Orthogonal Fabry-Pérot sensor array system for minimal-artifact 3D photoacoustic tomography

Robert Ellwood, Edward Zhang, Paul Beard and Ben Cox

Department of Medical Physics and Biomedical Engineering,
University College London, WC1E 6BT. UK

ABSTRACT

Photoacoustic images of exquisite quality have previously been obtained using planar Fabry-Pérot ultrasound sensors, as they can synthesize detection arrays with small, highly sensitive, elements. However, their planarity prevents reconstruction of structures perpendicular to the sensor plane, which gives rise to limited-view artifacts. Here, a novel FP sensor array configuration is described that incorporates two orthogonal planar arrays in order to overcome this limitation. Three dimensional photoacoustic images of suitably structured phantoms, obtained using a time reversal reconstruction algorithm, are used to demonstrate the significant improvement in the reconstructed images.

Keywords: photoacoustic imaging, planar Fabry-Pérot polymer film ultrasound sensor, orthogonal arrays, limited view

1. INTRODUCTION

Several different sensor array geometries have been used to detect the broadband ultrasonic fields produced from photoacoustic sources, including 2D planar[1][2], hemi-spherical, and spherical arrays[3][4][5]. While hemi-spherical and spherical arrays have the advantage that they offer a full view of the acoustic field inside them, the fabrication of such arrays with suitably small detection elements and sufficient sensitivity and bandwidth can be challenging. Optically addressed Fabry-Pérot (FP) interferometric sensor arrays[1], on the other hand, retain their sensitivity as the element size - the optically interrogated region - is reduced. However, for simplicity of production and interrogation FP sensors are usually planar. Planar sensors, in general, suffer from an incomplete view of the acoustic field, known as the limited aperture or limited view problem[6] (Figure 1(a)) which results in artifacts in the reconstructed photoacoustic images. This paper investigates the use of two planar arrays, mounted orthogonally, to overcome the limited view problem. By using a second 2D array orthogonal to the first, those wavefronts that would have otherwise not been detected by a single array can be detected. It has previously been shown that a similar approach using 1D linear arrays can result in improved images[7] , but linear arrays can only give 2D photoacoustic images. Here, 3D images have been obtained.

2. EXPERIMENTAL METHOD

2.1 Equipment configuration

In a previously designed system used to interrogate a single 2D FP sensor [1], the alignment of the interrogation beam with the sensor was achieved by adjusting the position of the sensor. With two planar sensors rigidly mounted perpendicularly, it is not possible to use this approach to align each sensor with its respective interrogation beam, so a new system, with custom mechanical armatures, was designed to allow precise alignment by moving the interrogation systems. The FP sensors consisted of two dielectric mirrors separated by a 20µm thick parylene C spacer layer deposited on a PMMA backing. These sensors have a bandwidth of 40MHz[1]. The arrays were mounted in a custom watertight mount. A 1064nm, 45mJ, Nd-YAG (Big Sky Ultra) laser was used, in forward mode, to generate photoacoustic signals in optically absorbing phantoms.

Photons Plus Ultrasound: Imaging and Sensing 2015, edited by Alexander A. Oraevsky, Lihong V. Wang
Proc. of SPIE Vol. 9323, 932312 · © 2015 SPIE · CCC code: 1605-7422/15/$18
doi: 10.1117/12.2081934

