Artifacts in photoacoustic imaging

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ABSTRACT

Photoacoustic imaging (PAI) is rapidly moving from the laboratory to the clinic, increasing the pressure to understand factors that confound image interpretation, such as noise and image artifacts, which might adversely affect patient care. Over the past five years, landmark studies have shown the potential clinical utility of PAI, from breast cancer to Crohn's disease and neuromuscular dystrophies, leading to recent FDA approval and CE marking of PAI devices. Here, with a view to better presenting and understanding confounding factors in PAI that could influence image interpretation, we will describe the cause and effects of several artifacts present in PA systems, and giving schematic overviews of their appearance to ease identification.

Keywords: artifacts, photoacoustic, optoacoustic, confounders, image quality, heterogeneity, limited view

1. INTRODUCTION

Photoacoustic (PA) imaging (PAI) is a novel modality that uses the acoustic emissions from absorbed optical energy to image tissue. In principle, PAI allows us to measure various biological features from tissue, such as (1) vascular architecture,[1–3] (2) signal intensity at a target wavelength,[4] (3) blood oxygen saturation,[5–7] (4) general molecular concentration information of, e.g., fatty tissue, glandular tissue, water, collagen,[8,9] and (5) contrast agent distribution.[10,11] In practice, however, there are several steps in this imaging pathway that impact our ability to quantify these parameters: emission and propagation of photons, absorption of photon energy, and transformation of their energy into an acoustic pressure, and finally the propagation and detection of acoustic pressure waves. Each of these steps affects the measurements and resultant image reconstruction. However, the combination of inaccurate modeling approximations of the physical processes and distortions introduced by the data collection processes can result in deviations called artifacts,[12,13] which can confound clinical interpretation. Understanding these artifacts in PAI is essential given the demand for reliable and accurate use in medical contexts.

Awareness about artifacts must be created, especially among the growing number of clinical photoacoustic imaging users,[14] so they can identify, understand, and improve their interpretation of *in vivo* photoacoustic images. We could potentially even take advantage of systematic artifacts, as they might carry diagnostic information if handled appropriately. Furthermore, developers of the technology should be able to recognize artifacts and understand their sources, so they can guide developments towards mitigation and hasten the progress towards clinical translation of PAI.

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Photons Plus Ultrasound: Imaging and Sensing 2025, edited by Alexander A. Oraevsky, Lihong V. Wang, Proc. of SPIE Vol. 13319, 1331912 · © 2025 SPIE
1605-7422 · doi: 10.1117/12.3043855

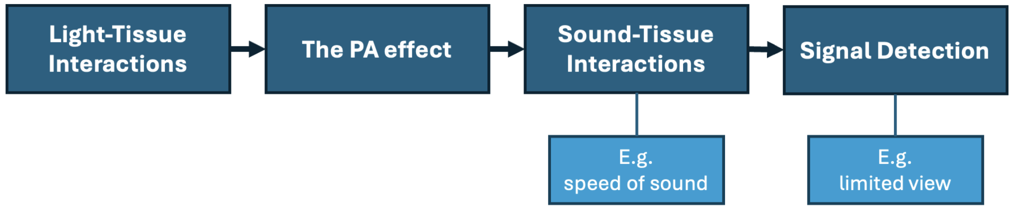

Figure 1. A high-level overview of artifacts sources (dark blue boxes), with the only two examples of artifacts (light blue boxes) treated in this proceeding.

We are investigating artifacts that can be encountered in PAI, by their *origin* and *source*. In this paper, we present two artifacts, discuss their underlying physical principles, and demonstrate them using with simulated images. The simulations are performed on simplified digital phantoms.

2. ARTIFACT CLASSIFICATION

While the physical principles of PAI are well understood, most PA images contain artifacts. The lack of artifact-free images can be explained by looking at the two parts of any PAI system: the data-acquisition hardware and the reconstruction method. These two parts result in two corresponding types of artifacts: (1) those resulting from incomplete measured data, e.g. limited array size or limited bandwidth, and (2) those resulting from incorrect assumptions in the image reconstruction algorithm, e.g. inaccurate approximations to the physical model or an overly-simple model of the detector response. Artifacts in PAI can also be classified based on the *source* of the artifact, by which we mean:

1. Light-Matter Interactions: arising from invalid assumptions about fundamental physical interactions between light and tissue.
2. The PA Effect: arising from unexpected deviations in photoacoustic efficiency.
3. Sound-Matter Interactions: arising from invalid assumptions about fundamental physical interactions between sound and tissue.
4. Signal Detection: arising from shortcomings during data acquisition leading to missing data.

Artifact *sources* can be thought of as the step in the imaging pathway they originate from. These artifact *sources* can be subdivided into artifact *causes*. An overview highlighting the artifacts considered in this proceedings article can be seen in Figure 1.

3. ARTIFACT EXAMPLES

The following sections will highlight two artifact causes encountered in PAI. Each artifact will be explained in text, and will be supported by a figure that demonstrates its origin through *in silico* simulations. The simulations are performed using SIMPA,[15] and are (unless otherwise noted) performed in ideal settings, such that a singular artifact can easily be seen and is not obscured by other artifacts. The exception is the fluence decay artifact, as this artifact is present in all *in vivo* PA images and lies at the core of PAI and is therefore also present in all our simulations.

