Freehand Spatial-Angular Compounding of Photoacoustic Images

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ABSTRACT

Photoacoustic (PA) imaging is an emerging medical imaging modality that relies on the absorption of optical energy and the subsequent emission of acoustic waves that are detected with a conventional ultrasound probe. PA images are susceptible to background noise artifacts that reduce the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). We investigated spatial-angular compounding of PA images to enhance these image qualities. Spatial-angular compounding was implemented by averaging multiple PA images acquired as an ultrasound probe was rotated about the elevational axis with the laser beam and PA target fixed in the same location. An external tracking system was used to provide the position and orientation (i.e. pose) information of each PA image. Based on this pose information, frames in similar elevational planes were filtered from the acquired image data and compounded using one of two methods. One method registered overlapping signals between frames prior to compounding (using the pose information), while the second method omitted this spatial registration step. These two methods were applied to pre-beamformed RF, beamformed RF, and envelope-detected data, resulting in six different compounding pipelines. Compounded PA images with similar lateral resolution to a single reference image had factors of 1.1 - 1.6, 2.0 - 11.1, and 2.0 - 11.1 improvements in contrast, CNR, and SNR, respectively, when compared to the reference image. These improvements depended on the amount of relative motion between the reference image and the images that were compounded. The inclusion of spatial registration prior to compounding preserved lateral resolution and signal location when the relative rotations about the elevation axis were 3.5\(^\circ\) or less for images that were within an elevational distance of 2.5 mm from the reference image, particularly when the method was applied to the enveloped-detected data. Results indicate that spatial-angular compounding has the potential to improve image quality for a variety of photoacoustic imaging applications.

Keywords: spatial compounding, photoacoustic image, electromagnetic tracking, ultrasound imaging

1. INTRODUCTION

Photoacoustic (PA) imaging is a real-time medical imaging modality based on the conversion of light waves to acoustic waves through optical absorption, localized thermal expansion, and a resulting pressure transient [1, 2]. Thus, PA images are intimately linked to the optical and acoustic properties of a target, such as soft tissue or blood vessels. Potential applications of PA imaging include detection of breast cancer, identification of atherosclerotic plaques, and monitoring of thermal therapy [3, 4]. PA imaging is useful in these applications to visualize internal structure and function, owing to merits such as high contrast, sufficient spatial and temporal resolution, and non-invasive and non-ionizing properties.

PA images are known to suffer from noise artifacts such as acoustic clutter [5, 6]. These noise artifacts reduce the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) of images. In addition, PA images have poor SNR and CNR when low-power lasers are used or when there is inherent misalignment between the light source and target. To enhance the quality of PA images, several methods have been researched, such as short-lag spatial coherence beamformers [5, 6], minimum variance beamformers [7], and alteration of implanted targets to increase optical absorption [8, 9].

As an alternative, PA images acquired with the ultrasound probe, laser, and target fixed in the same position may be
averaged to improve image quality [5, 10]. However, this type of frame averaging has limited ability to reduce statistically dependent background noise (e.g. when acquired images have the same noise pattern) [11, 12]. In addition, this approach may not be suitable for maintaining spatial resolution with hand-held probes due to subtle operator-dependent hand motions that are difficult to avoid.

To overcome the limitations of frame averaging and improve image SNR and CNR, we introduce spatial-angular compounding of PA images, which relies on spatial registration of images acquired with freehand motion. The proposed method is similar to the spatial compounding methods used to improve the quality of ultrasound B-mode [13-16] and strain images [17-19]. An electromagnetic sensor may be attached to the handheld ultrasound probe to track the spatial position and orientation (i.e. pose) information of acquired PA images. PA images are either selected or rejected based on their pose, and the selected images are combined to form a single compounded PA image.

2. MATERIALS AND METHODS

2.1 Frame Selection

To select appropriate images for spatial-angular compounding, an external tracking system recorded the pose of the ultrasound probe with each image acquisition. This pose was converted to the PA image pose through a calibration transformation [20], as illustrated in Figure 1 (a). The pose information of each PA image was expressed relative to the first frame in an acquired image sequence (i.e. the reference frame).

