Modeling Photoacoustic Tomography using k-Wave

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Abstract

Photoacoustic tomography (PAT) is a hybrid imaging technique that offers similar medical potential as ultrasound and optical imaging. Although efforts to innovate Photoacoustic scanners have been scarce, newer developments such as k-Wave will enable their optimal imaging capability. Despite k-Wave's ability to simulate PAT, few researchers utilize this technology. Thus, this project explored the effects of altering the properties of Photoacoustic scanners on the reconstruction through the use of k-Wave. With the capability to optimize photoacoustic sensors through simulations, PAT in general will become more effective.

Introduction

The photoacoustic effect, which is what photoacoustic tomography is based on, is the generation of acoustic waves from an object absorbing light. The effect was discovered by Alexander Graham Bell in 1880, but very little substantial progress has been made until recently. Photoacoustic tomography (PAT) is an up and coming imaging technology utilizing the photoacoustic effect. PAT has been used for more effectively administering medical treatments[2], visualizing signs of tumors in tissue[3], studying epilepsy's effects on the brain[4], and viewing the effects of heart attacks[5]. These various uses have increased PAT research in diverse science fields such as imaging, chemistry, physics, and biomedicine. For the past decade, researchers have been focusing on making PAT more optimal. For example, the process of Multispectral Optoacoustic Tomography (MSOT) has been used to tune PAT specifically for certain tissue by utilizing its absorption properties and exciting the tissue to give a more pronounced image[6]. Given that PAT research is relatively new, researchers continue to seek more and more improvements for PAT by finding more and more applications for it, and optimizing the process for certain cases. This study considers k-Wave because this MATLAB toolbox simulates reconstructions of photoacoustic wave fields. Although several researchers investigate the development of k-Wave, few studies utilize k-wave to optimize PAT.

Photoacoustic Theory

The initial step in photoacoustic tomography is the laser excitation. The laser frequency is related to the absorption/thermal expansion of the source as well. To generate high frequency (short wavelength) sound waves from the source, which will allow for higher resolutions, the laser pulse must be shorter than both the thermal relaxation time $\tau_{(th)}$ and the stress relaxation time $\tau_{(s)}$ respectively defined by the below equations[7]. (The speed of sound in tissue (vs) is typically about 1500m/s due to the density of the media in the body)[8].

$$\tau_{th} = \frac{d_c^2}{\alpha_{th}} \quad (1) \qquad \tau_s = \frac{d_c}{v_s} \quad (2)$$

In these equations d_c is the characteristic dimension of the source, α is the thermal diffusivity, and v_s is the speed of sound in the medium. Since blood is the major absorber in biological tissue (specifically the hemoglobin in the blood), the majority of signals occurs where there is a high concentration of blood[9].

With scattering being orders of magnitude smaller for sound waves as opposed to light propagating through the body, the major concern is with attenuation in certain media, which can modeled by this equation.

$$\alpha = af^b [dB/cm] \quad (3)$$

In equation (3), a is a constant dependent on the tissue, and b is generally assumed to be 1, which will typically work. This attenuation a is more present in higher frequencies f, thus resolution will be decreased. If the penetration depth (cm) is reduced, the resolution can be increased as there will be less attenuation present. This trade-off leads to multispectral systems, since low frequencies are better for depth and signal to noise ratio, and higher frequencies have better resolution.

k-Wave

k-Wave[10] is a toolbox that simulates acoustic wave propagation. Recently, work has been done to extend this use specifically for both ultrasound imaging and photoacoustic tomography. As indicated in the Approach to Improvement section, it utilizes specific parameters, such as the medium's sound speed, the source's properties, and many more, to propagate the waves. Time reversal and Fast Fourier Transforms (FFT) are the methods which enable k-Wave to calculate the partial differential equations related to the reconstruction. The most commonly used numerical methods for solving partial differential equations in acoustics are the finite-difference, finite-element, and boundary-element methods. Although appropriate for many applications, for time domain modeling of broadband or high-frequency waves, they can become cumbersome and slow. This is due to the requirements for many grid points per wavelength and small time-steps to minimize unwanted numerical dispersion. The finite difference scheme is used in k-Wave because it is the only scheme that can calculate rates of change in the time domain. Pseudo-spectral methods (an extension of finite difference methods) improve the efficiency, but lose the capability to calculate rates of change in the time domain. In a homogenous medium, the pseudo-spectral method can be effectively utilized without the loss of information.

