International Journal of Medical, Medicine and Health Sciences
ISSN: 2517-9969
Vol:10, No:4, 2016

Comparison of Back-Projection with Non-Uniform Fast Fourier Transform for Real-Time Photoacoustic Tomography

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***Abstract*—**Photoacoustic imaging is the imaging technology that combines the optical imaging and ultrasound. This provides the high contrast and resolution due to optical imaging and ultrasound imaging, respectively. We developed the real-time photoacoustic tomography (PAT) system using linear-ultrasound transducer and digital acquisition (DAQ) board. There are two types of algorithm for reconstructing the photoacoustic signal. One is back-projection algorithm, the other is FFT algorithm. Especially, we used the non-uniform FFT algorithm. To evaluate the performance of our system and algorithms, we monitored two wires that stands at interval of 2.89 mm and 0.87 mm. Then, we compared the images reconstructed by algorithms. Finally, we monitored the two hairs crossed and compared between these algorithms.

***Keywords*—**Back-projection, image comparison, non-uniform FFT, photoacoustic tomography.

I. Introduction

PHOTOACOUSTIC tomography is based on the reconstruction of an internal PA source distribution from measurements acquired by scanning small-aperture ultrasound detectors over a surface that encloses the source under study [8]. Upon absorption of a short EM pulse, the spatial distribution of the acoustic transient pressure inside the tissue that acts as the initial source for the acoustic waves is simultaneously excited by thermal elastic expansion. The acoustic waves from the initial acoustic source reach the surface of the tissue with various time delays. Ultrasound receivers are placed around the tissues to measure these outgoing acoustic waves, which are further used to determine the initial acoustic source distribution that maps the EM energy deposition functions or absorption properties [3].

Photoacoustic imaging (PAI) is a novel promising tool for visualizing light absorbing structures in an optically scattering medium, which carry valuable information for medical diagnostics [1]. PA imaging can be considered either an ultrasound mediated EM imaging modality or an ultrasound imaging modality with EM-enhanced contrast [3]. Since ultrasound scattering is two to three orders of magnitude weaker than optical scattering in biological tissues, [4] ultrasound can provide a better resolution than optical imaging in depths greater than 1 mm. However, pure ultrasound imaging is based on the detection of the mechanical properties in biological tissues, so its weak contrasts are not capable of revealing early stage tumors. Moreover, ultrasound cannot image either oxygen saturation or the concentration of hemoglobin, to both of which optical absorption is very sensitive. These physiological parameters can provide functional imaging. Likewise, pure rf (radio frequency) imaging cannot provide good spatial resolution because of its long wavelength [5]. Utilizing operating frequencies in the range of 500–900 MHz, pure rf imaging can only provide a spatial resolution of 1 cm [6]. The significance of PA imaging is that it overcomes the above problems and yields images of high EM contrast at high ultrasonic resolution in relatively large volumes of biological tissues [7].

The purpose of this paper is to compare the reconstructed image between back-projection algorithm and non-uniform algorithm. Using the developed real-time PAT system, we conduct the experiment to detect the crossed hair image with PAT and ultrasound system using back-projection algorithm and non-uniform FFT algorithm, respectively.

II. Material and Methods

A. Back-Projection Algorithm

Universal back-projection algorithm is one of the reconstruction methods of photoacoustic image [8]. This method reconstructs the PAT image in time domain. It produces the exact inverse equations in three geometries. Equation (1) represents the universal back projection equation in fourier domain.

$$P_0 = \int_{\Omega_0} \frac{d\Omega_0}{\Omega_0}\left[2p(\vec{\boldsymbol{r}}_{\boldsymbol{0}}, \boldsymbol{v_s t}) - 2\boldsymbol{v_s t}\frac{\partial p(\vec{r}_0, v_s t)}{\partial v_s t}\right] \quad (1)$$

where $\vec{\boldsymbol{r}}_{\boldsymbol{0}}$is the measurement point, $\boldsymbol{v_s}$is the speed of sound in the medium. The parameter $\mathbf{t}$ is given by,

$$t = \left|\vec{\boldsymbol{r}} - \frac{\vec{\boldsymbol{r}}_{\boldsymbol{0}}}{\boldsymbol{v_s}}\right|$$

