential resolution without using any negative acoustic lens or custom made detectors. This algorithm is validated experimentally in this paper using different phantoms for both unfocused and cylindrically focused transducers.

Fig. 1: Schematic diagram of the PAT experimental set up. SM: Stepper Motor, DAQ: Data acquisition card, R/A/F: Receiver, Amplifier, Filter, UST: Ultrasound transducer, L1: Plano concave lens, P1: Uncoated prism.

2. MATERIALS AND METHODS

2.1 Modified delay-and-sum reconstruction algorithm

The modified delay-and-sum reconstruction algorithm is briefly summarized here. Detailed explanation of this algorithm is explained elsewhere.¹⁵ A delta light illumination $\delta(t)$ creates an initial pressure rise at a position $\vec{r}$ is given by $p_o(\vec{r}) = \Gamma(\vec{r})A(\vec{r})$ where $A(\vec{r})$ is spatial light absorption function and $\Gamma(\vec{r})$ Gruneisen parameter of the tissue. The source $p_o(\vec{r})$ initiates the acoustic pressure $p(\vec{r}_o, t)$ at position $\vec{r}_o$ and time t which satisfies the photoacoustic wave equation in an acoustically homogenous medium:

$$\nabla^2 p(\vec{r}_o, t) - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} p(\vec{r}_o, t) = -p_o(\vec{r}) \frac{\partial \delta(t)}{\partial t}, \quad (1)$$

where, c is the speed of the sound. The main aim of the reconstruction in PAT is the estimation of initial pressure rise which is obtained by backprojecting in time domain as follows:²⁰

$$p_o(\vec{r}) = \int b\left(\vec{r}_o, t = \frac{|\vec{r}-\vec{r}_o|}{c}\right) \frac{d\Omega_o}{\Omega_o}, \quad (2)$$

where, Ω_o is the solid angle subtended by the measuring surface S_o with respect to the reconstruction point --- on the surface S_o . For spherical and cylindrical geometries $\Omega_o = 4\pi$ and for planar geometry $\Omega_o = 2\pi$. $b(\vec{r}_o, t)$ is the backprojection term, $d\Omega_o$ is the solid angle subtended by detection element dS_o with respect to the reconstruction point $\vec{r}$. The term $d\Omega_o/\Omega_o$ is a weighing factor contributing to the reconstruction from detection element, dS_o [Fig. 1 and 2 in Ref.²⁰]. In conventional delay-and-sum reconstruction algorithm, the larger aperture detectors are considered as point detector which induces artifacts in the reconstructed image. In modified delay-and-sum reconstruction algorithm, the entire surface area of the detector was taken into consideration for backprojecting.¹⁵ As the simulations were done in two dimensions, the recording surface of the transducer is a line segment instead of a circular surface [Fig. 1 of Ref.¹⁵]. Hence, many small segments on the line have been considered during backprojecting instead of single center point, to reconstruct the PA signal.

2.2 Experimental Method

The experimental schematic diagram is shown in Fig. 1(a). A Q-switched Nd:YAG laser was used to deliver 5 ns laser pulses with 10 Hz repetition rate at 532 nm wavelength. The optical fluence was maintained around ~ 3 mJ/cm² (< ANSI safety limit²⁸ of 20 mJ/cm² at 532 nm wavelength). A 2.25 MHz central frequency non-focused UST (Olympus NDT, V306-SU) and a cylindrically focused UST (Olympus NDT, V306-SU-NK, CF = 1.90 inch) with 13 mm diameter active area and with ~70% nominal bandwidth were used to acquire the PA signal. The PA data was acquired around the sample in full 360° in circular geometry for 60 sec with rotational speed of 6 degrees/sec. The acquired PA signals (with sampling rate of 25 MHz) were averaged into 200 A-lines.^{29, 30} The PA signals after amplification and filtering by a pulse amplifier (Olympus-NDT, 5072PR) were recorded using a data acquisition card (GaGe, compuscope 4227) inside a desktop.

3. RESULTS AND DISCUSSIONS

The first phantom used was the point source phantom made using 5 pencil leads of 0.5 mm diameter that are adhered on an acrylic slab using pipettes as shown in Fig. 2(a1). The leads were placed approximately at 0 mm, 8 mm, 16 mm, 24 mm and 32 mm from the scanning centre. The reconstructed images for the five point source phantom are shown in Fig. 2. Fig. 2(a) shows conventionally reconstructed PAT images of five point target objects obtained using non focused UST. The zoomed-in images of point targets 1 to 5 are shown in Fig. 2(c-g).