Since a finite sized computational grid is being used for these wave fields, a special scheme will be needed for calculations near the boundaries. To account for that, a perfectly matched layer (PML) is implemented on the boundaries of the computational grid. The PML is an added area to the outer borders of the computational grid that absorbs remaining amplitudes as they propagate to the boundaries so unnecessary reflections do not occur. With the PML included, the first order acoustic equations become[11]:

$$\frac{\partial \mathbf{u}}{\partial t} = -\frac{1}{\rho_0} \nabla p - \boldsymbol{\alpha} \cdot \mathbf{u} \quad (4)$$

$$\frac{\partial \rho_x}{\partial t} = -\rho_0 \frac{\partial u_x}{\partial x} - \alpha_x \rho_x \quad (5)$$

$$p = c_0^2 \sum \rho_{x,y,z} \quad (6)$$

Equation (5) is used for directions [x, y, and z] as well (if 3 dimensional). [Alpha] is the anisotropic absorption in nepers/meter which is only nonzero in the PML. [p] is the acoustic density, [u] is the acoustic particle velocity, and [c] is the thermodynamic sound speed.

Two types of reconstruction are used in k-Wave, time reversal image reconstruction, and one-step reconstruction using Fast Fourier Transforms. In time reversal, the data recorded by the sensors is put in reverse order and distributed over a surface as similar to the conditions in which the data was captured, but in the reversal, the original source is removed leaving an empty grid. The reconstruction is stopped at a certain time at which point the original source should be recreated. Time reversal is derived for homogenous media, but with the application of Green's theorem it can be further applied to heterogeneous media[12].

Approach to Improvement

Instead of finding specific optimal conditions, trends of improvement will be observed. A reason for this is because every scenario in which PAT is used is different and will most likely have different optimal settings, but if trends of improvement through altering the parameters can be found, then these observations can be used across many applications. k-Wave allows for a very thorough customization of many of the system's parameters. Alterations to these parameters will be analyzed to obtain the most beneficial design for certain scenarios. Some parameters will be the number of sensors in the array, initial propagation magnitude, reconstruction algorithm, single emission vs pulse rates, and others as will be discussed in the conclusion. Due to the nature of this analysis, only graphical comparisons will be used. Since trends are what are being analyzed, graphical depictions should allow for more than enough detail.

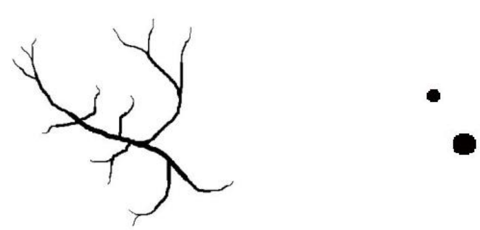

Figure 1, 2: The study will look at the effects of changing the parameters for two discs as well as a more complex shape as would be seen in the vascular system. Here are bitmap images of the sample sources used in the reconstructions.

Findings
This section will present the effects that changing each of the parameters had and briefly compare the parameters against each other.

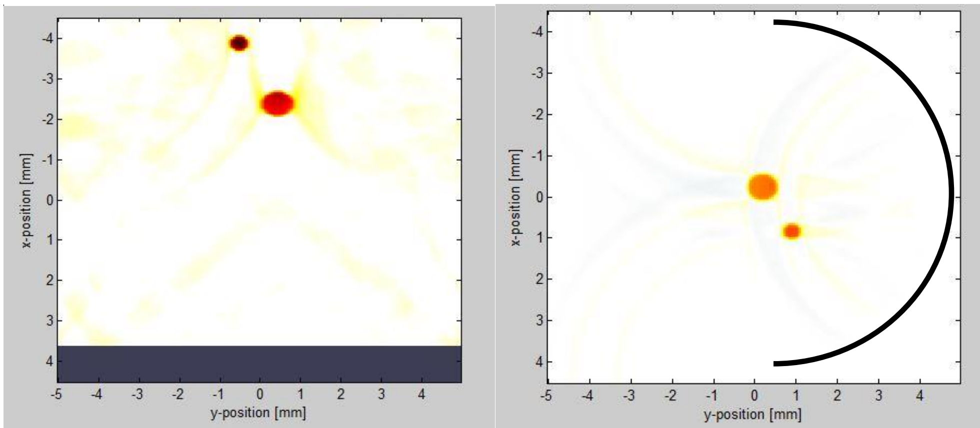

Figure 3, 4: (Left) FFT reconstruction of the disc image. The sensors are a linear array on the upper border of the graph. (Right) Reconstruction using time reversal with the same source, just positioned toward the focal point of the array. Both images use a magnitude of 1 pascal and 225 sensors.