The initial distribution of photoacoustic pressure is given by $\boldsymbol{P_0}$ and the measured photoacoustic pressure is given by $\mathrm{P}(\vec{\boldsymbol{r}}_{\boldsymbol{0}}, \boldsymbol{v_s}\mathbf{t})$. when the sound of speed is constant, signals can be exactly reconstructed by back-projection algorithm. The critical point of inverse problem is that the initial distribution

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$\boldsymbol{P_0}$ should be calculated by the measured signal $P(\vec{\boldsymbol{r}}_0, \boldsymbol{v_s}\mathbf{t})$ at $\vec{\boldsymbol{r}}_0$. The only limit of this algorithm is when the signal is an acoustic inhomogeneity, it can result in the distortion.

B. Non-Uniform FFT Algorithm

The exact FFT reconstruction of PAT is given by, [2], [9].

$$\boldsymbol{F}f(K_x, K_y) = \frac{2K_x(\boldsymbol{FQ}f)\left(K_x, sign(K_y)\sqrt{|K_x|^2+K_y^2}\right)}{K_x, sign(K_y)\sqrt{|K_x|^2+K_y^2}} \quad (2)$$

where $\boldsymbol{F}$ is the fourier transform, $\boldsymbol{Q}f$ is the photoacoustic signal acquired by transducer. s*ign* is the signum function. The problem of exact FFT reconstruction is not uniform of K_y compared with K_x. The non-uniform FFT algorithm can resolve the frequency space mismatching of K_y.

The 2-D non-uniform FFT reconstruction of PAT is given by,

$$\hat{f}_{n,m} = \frac{1}{N^2}\sum_{k,l=-\frac{N}{2}}^{\frac{N}{2}-1} e^{\frac{i(km+ln)2\pi}{N}}\hat{f}_{k,l} \quad (3)$$

where $\hat{f}_{n,m}$ is the reconstruction data, (*k,l*) is the space of frequency domain, and $\hat{f}_{k,l} = \frac{2k\hat{g}_{k,l}}{w_{k,l}}$. $\hat{g}_{k,l}$ is the frequency data acquired by ultrasound transducer, $w_{k,l}$ is the signum function.

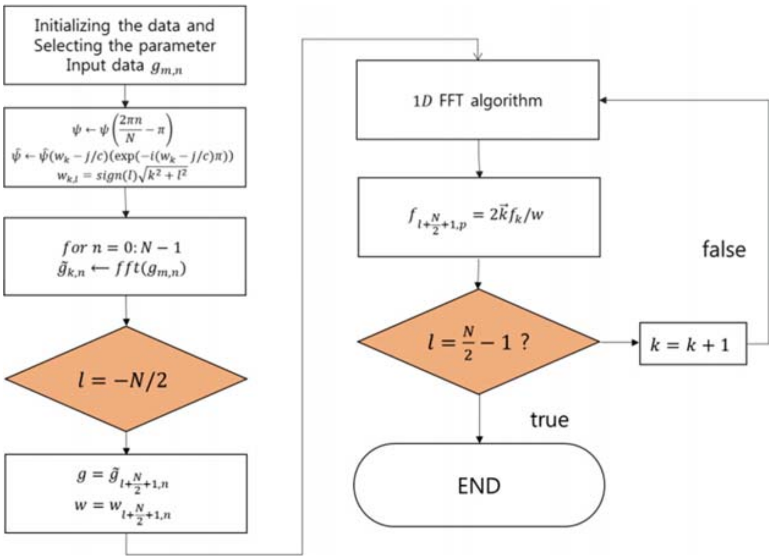


Fig. 1 Flow chart of 2D non-uniform FFT algorithm

Fig. 1 is how to reconstruct the data using input ultrasound signal $g_{m,n}$ where ψ, $\hat{\psi}$ are the time and frequency domagin window function, repectively. We choose this function with Kaiser-Bessel window function because of rejecting the signal like noise.

III. Experiment Setup

A. Hardware Setup

In order to make the real-time PAT system, it is required to make multi-channel, high speed sampling device. We choose FPGA (field-programmable gate array) PXI platform, providing the analog input multi-channel, 50MHz sampling rate and 12bits resolution power.

When the input signal is detected, FPGA program conduct the sampling with 50MHz and transmit the signals into PC (host program).