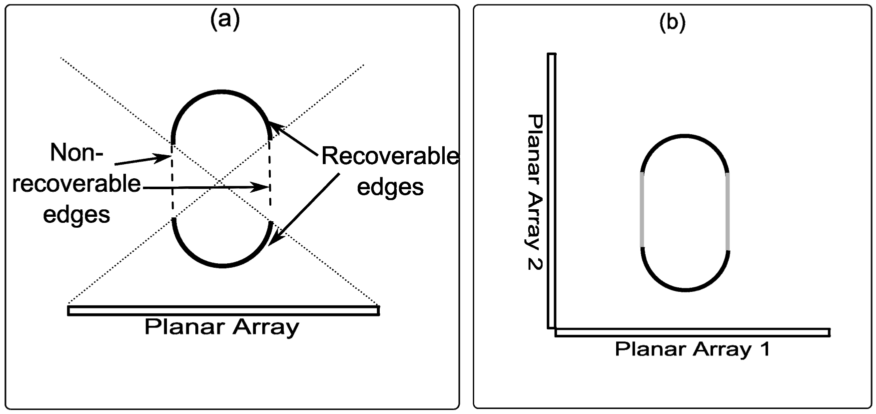

Figure 1. (a) In the limited aperture problem with planar arrays, not all the wavefronts reach the sensor plane. In order for an edge to be visible in the image, its normal must pass through the planar array. (b) Diagram demonstrating the use of a second, orthogonal, array to capture the previously undetected components. In this example, the black lines are visible to array 1, while the grey lines are visible to array 2.

2.2 Sensor registration

In order to reconstruct photoacoustic images using data from both arrays, the positions of the detection points on both sensors must be known in a common coordinate system. To determine the relationship between the 2D coordinates in the plane of one sensor to the 2D coordinates in the plane of the other, a phantom consisting of four carbon microspheres (300µm diameter) was photoacoustically imaged by both sensors, and the data from each was used separately to generate two photoacoustic images. The carbon microspheres appeared in both images, so once the correspondence between them had been manually assigned, the transformation between the two sensors' coordinate systems could be calculated from the coordinates of the microspheres.

2.3 Image reconstruction

A time reversal algorithm from the *k-Wave* Matlab Toolbox[8][9] was used to reconstruct photoacoustic images using the data from both arrays together, as well as each individually for comparison. The sound speed was set manually.

3. EXPERIMENTAL RESULTS

3.1 Grid phantom

A grid phantom, with lines separated by 1mm, was produced by laser printing onto a sheet of acetate (Figure 2(a)). The grid structure was placed into the system so that the lines ran parallel and perpendicular to each array. The grid phantom was acoustically coupled to the arrays using de-ionized water with a sound speed of 1480ms^{-1}. Figure 2 (b and c) were reconstructed from the data recorded on only one array, positioned either on the top (b) or to the left (c) of the image as shown. The lines of the grid perpendicular to the sensor plane have not been recovered, as expected due to the limited aperture problem. This is overcome in Figure 2 (d) which was reconstructed using data from both sensor arrays. Both sets of orthogonal lines are clearly present in the reconstruction, demonstrating the capability of the system to recover structures at these angles.