As can be seen in figure 3 using the time reversal reconstruction algorithm, there are interference artifacts, but the overall image reconstruction is good. Also the disc nearer to the sensors has very solid edges; meanwhile the other disc’s edges lose some resolution and there are more artifacts in the immediate area. In figure 4, regardless of the disc being at the focal point, it retained good shape.

The time-reversal reconstruction method uses the length of the time array and reverses the temporal array to capture what the initial pressure source would look like. The information being sent out from each sensor collides with one, which explains the added artifacts, but produces a very accurate reconstruction.

As mentioned earlier, the variables to be tested are the number of sensors in the array, the number of pulses, the reconstruction algorithm, and how the source characteristics affect the reconstructed image.

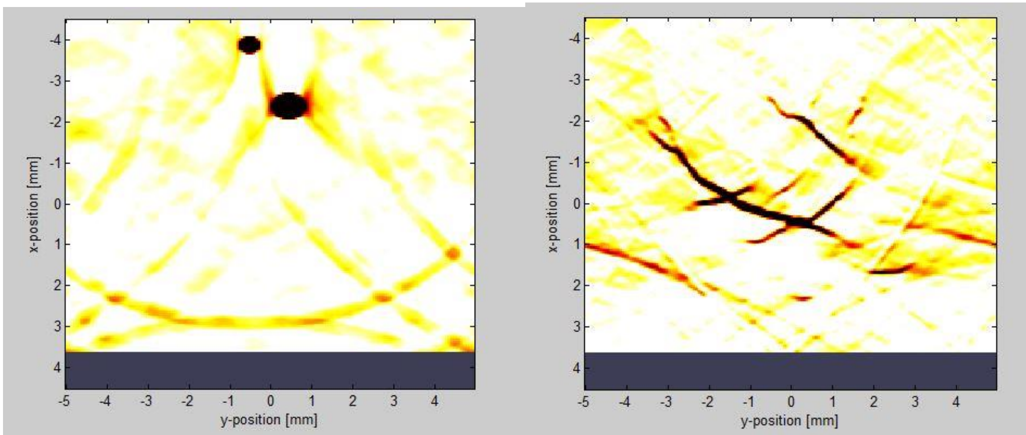

Figure 5, 6: Reconstruction using a magnitude of 3 pulses, 175 sensors, 8 pulses, and FFTs. As can be seen, the FFT reconstruction method could not image well with multiple pulses and could not image the vascular image at all due to its distance from the array.

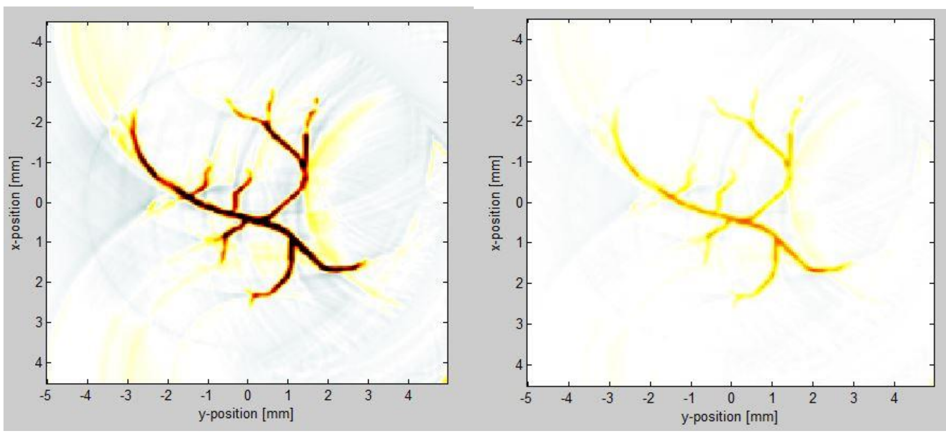

Figure 7, 8: Contrasting these two figures shows how the initial magnitude affects the reconstruction. On the left was a magnitude of 3 pascals, and it was only 1 pascal on the right, which was the only difference. While the edges were not as well defined, many of the artifacts were reduced, so pending on the application, a much lower initial magnitude may be desired.