We use the linear array probe(L14-5/38) composed of 128 transducer with center frequency of 5MHz to detect the photoacoustic signal. And, we developed the pre-amplifier and filter with 40dB gain and 5MHz band-width because the received signal is very weak and adding the noise. It is placed in front of the DAQ board.

We use the Q switched Nd:YAG Laser. It provides 532nm wavelength and repetition of 1Hz. Also, the laser produces the trigger due to photo-diode. When the laser is irradiated, the photo-diode produces the signal, and signal is transmitted into the PXI platform.

Fig. 2 is the real-time PAT image system. When the laser is irradiated into sample, sample is exited and makes ultrasound. After detecting this signal to array transducer, it is transmitted into pre-amplifier and ultrasound device. Then, transmitted signal is amplified and filtered in the pre-amplifier, transmitted into PC.

A. Software Setup

Software is programmed by NI-labview 2012. In this experiment, there are two types of reconstruction algorithm, back projection and non-uniform FFT algorithm. The signal received by PXI platform is filtered one more by software filtering.

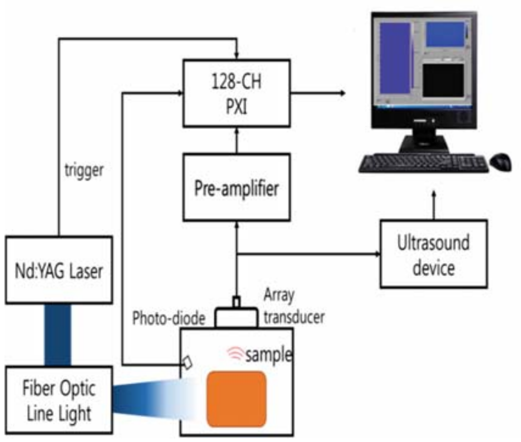


Fig. 2 Real-time photoacoustic system block diagram

IV. Experiment

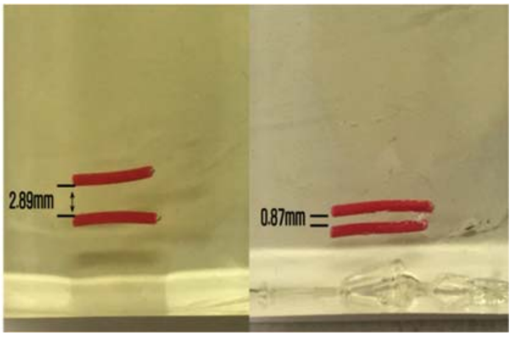
We conduct the two experiments, wire experiment and crossed hair experiment. The former is to evaluate the performance of two algorithms, the latter is to compare images of the algorithms. We make gelatin (protein: 84~90%, water: 8~10%) to mimic the tissue.

A. Wire Phantom Experiment

This experiment conducts using two wires. The wires are inserted into the gelatin, spaced between 2.98mm 0.87mm, respectively. Fig. 3 is the phantom of wires. The construction image is acquired in real-time system using Fig. 3 phantom.

Fig. 4 is the reconstruction image of Fig. 3 (a) using back projection, non-uniform FFT algorithm, respectively. Fig. 4 is the reconstructed image of the algorithms. The images are clearly reconstructed. Due to limited angle view, it has poor information of opposite angle. Then, the blurring is shown in the images.

Fig. 5 shows the reconstruction image using Fig. 3 (b). Fig. 5 has much blurring compared with Fig. 4 because distance between wires is so closed up to system's resolution. Comparing Fig. 5 (a) with 5 (b), back projection algorithm has much more noise than non-uniform FFT algorithm. Due to each wire's blurring and noise of the signal processing, the reconstructed target image of non-uniform FFT algorithm is hide.



(a) (b)

Fig. 3 The wire phantom spaced (a) 2.89mm (b)0.87mm

In this experiment, we can illustrate the back projection algorithm has much better signal to noise ratio than back projection algorithm.