In-plane images were filtered using the relative pose information of each PA image, while out-of-plane images were rejected. Figure 1 (b) illustrates how an in-plane or out-of-plane image was defined using the relative elevational distance threshold. If the maximum elevational distance between an image being considered and the reference image was smaller than this threshold, then the image was sorted as being in-plane, and it was used for the compounding operation. The second threshold value was the relative elevational rotation angle, as the recorded PA signal and noise regions are dependent on both translations and rotations of the ultrasound transducer. Images outside of these two threshold values were considered as out-of-plane images and rejected from the compounding operation.

Figure 1. (a) Coordinate system of spatially tracked PA images and (b) definitions of in-plane and out-of-plane images according to the user-defined elevational distance thresholds.


2.2 Compounding PA images

The compounding operator was applied with and without spatial registration of images to be compounded, as described by the following equation:

\[
I_{m_g \text{compounded}}(i_c, j_c) = \frac{1}{N} I_{m_g \text{reference}}(i_c, j_c) + \frac{1}{N} \sum_{n=2}^{N} I_{m_g \text{selected}}(i_s(n), j_s(n))
\]  

(1)

where \(I_{m_g \text{compounded}}\), \(I_{m_g \text{reference}}\) and \(I_{m_g \text{selected}}\) are the signal intensities of the compounded image, reference image, and the images to be compounded (i.e. selected in-plane image), respectively. The indices \(i_s(n)\) and \(j_s(n)\) represent the lateral and axial pixel locations, respectively, in one of the selected in-plane images. The indices \(i_c\) and \(j_c\) represent the lateral and axial pixel locations, respectively, in the final compounded image. \(N\) is the total number of compounded images.

When no spatial registration was applied to compounded images, \(i_s(n)\) and \(j_s(n)\) were the same as \(i_c\) and \(j_c\) in equation (1), as described by the following equation:

\[
\begin{bmatrix}
i_s(n) \\
j_s(n)
\end{bmatrix} = \begin{bmatrix}
i_c \\
j_c
\end{bmatrix}
\]

(2)

Compounding with spatial registration was applied by considering the relative pose information of each image to calculate \(i_s(n)\) and \(j_s(n)\) in equation (1) as follows:

\[
\begin{bmatrix}
i_s(n) \\
j_s(n)
\end{bmatrix} = \begin{bmatrix}
1/si_c(n) & 0 \\
0 & 1/sj_c(n)
\end{bmatrix} \cdot \begin{bmatrix}
i_c \\
j_c
\end{bmatrix} = \begin{bmatrix}
i_c \\
j_c
\end{bmatrix} \cdot \begin{bmatrix}
si_c & 0 \\
0 & sj_c
\end{bmatrix} \cdot \begin{bmatrix}
R_{sc}(n) & \vec{p}_{sc}(n)
\end{bmatrix}
\]

(3)

where \(R_{sc}(n)\) and \(\vec{p}_{sc}(n)\) represent the relative rotations and translations, respectively, between the reference image and selected in-plane image, \(si_c\) and \(sj_c\) represent the lateral and axial pixel spacings of the compounded image, respectively, in units of mm/pixel, and \(si_c(n)\) and \(sj_c(n)\) represent the lateral and axial pixel spacings (mm/pixel) of the selected in-plane image. These two compounding methods are illustrated schematically in Figure 2.

The two compounding operators were applied to pre-beamformed RF, beamformed RF and enveloped-detected data, resulting in six different compounded image combinations (i.e. pipelines). A flowchart describing the six different pipelines is shown in Fig. 3. A delay-and-sum beamforming algorithm was implemented with a 33-element aperture size for beamforming channel data. A Hilbert transformation was implemented to demodulate the beamformed RF data and create envelope-detected data.
2.3 Experimental Test

