Piezoelectric annular array for large depth of field photoacoustic imaging

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Abstract: A piezoelectric detection system consisting of an annular array is investigated for large depth of field photoacoustic imaging. In comparison to a single ring detection system, X-shaped imaging artifacts are suppressed. Sensitivity and image resolution studies are performed in simulations and in experiments and compared to a simulated spherical detector. In experiment an eight ring detection systems offers an extended depth of field over a range of 16 mm with almost constant lateral resolution.

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1. Introduction

Photoacoustic imaging is based on the excitation of ultrasound waves by absorption of short laser pulses. It is able to provide high resolution and high contrast images of light-absorbing structures such as blood vessels in biological tissue. Since photoacoustic (also called optoacoustic) imaging is based on optical contrast on the one hand but on the other hand
yields ultrasound resolution, it combines the advantages of these two imaging methods. Photoacoustic (PA) imaging is believed to have a great potential in clinical and preclinical applications like early breast cancer diagnostics and small animal imaging [1–3]. Acquisition of PA images with a scanning, focused detector is a vital field of ongoing research [4]. A single receiving transducer with an acoustic lens can be optimized for the required resolution by selecting its bandwidth and numerical aperture. However, the acquisition of images by detection of amplitude (A-) scans, where the depth information is contained in the time of flight of signals, is limited to the focal depth of the lens. To achieve a larger depth of field, various transducer geometries that focus onto their symmetry axis rather than on a point have been recently investigated. Axicon [5] transducers with conical shape or ring transducers [5–8] show this kind of focusing behavior. However, when images are taken by scanning a single ring or conical axicon transducer across an object, severe imaging artifacts are created. Typically, a point shaped structure like the cross section of a small blood vessel appears as an “X”. In an effort to improve resolution and to reduce this artifact, Kolkman et al. [7] used a double ring sensor. Also deconvolution of images taken with an axicon transducer has been reported [5].

To achieve an even higher suppression of artifacts and to amplify signals excited on the detector axis, we propose in this work the use of an array of several concentric ring detectors that simultaneously record waves coming from photoacoustic excitation in an object. Structures lying on the axis within a wide depth range can be localized by using dynamic focusing. Axial and lateral resolution, sensitivity and depth of field depend on widths and diameters of the used concentric ring elements. We use simulations to estimate the properties of the annular array and to compare it with a spherical lens detector. Furthermore, we show an experiment to demonstrate the depth of field of this device.

2. Annular array detector

An annular ultrasound detector array consists of several concentric piezoelectric ring sensors (Fig. 1). Each of these rings can be described by its radius \( r_i \) and by its width \( w_i \). The inner and outer radii are given by \( r_i \pm 0.5\cdot w_i \). An acoustic wave generated at a point on the axis at \( t = 0 \) arrives at time \( t_i \) on the \( i^{th} \) ring area. This well-defined delay time can be calculated for each ring using \( r_i \) and the speed of sound, \( c \). Conversely, it is possible to calculate the distance \( z \) of a source to the plane of the ring array from the arrival time of the acoustic wave. By doing this, signals detected by all rings can be interpolated to a common \( z \)-axis and summed to achieve dynamic focusing. Before that, signals are Hilbert transformed. The Hilbert transform causes a phase shift in the bipolar pressure signals, creating a maximum at the transition from positive to negative pressure. Since this intercept corresponds approximately to the center of the source, Hilbert transformed signals are better suited for reconstruction than raw pressure signals:

\[
SH(z) = \sum_{i=1}^{N} [H(S_i(z))], \quad z = \sqrt{(ct_i)^2 - r_i^2}.
\]  

Here, \( S_i \) is the signal received by the \( i^{th} \) ring and \( H \) denotes the Hilbert transform. Dynamic focusing enhances the magnitude of reconstructed sources on the axis by a factor depending on the number of rings and suppresses artifacts in areas away from the axis. For example, an eight-ring detector system theoretically enhances signals originating on the axis by a factor of eight compared to a single ring detector. To enhance the suppression of imaging artifacts and to improve image quality we calculated a coherence factor \( CFH(z) \) [9,10] for the Hilbert transformed signals:
If the signals of each ring interfere perfectly, the coherence factor becomes 1. In the experiment this maximum value is usually lower but still close to one, whereas the imaging artifacts are suppressed because they do not interfere constructively. To calculate the weighted signals $SWH(z)$, the coherence factor $CFH(z)$ has to be multiplied with the Hilbert transformed summed signals $SH(z)$:

$$SWH(z) = SH(z) \cdot CFH(z).$$

Each of the signals obtained in this way is treated as an amplitude scan (A-scan). An image is formed by scanning the detector in $x$- and $y$-directions and by arranging A-scans in a two- or three-dimensional image array.