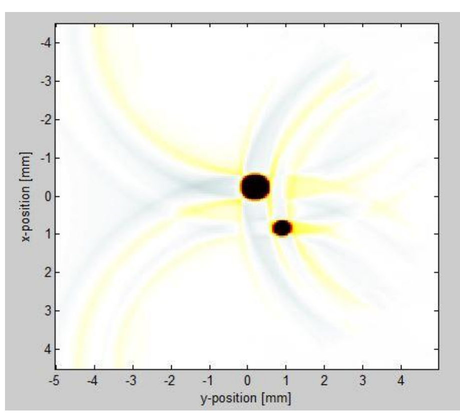

Figure 9: In comparison to figure 4, this figure has much more defined artifacts, where in figure 4 the disc was still well defined. If there is a simple image in the focal point (or near) of the array, then a lower initial magnitude will create a better image.

If the other variables are held constant, it can be observed that there is a point of diminishing returns in the number of sensors once 175 sensors are used for image reconstruction and 125 sensors for FFT reconstruction.

While it was shown that FFT reconstruction did not have many uses for the tested variables, it must be mentioned that it performs much quicker than time reversal. The near field image reconstruction is good enough that it has potential use as a real-time scanner for small depths.

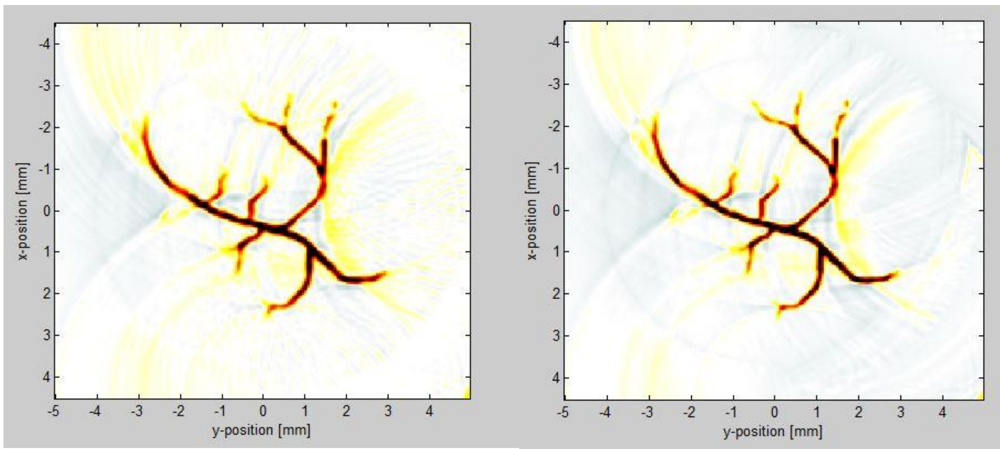

Figure 10, 11: The image on the left uses 8 pulses, while the image on the left uses only 1. It can be seen that adding the extra pulses did not necessarily affect the source, but it helped in reducing the artifacts around the source.

To determine the effectiveness of the pulses, each pulse was stored in the sensors, then the average of each pulse's reconstruction is taken to get a more consistent result. The effect of the pulses is minimal, but where it does improve the reconstruction is in the precise areas such as the vertices of the vascular image.

Discussion

This paper showcases the modeling properties of k-Wave for photoacoustic tomography. Using a standard design for a photoacoustic scanner, modifications were made to investigate any improvements that could be made. k-Wave showed good diversity in being able to accurately model current imaging capabilities and had enough diversity to add useful altercations. For more detailed images and for images at greater depth, the results show that the time-reversal image reconstruction method was superior. The only real benefits of FFT image reconstruction was the speed at which it could be done.

Due to time constraints, not all the capabilities of k-Wave were utilized. Future work could introduce using transducers as sensors as opposed to infinitely small points. This would add an entire dimension of designing the transducer properties and how the reconstruction would be affected. Image reconstruction in three dimensions also needs to be explored and is well within the capabilities of k-Wave. k-Wave has shown promising features to help the thriving development of Photoacoustic Tomography.

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