Figure 4 represents the system components and work flow required for free-hand spatially-tracked photoacoustic images. A stationary plastic phantom embedded with a black rectangle was irradiated with a Q-switched Nd:YAG laser (QUANTEL, Les Ulis, France) operated at a wavelength of 1064 nm. The laser beam was fixed relative to the phantom. A SONIX-DAQ (Ultrasoundix Co., Vancouver, Canada) device connected to a Sonix-CEP ultrasound system and a hand-held L14-5W/38 ultrasound probe was used to acquire the resulting radio frequency PA data. Pose information of the ultrasound transducer was recorded with a medSAFE (Ascension Technology Co., Milton, USA) electromagnetic tracker. The hand-held ultrasound probe was rotated about the elevational axis during image acquisitions. Rotations about the axial and lateral axes were minimal. A custom-built controller board was used to synchronize the acquisitions of PA data and ultrasound probe pose information with the transistor-transistor logic (TTL) trigger signal from laser system.

To determine optimal threshold values for the frame selection process, the relative elevational distance threshold was varied from 0.5 mm to 2.5 mm in 0.5 mm increments with the relative elevational rotation threshold fixed at values ranging from 0.25° to 7° with 0.25° increments.
To evaluate the quality of compounded PA images, lateral resolution, contrast, CNR and SNR were considered. The lateral resolution of the reference image and each compounded PA image was estimated by measuring the full width at half maximum (FWHM) of the PA signal. Regions of interest (ROIs) surrounding the maximum signal intensity and the background noise in each image were selected to compute contrast, CNR and SNR according to the following equations:

\[
\text{Contrast} = \frac{\text{Signal}_{avg} - \text{BNoise}_{avg}}{\text{BNoise}_{avg}} \\
\text{CNR} = \frac{\text{abs}(\text{Signal}_{avg} - \text{BNoise}_{avg})}{\text{BNoise}_{std}} \\
\text{SNR} = \frac{\text{Signal}_{avg}}{\text{BNoise}_{std}}
\]

where \(\text{Signal}_{avg}\) represents the average value of the image intensities in the selected signal ROI. \(\text{BNoise}_{avg}\) and \(\text{BNoise}_{std}\) represent the average and standard deviation, respectively, of image intensities in the background noise ROI. The size of the ROIs were fixed to 2.7 mm in the axial dimension and 0.58 mm in the lateral dimension. The noise ROI was located proximal to the signal ROI, and the distance between the two ROIs was fixed to 0 mm in the lateral dimension and 1.6 mm in the axial dimension.

3. RESULTS

Figure 5. Relative elevation poses of tracked PA images. The red dots indicate selected frames given the following threshold values: (a) 1.75° relative elevational rotation and 0.5 mm relative elevational position; (b) 7.0° relative elevational rotation and 2.5 mm relative elevational position

Figure 5 shows the relative elevational pose of the tracked PA images. Each point represents one relative elevational pose and the connector lines show the time history from the reference frame. The red points indicate images that were selected based on the user-defined thresholds. In Figure 5(a), the relative elevational rotation and position thresholds were 1.75 ° and 0.5 mm, respectively. This represents very small deviations about the reference image. Larger deviations were allowed by the frame selection parameters displayed in Figure 5(b), where the relative elevational rotation and position thresholds were 7.0 ° and 2.5 mm, respectively. Note that increasing the threshold values increases the number of images that are compounded.

Figure 6 displays reference and compounded PA images based on the selected frames shown in Figure 5. The maximum signal intensity shift between the reference and compounded images are reported below each image as dx and dy. Positive and negative values of dx represent lateral signal shifts to the right and left, respectively, while positive and negative values of dy represent axial signal shifts up and down, respectively. For pre- or post-beamformed RF data, the absolute values of the measured shifts were 0.15-1.8 mm for the larger elevational pose thresholds, compared to 0.0-0.3 mm for the smaller elevational pose thresholds. In addition to these signal shifts, the shape and distribution of the PA signal were distorted in images compounded with pre- and post-beamformed RF data, when compared to the reference image, particularly for large relative elevational motion. These artifacts were minimal when spatial registration was applied to envelope-detected data.
Lateral FWHM, contrast, SNR, and CNR were evaluated for the two compounding methods applied to envelope-detected data. The image quality metrics were varied as a function of threshold values, as shown in Figure 7. The lateral FWHM of the single reference image was 3.9 mm. The exclusion of spatial pose information resulted in compounded images with similar or better lateral resolution when the relative elevational rotation was 0.75° or less. For this range of elevational rotations, the contrast, SNR, and CNR were respectively 1.2-1.5, 2.3-5.6, and 2.3-5.6 times better than the corresponding metrics in the reference image. For relative elevational rotations larger than 0.75°, the SNR and CNR were better than the reference image, but the lateral FWHM was larger, as shown in the Figure 7 (top row).