Fig. 1. (a) Principle setup for an annular array of detectors (b) top view of the transducer (c) bottom view.

The achievable resolution for each ring depends on the depth $z$ of the photoacoustic source, further on the diameter and width of the used ring. Generally, as with all imaging systems, a large numerical aperture (NA) is required for a good lateral resolution. Because there is no defined focal length, the NA for each ring depends on depth.

Breaking down the aperture of a circular disk shaped area into several concentric rings has some further effects on sensitivity and resolution. Because of the oblique incidence of the acoustic waves on the rings, only for vanishingly small ring widths compared to the acoustic wavelength the integrating effect over the detector area can be neglected.

For estimating the influence of a finite ring width, consider a source of radius $a$ located at distance $z$ from a single ring and centered at the ring axis. When illuminated by a short pulse (considerably shorter than $a/c$) it emits a symmetric bipolar pressure pulse of length $2a$, which can be regarded as the typical acoustic wavelength for this problem. Integration over the ring area has a noticeable influence on the signal as soon as the whole positive part of the pressure pulse, which has a length of $a$, is spread over the area of the ring.

The transition from negligible ring width to a ring with integrating properties is demonstrated in Fig. 2. Signals generated by a homogenously heated sphere with $a = 85 \, \mu m$ located at $z = 16 \, mm$ on the axis of a ring with $r_l = 5.0 \, mm$ are simulated. A very thin ring ($w = 100 \, \mu m$) measures the typical N-shaped signal that would also be measured with a point-like detector. When the ring width increases, the signal is transformed to a sinusoidal signal with higher amplitude. For larger ring width the amplitude of the received signal does not rise but the total duration of the signal increases, deteriorating both, the axial and lateral resolution.
Fig. 2. Transformation of a signal generated by a homogenously heated sphere when measured with a ring detector with increasing outer ring radius ($r_a$) – ring widths $w$: blue: 100 µm, red: 300 µm, green: 500 µm, purple: 700 µm.

For a certain depth of a source with radius $a$, the ring widths should therefore not exceed a value given by

$$w_i = a / \sin \phi_i,$$

where $\phi_i$ is the incident angle on the $i^{th}$ ring, in order to optimize the resolution. For example, for a depth of 16 mm, a ring with a radius of 18 mm should have a width not exceeding about 130 µm to resolve a source of 100 µm radius.

To demonstrate the effect of ring width on resolution and sensitivity, we simulated images with an eight ring array. As ring radii we used the same values as for the experimental device. Four cases are compared in Fig. 3. In Fig. 3a, all rings widths are calculated according to $w_i$ in Eq. (4), in part (b) the ring widths are $w_i/3$ and in part (c) they are $3w_i$. For comparison, also an image for 2 rings with radii of 7 and 12 mm, using widths given by Eq. (4), is calculated and shown in figure part (d). A sphere with radius of 100 µm at a distance of 16 mm from the array was assumed. The reduced and the “ideal” ring widths (according to Eq. (4)) yield the same resolution. However, an array based on the ideal ring widths gives a higher amplitude. Increasing the ring widths further, the amplitude is slightly reduced but the resolution becomes much worse. Furthermore, comparing eight and two ring arrays clearly shows that the latter has lower amplitude and a higher level of artifacts.

Since not the entire area of the array is active, the sensitivity of a ring array is certainly smaller than that of a spherical lens detector with the same aperture, where the whole area is hit at once by a wave coming from a source in the focus. This will be quantitatively described below.

A design concept in the implementation of the ring array was to achieve similar contributions from each ring. Therefore the widths of the rings were chosen for constant area, leading to decreasing width with increasing ring diameter.

3. Experiment

For experiments we built an eight ring array using the piezoelectric polymer polyvinylidenfluoride (PVDF). A PVDF film with 28 µm thickness and with metalized upper surface was glued onto a conductor board with copper electrodes in the shape of concentric rings. The upper, metalized side of the PVDF film was contacted to the housing of the
Fig. 3. Simulated images with (a) an eight ring array using the optimum ring widths given by Eq. (4), (b) an eight ring array with reduced ring widths, (c) an eight ring array with enhanced ring widths, and (d) a two ring array, using again the optimum ring widths.