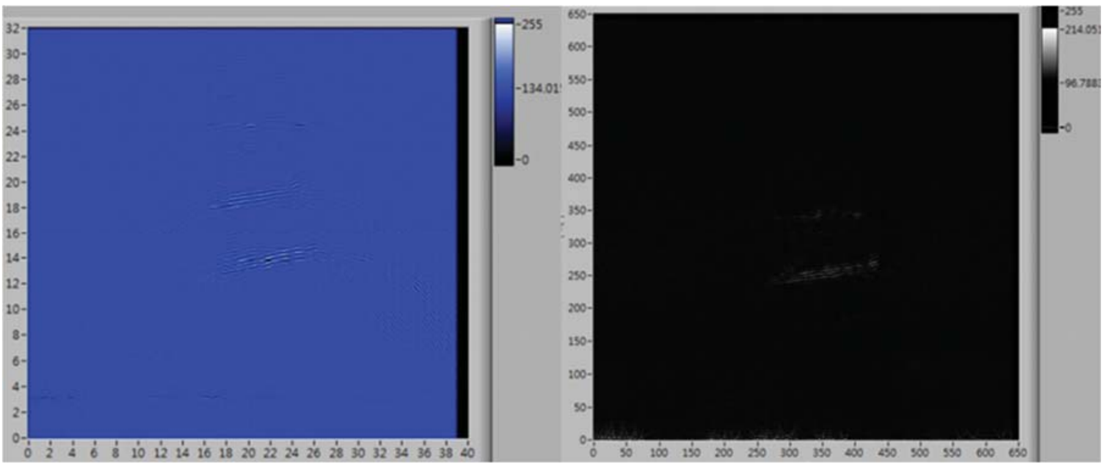
B. Crossed Hair Experiment

Two experiments we conduct is to evaluate the performance between back projection and non-uniform algorithm. We perform the experiment of the crossed hair. Hair's diameter is around 0.1mm, and crossed hair is placed into the gelatin.

Fig. 6 is the phantom of the crossed hair.

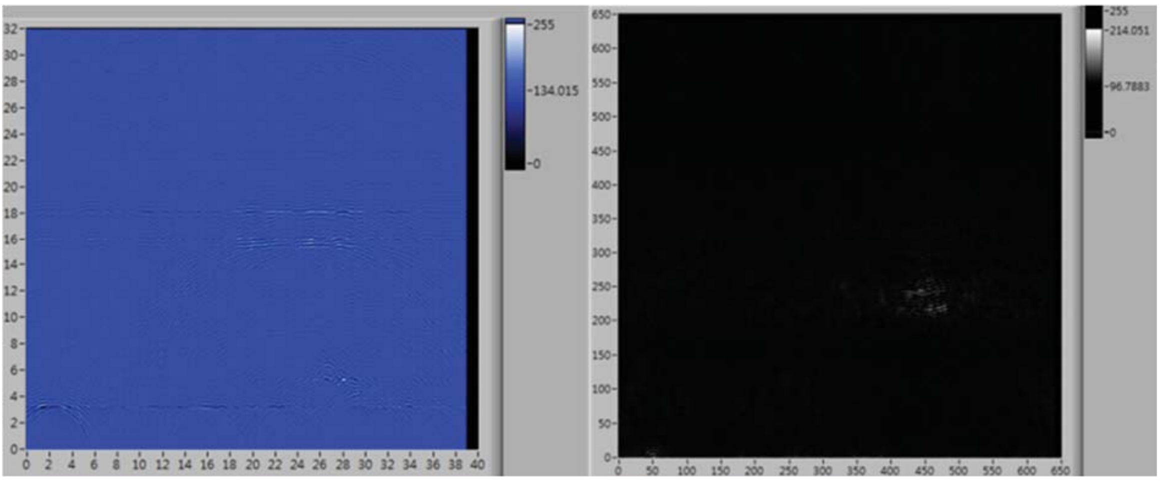
We conduct this experiment due to the blurring and compare the images between algorithms. The reconstruction image of Fig. 6 is shown in Fig. 7.