The inclusion of spatial registration generated compounded PA images with a similar lateral FWHM to the reference image (3.9 mm) for elevational rotations up to 3.5°. For this range of elevational rotations, the contrast was 1.2-1.6 times better than that of the reference image. In addition, the SNR and CNR were at most 11.1 times greater than the reference for this range of threshold values. Thus, similar lateral resolution and contrast, with larger SNR and CNR, were achieved over a wider range of relative elevational rotations when the images were spatially registered prior to compounding, when compared to corresponding metrics achieved with the omission of this spatial registration step.
Figure 7. (a) Lateral resolution, (b) contrast, (c) SNR, and (d) CNR of compounded PA images after envelope detection, as the user defined thresholds for elevational rotations and translations, relative to the reference image were varied. The upper limit of elevational rotations denotes the maximum values for preservation of lateral resolution in each compounding method.

4. DISCUSSION

For the first time, we demonstrate that spatial-angular compounding is a useful technique to improve the quality of PA images acquired with a handheld probe. Tracking the pose of images acquired with free-hand motion enables preferential selection of images to be compounded. This feature was used to generate compounded PA images with greater contrast, SNR, and CNR and similar lateral resolution, compared to a single image. The image quality metrics were improved for 0-3.5° relative elevational rotations and 0-2.5 mm relative elevational translations when images were spatially registered prior to compounding. If lateral resolutions within 1 mm of the reference image are acceptable, elevational rotations could be as large as 7.0° with marginal additional improvements in CNR and SNR.

The absence of spatial registration prior to compounding is comparable to averaging PA images acquired with free-hand motion. Good image quality was achieved with minimal pose deviations from the reference frame (e.g. less than 1° of relative elevational rotations), while the lateral resolution of PA signals were degraded with larger deviations. These results highlight the importance of using spatial tracking information when it is not possible to constrain probe rotations and translations. This tracking information may be used to either filter unwanted motion prior to averaging or register filtered frames prior to compounding.

With spatial registration using pose information, the PA signals in the reference and compounded images were most similar in size, shape, and location when compounding was applied to enveloped-detected data, compared to the signals in images compounded using pre- or post-beamformed RF data. These characteristics likely occur because envelope-detected data has positive signal values, whereas pre- or post-beamformed RF data contains positive and negative values (i.e. phase information) that constructively and destructively interfere after compounding. Thus, the utilization of RF data requires high tracking accuracy to minimize the constructive and destructive interference caused by phase differences. In the future,
we can potentially minimize this interference by considering the accuracy of the tracking system when selecting in-plane images to be compounded.

Clinically, spatial-angular compounding could be implemented by preferentially selecting frames to acquire based on the operator’s hand motion. In this approach, the laser and ultrasound scanner would be synchronized to transmit light and acquire images only when the pose of the ultrasound transducer is within pre-determined, user-defined threshold values.

5. CONCLUSIONS

To the authors’ knowledge, this work is the first to demonstrate that spatial-angular compounding enhances the quality of PA images. The compounding method was tested with a phantom experiment. Various combinations of elevational distance and rotation threshold values were applied to determine suitable images for inclusion in the compounding operation. Spatially registering the tracked images allowed more images to be compounded with similar signal shape, size, and location, compared to a single reference frame, particularly when images were compounded after envelope-detection of the PA data. This method has promise to increase contrast, SNR, and CNR in a multitude of photoacoustic imaging applications.

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REFERENCE