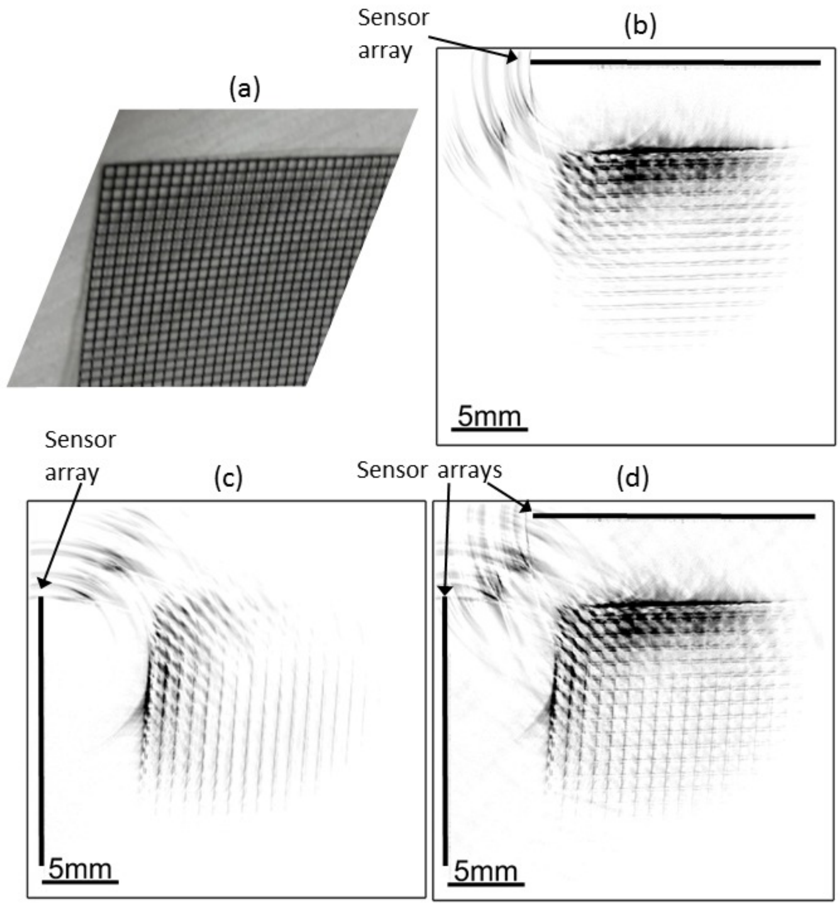

Figure 2. (a) Photo of grid phantom. (b,c,d) Maximum intensity projection (MIP) of reconstructed image of the grid phantom (b,c) using only data from one array, on the top (b) and left (c), and (d) using data from both arrays, left and top. Only one set of lines is visible in the reconstruction using the single arrays data, whilst orthogonal lines become visible when both sets of data are used.

3.2 Leaf Phantom

The complex structure of a skeletal leaf, coated in India ink to provide contrast, provides an example of the orthogonal arrays ability to image more complex perpendicular structures (Figure 3(a)). The phantom was positioned approximately perpendicular to both sensor planes. The phantom was coupled acoustically to the sensors using de-ionised water (sound speed of 1480ms^{-1}). Again, three reconstructions were completed. Figure 3 (b and c) show an image reconstructed using data from just one array. The image in Figure 3(d) was reconstructed using data from both arrays. Comparing either reconstruction that used only data from one array to the photo of the leaf in Fig. 3(a) it is clear that a lot of structure is missing from each reconstruction. When data from both arrays was used in the reconstruction, the missing structure becomes clearly visible.

4. DISCUSSION

The use of orthogonal 2D arrays improves the image compared to that obtained using a single 2D array in two related ways. First, features previously undetected due to their being almost perpendicular to the array were detected, and second, there was a reduction of limited aperture artifacts (blurring) generally in the images. However, it is clear from the top left region of the images that in these experiments some artifacts remain. These arise because the detection points - the points at which the acoustic field was measured - do not extend all the way into the corner of the V-shaped sensor array; there is a strip around each planar sensor that is insensitive. This is a fabrication issue, which will be addressed in future work.