In Fig. 7, both algorithms can reconstruct the image clearly. But due to blurring, back projection algorithm has much more SNR than non-uniform algorithm



(a) (b)

Fig. 4 (a) Reconstruction image of back-projection (b) Reconstruction image of non-uniform FFT algorithm



(a) (b)

Fig. 5 (a) Reconstruction image of back-projection (b) Reconstruction image of non-uniform FFT algorithm

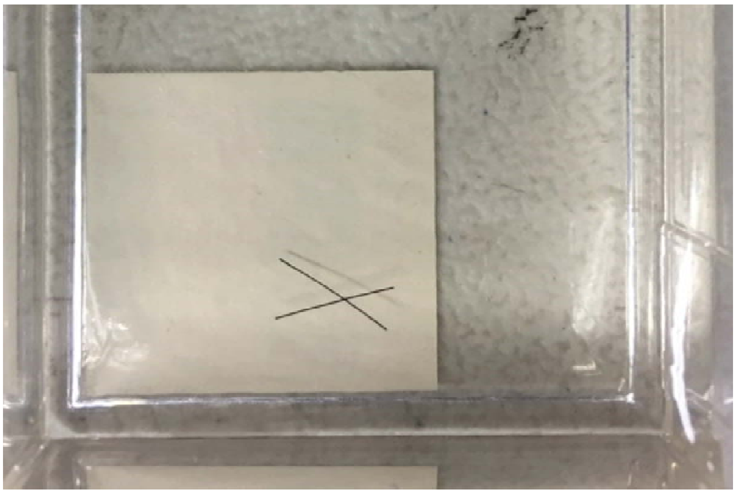
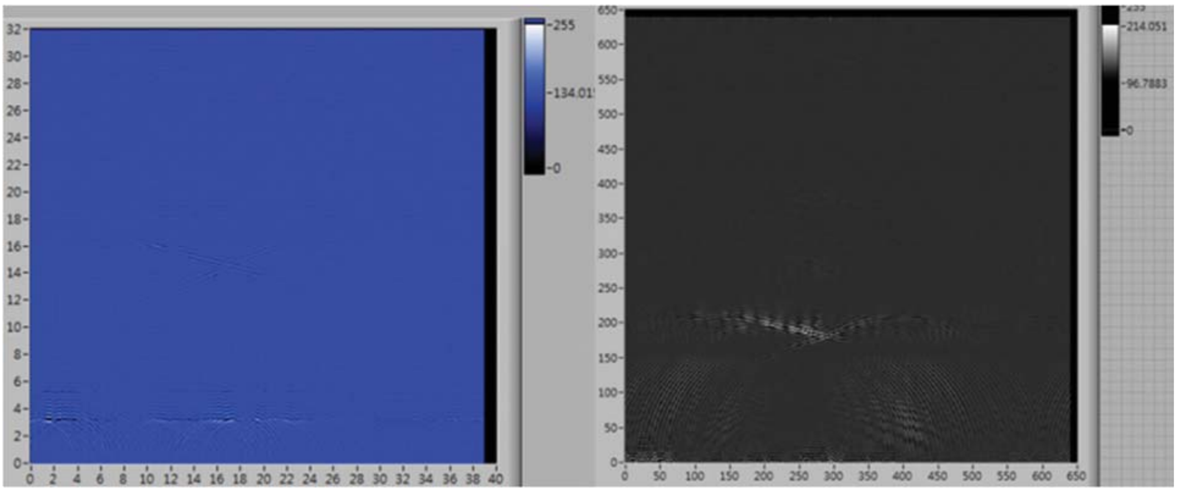


Fig. 6 The phantom of crossed hair



(a) (b)

Fig. 7 (a) Reconstruction image of back-projection of crossed hair (b) Reconstruction image of non-uniform FFT algorithm of crossed hair

V. Conclusion

In order to compare images between back projection and non-uniform FFT algorithm, we developed the PAT system using PXI platform and pre-amplifier. We used the wavelength of 532nm, repetition of 1Hz.

In the experiment of wire, we can illustrate that when the massive targets get closer, back projection algorithm is clearly visible. But in case of non-uniform FFT algorithm, blurring is occurred between targets.

In the experiment of crossed wire as shown in Figs. 4 and 5, the back projection algorithm detects the target clearly and noiseless. In case of non-uniform FFT algorithm, it can detect the targets with the blurring. As the result, back projection algorithm has much more SNR than non-uniform FFT. Currently, PAT combines the contrast agent like Indo-cyanine green in order to amplify the signal. As shown in Figs. 4 and 5, the intensity of the signal of non-uniform FFT algorithm is better than back-projection without the blurring. So It is required to demonstrate image quality between algorithm's using the contrast agent.

Acknowledgment

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) and by the Human Resources Development program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy.

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