It can be observed from these reconstructed PAT images that there is an elongation of the point targets in tangential direction. The elongation is much higher for the point targets away from the scanning centre i.e. closer to the transducer. The modified reconstruction algorithm improves the tangential resolution as can be seen from zoomed in images [Figs. 2(h)-(l)]. There was a twofold improvement in the tangential resolution. Fig. 2(y) shows the quantified tangential resolution versus distances from the scanning centre. From the plots, it can be clearly seen that modified delay-and-sum reconstruction algorithm improves the tangential

resolution compared to conventional delay-and-sum algorithm. Similar trends can be observed using cylindrically focused transducers [Fig. 2(m-x,z)].

To demonstrate that the modified delay-and-sum reconstruction algorithm retains the shape of the object, a study was conducted with low density polyethylene (LDPE) tubes of 5 mm inner diameter filled with black Indian ink as shown in Fig. 3(m). One tube was placed at the scanning center and the other was placed ~1.5 cm away from the scanning center. Fig. 3(a), (b) show the reconstructed cross sectional PAT images using conventional and modified reconstruction algorithms for the PA signals acquired using unfocused UST. As can be seen from the Fig. 3(d), there is a distortion in the shape of the circular object. But by using modified reconstruction, the shape can be retained as shown in Fig. 3(f). Similar shape preservation can be observed for the data collected using cylindrically focused UST [Fig. 3(g)-(l)].

To show the feasibility of using this modified delay-and-sum algorithm for realistic phantom imaging, a study was carried out with 0.38 mm inner diameter LDPE tubes filled with mice blood. These tubes were embedded on chicken breast tissue to mimic the blood vessel network in the shape of 'N' (1.5 cm x 1.5 cm) as shown in Fig. 4(a). Another layer of the tissue (5 mm thick) was placed on top. The cross sectional reconstructed PAT images for the data obtained using flat UST are shown in Fig. 4(b),(c) using conventional and modified reconstruction algorithms respectively. As can be seen in Fig. 4(b) which was reconstructed using conventional algorithm, the curvings and bendings of the blood vessel network resulted in distorted shape. These distortions were corrected in Fig. 4 (c) using modified delay-and-sum reconstruction method. Similar corrections in the shape distortions can be seen from Figs. 4(d) and (e) for the data collected using cylindrically focused UST.

4. CONCLUSIONS

It was proved experimentally that by using modified delay-and-sum reconstruction algorithm, the tangential resolution of PAT images can be improved twofold for unfocused and cylindrically focused transducers. Also, the shape of the target objects can also be preserved. Hence, the usage of any external negative acoustic lens on the detector surface can be avoided.

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Fig. 2: (a)-(l): Experimental results of point source phantom using non focused UST. (a) Conventionally reconstructed cross sectional images of 5 point targets (b) Modified delay-and-sum algorithm reconstructed cross sectional images (c)-(g): Zoomed in images of points 1 to 5 in (a). (h)-(l): Zoomed in images of points 1 to 5 in (b). (y) Comparison of tangential resolution between conventional and modified reconstruction algorithm as a function of distances from the scanning center for unfocused UST. (m)-(x): Experimental results of point source phantom using cylindrically focused UST. (m) Conventionally reconstructed cross sectional images of 5 point targets (n) Modified delay-and-sum algorithm reconstructed cross sectional images (o)-(s): Zoomed in images of points 1 to 5 in (m). (t)-(x): Zoomed in images of points 1 to 5 in (n). (z) Comparison of tangential resolution between conventional and modified reconstruction algorithm as a function of distances from the scanning center for cylindrically focused UST. Red arrows point to the improvement in tangential resolution. (a1) Picture of 5 pencil leads (point source phantom).

Fig. 3: (a)-(f) Experimental results of circular shaped phantom using non focused UST. (a) Using conventional reconstruction algorithm. (b) Using modified reconstruction algorithm. (c,d): Zoomed in individual circles in (a). (e,f): Zoomed in individual circles in (b). (g)-(l): Experimental results of circular shaped phantom using cylindrically focused UST. (g) Using conventional reconstruction algorithm. (h) Using modified reconstruction algorithm. (i,j): Zoomed in individual circles in (g). (k,l): Zoomed in individual circles in (h). Red arrows point to the improvement obtained. (m) Picture of LDPE tubes filled with Indian black ink (circular shaped phantom).

Fig. 4: (a) Picture of 'N' shaped blood vessel phantom on chicken tissue; (inset: layer of chicken tissue (5 mm thick) on top of the blood vessel network). (b) Cross sectional reconstructed PAT image using conventional algorithm for flat UST data (c) Reconstructed using modified algorithm for flat UST. (d) and (e) are the reconstructed PAT images for cylindrically focused data using conventional and modified reconstruction algorithms.

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