3.1 Speed of sound

Accurate photoacoustic image reconstruction relies on being able to map measured time series back into the spatial domain through knowledge of the speed of sound. One can assume a speed of sound that is constant throughout tissue, or something more complex, but incorrect assumptions on the speed of sound map will result in a distorted reconstructed image. This is demonstrated in Figure 2, where we see three circles being imaged with PAI. In Figure 2 A-C, there is a circle with a higher speed of sound, in Figure 2 A-C there is an entire layer with a higher speed of sound. In both cases there is an (incorrect) assumption of a spatially homogenous speed of sound during the reconstruction. Both aberrations cause distinct distortions in the reconstruction, which leads to the speed of sound heterogeneity artifact.

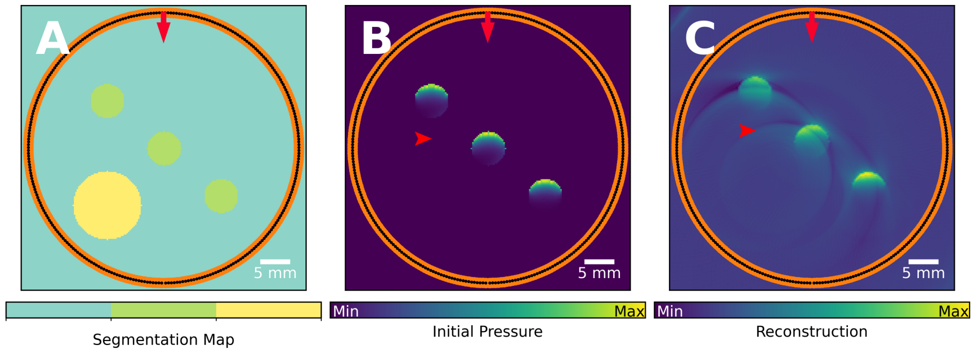

Figure 2. Acoustic heterogeneity artifact. Three circles are imaged in identical settings, except the speed of sound differs spatially. During the reconstruction, the speed of sound is assumed to be 1540 m/s everywhere, which is only valid for the background and circles, not for the aberrations (as shown in yellow in A). The aberration has a higher speed of sound (1800 m/s), while the assumption is still that of homogeneous 1540 m/s. This violation causes distortions in the reconstruction, as e.g. indicated by the red arrowhead.

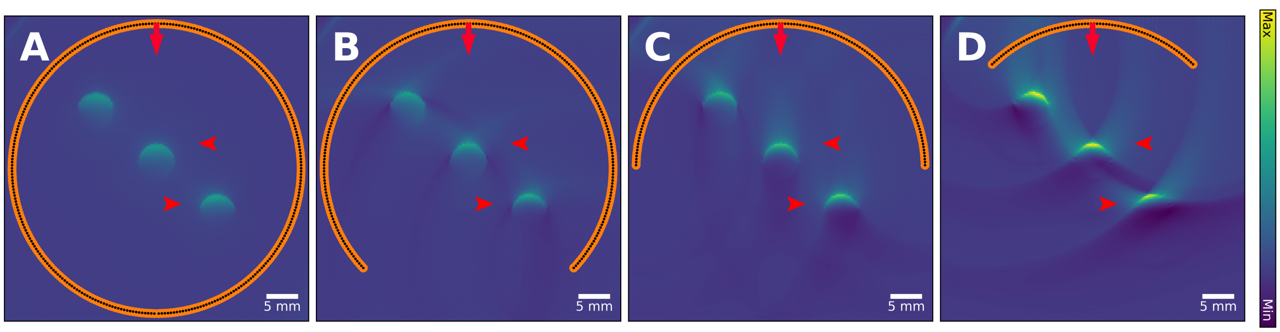

Figure 3. Limited view artifact. Three circles are imaged under identical settings, except the detector opening angle changes. As the opening angle becomes smaller (A: 360°, B: 270°, C: 180°, D: 90°) the image quality increasingly decreases, as e.g. indicated by the red arrowheads.

3.2 Limited View

For non-linear detectors, one can define a detection region, the envelope of the detection curve (2D) or area (3D), where an object can in theory be reconstructed accurately.[16] However, the same cannot be said for objects that are outside of this detection region, or in the case of a linear detector, lines that lie perpendicular to the detection plane. As this information is not recorded, the reconstructed image will be degraded, which can be seen in Figure 3 and is referred to as the limited view artifact.

4. CONCLUSION

Artifacts in PAI occur frequently and can hamper quantitative and qualitative interpretation, therefore limiting the clinical adoption. To improve interpretation, but also guide developments in artifact mitigation, awareness and understanding of PA artifacts is key. We have taken the first steps by providing an overview of the sources of artifacts and discussing two example artifacts. This forms the basis for ongoing work to comprehensively understand and illustrate the wide variety of artifact sources and artifacts encountered in our field. In future work, we will also investigate ways by which these artifacts can be (partly) mitigated, using e.g. improved hardware or deep learning techniques. However, currently clinical requirements, physics constraints and/or practical limitations often prevent this, so artifact-free PAI remains elusive.

ACKNOWLEDGMENTS

MR and SM for funding from KWF, TKI-Life Sciences and Health and Seno Medical Instruments in project THYNAS+. SM for funding from EFRO-Oost project 00103 Elastografie voor snellere herkenning van borstkanker in 3D fotoakoestieche mammografie. The work of JG was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under projects GR 5824/1 and GR 5824/2. TRE and SEB acknowledge funding support from CRUK (C9545/A29580) and EPSRC (EP/R003599/1, EP/V027069/1 and EP/X037770/1). BTC acknowledges support from the Engineering and Physical Sciences Research Council, UK (EPSRC), grants EP/W029324/1, EP/T014369/1.

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