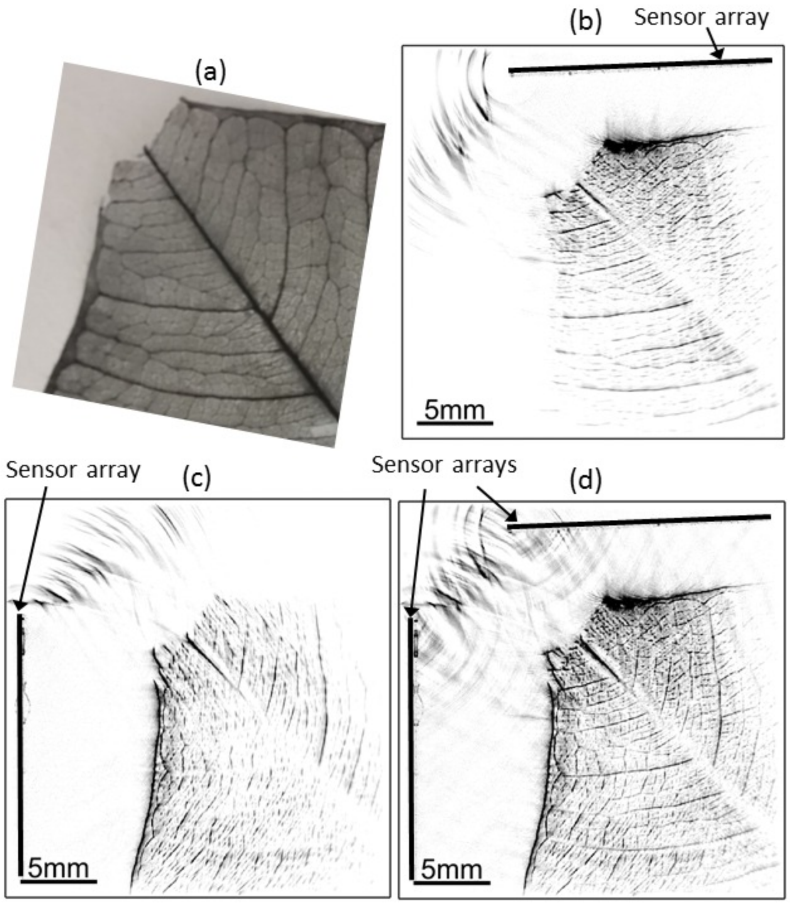

Figure 3(a) picture of leaf phantom. (b and c) MIP of reconstruction using only one arrays data, with the array at the top (b) and to the left (c) of the domain. (d) MIP of reconstruction using both arrays data. A host of extra features are evident in (d) as well as the image being sharper. The faint lines in the reconstruction at the left hand side and top of the MIP correspond to the position of the arrays.

ACKNOWLEDGMENTS

The authors acknowledge support from the Engineering and Physical Sciences Research Council, UK, and European Union project FAMOS (FP7 ICT, Contract 317744).

REFERENCES

[1] Zhang, E., Laufer, J. and Beard, P. C., "Backward-mode multiwavelength photoacoustic scanner using a planar Fabry-Perot polymer film ultrasound sensor for high-resolution three-dimensional imaging of biological tissues," Applied Optics, 47(4), 561-577, (2008) 10.1364/AO.47.000561

[2] Kim, C., Erpelding, T., Jankovic, L., Pashley, M. and Wang, L., "Deeply penetrating in vivo photoacoustic imaging using a clinical ultrasound array system", Biomedical Optics Express, 1(1), 278-284, (2010), 10.1364/BOE.1.000278

[3] Razansky, D., Distel, M., Vinegoni, C., Ma, R., Perrimon, N., Koster, R. and Ntziachristos, V., "Multispectral opto-acoustic tomography of deep-seated fluorescent proteins in vivo", Nature Photonics, 3, 412-417, (2009), 10.1038/nphoton.2009.98

[4] Brecht, H., Su, R., Fronheiser, M., Ermilov, S., Conjusteau, A. and Oraevsky, A., "Whole-body three-dimensional optoacoustic tomography system for small animals", Journal of Biomedical Optics, 14(6), 064007-1-8, (2009), 10.1117/1.3259361

[5] Kruger, R., Lam, R., Reinecke, D., Del Rio, S. and Doyle, R., "Photoacoustic angiography of the breast", Medical Physics, 37 (11), 6096-6100, (2010), 10.1118/1.3497677

[6] Paltauf G., Nuster R., Haltmeier M. and Burgholzer P., "Experimental evaluation of reconstruction algorithms for limited view photoacoustic tomography with line detectors", Inverse Problems, 23, S81-94, (2007), 10.1088/0266-5611/23/6/s07

[7] Schwarz M., Buehler A. and Ntziachristos V. "Isotropic high resolution optoacoustic imaging with linear detector arrays in bi-directional scanning" Journal of BioPhotonics, 8(1-2), 60-70, (2015), 10.1002/jbio.201400021

[8] Treeby, B. E. and Cox B. T., "*k-Wave*: MATLAB toolbox for the simulation and reconstruction of photoacoustic wave fields," Journal of Biomedical Optics, 15(2), 021314-1-12, (2010), 10.1117/1.3360308

[9] Treeby, B. E., Zhang E. and Cox, B. T., "Photoacoustic tomography in absorbing acoustic media using time reversal", Inverse Problems, 26, 115003, (2010), 10.1088/0266-5611/26/11/115003

[10] Laufer J., Johnson P., Zhang E. et al. "In vivo preclinical photoacoustic imaging of tumor vasculature development and therapy", Journal of Biomedical Optics, 17(5), 056016, (2012), 10.1117/1.jbo.17.5.056016