detector array (Fig. 1b). Ring radii were $r_i = 3.2, 5.14, 7.10, 10.07, 12.65, 14.05, 16.04, 18.04$ mm and ring widths were $w_i = 400, 280, 200, 150$ for the inner rings and $130 \mu$m for the four outer rings (Fig. 1a). According to the estimation shown above, for sources with a radius larger than $85 \mu$m lying at $z > 16 \text{mm}$ the resolution should not be influenced by the finite ring width. Taking $170 \mu$m as the characteristic wavelength gives a frequency range up to $9 \text{MHz}$. This is also the effective bandwidth limit of the whole device, since other bandwidth limiting factors such as PVDF film thickness and electrical amplification would allow a higher upper frequency limit. In the etching process of the conductor board the minimum achievable width of electrodes was $130 \mu$m, resulting in slightly larger areas of the outer rings. To contact each ring separately with the amplifier, wires with a diameter of $100 \mu$m were embedded in holes drilled from the bottom side (Fig. 1c). Signals coming from each piezoelectric detector were amplified with a gain of 80. We used preamplifiers (OPA847 – Texas Instruments) optimized according to the capacity of each ring to cover a bandwidth from approximately $300 \text{kHz}$ up to a theoretical limit of $48 \text{MHz}$. The signals coming from the electric crosstalk between the rings were very low compared to the real signals and were therefore neglected. For parallel collection of data we used an eight channel 12-bit acquisition card (PXI-5105 National Instruments).

The sample was illuminated from below, through a sealed hole in the center of the annular array with a free beam of $532 \text{nm}$ Nd:YAG laser pulses with $10 \text{ns}$ duration. A water tank for acoustic coupling was placed on the top of the annular array.

For acquisition of a section image the sample has to be moved in a direction perpendicular to the transducer axis. For a full 3D image the phantom has to be scanned over the $x,y$ plane.

As a phantom for the resolution experiment we used an optical fiber with diameter of $100 \mu$m. The end face was dipped into black acrylic dye. Cross section images of the point source were taken by scanning the fiber over a length of $3 \text{mm}$ in $x$-direction with an increment of $10$
µm. No signal averaging was necessary. For each ring the measured signals were band-pass filtered (125 kHz up to 48 MHz) to reduce high-frequency noise and low-frequency ripple.

4. Results

The photoacoustic source was placed at 11 different depth positions \( z_m \) between \( z_1 = 16.13 \) mm and \( z_8 = 32.82 \) mm. The same positions for experiment and simulation were chosen.

To demonstrate the large depth of field the annular array is compared with a spherical detector in simulations. This detector was modeled as a spherical cap with a radius of curvature of 25.22 mm, which gives its focal length. The diameter of the cap was set equal to the diameter of the largest ring, number eight (\( r_8 = 18.04 \) mm), giving the same numerical aperture \( NA = 0.72 \) for the annular array and the spherical lens.

To include the effect of directional response, the simulated signals for the annular array were weighted with the cosine of the incident angle \( \phi \). Both, the Hilbert transform and the coherence factor were implemented in the simulation of the annular array. For the spherical detector only the Hilbert transform was performed. In both cases, simulated annular and spherical detector, a sphere with a diameter of 100 µm was chosen as a photoacoustic source.

4.1. Depth of field and resolution

Figure 4 compares measurement and simulation of an image taken with the ring array to the simulated image calculated for a spherical lens detector. Figure 4(a) shows the measurement, (b) the simulation of the array and (c) the simulation of the spherical detector with \( NA = 0.72 \). The image (a) was obtained by adding images from subsequent scans, where the depth of the point source was varied.

Fig. 4. Comparison of measured and simulated photoacoustic images for different depths of a small (100 µm) source. (a) measurement with the annular array, (b) simulated array, (c) spherical detector with \( NA = 0.72 \).
The annular array has a clearly extended depth of field in comparison to a spherical detector. Figure 5(a) compares the depth of field between the annular detector (simulation and measurement) and a spherical detector (simulation) focusing at 25.22 mm.

Figure 5(b) compares the lateral widths of the 100 µm source located at the focus of the spherical lens, taken from the images displayed in Fig. 4. The width of the profile, given here as the full width at half maximum (FWHM), of the image obtained with the simulated array is 140 µm. The experimentally determined value is 195 µm. In contrast, the FWHM for the spherical detector is 410 µm (NA = 0.72) and 330µm (NA = 1). Using the same aperture, an annular array offers a higher lateral resolution.

In the simulation the FWHM in lateral direction increases with depth (Fig. 6). This is expected because the numerical aperture is decreasing with depth as is the integrating effect of the finite ring width. In the measurement the FWHM of the profiles is almost constant over 16 mm. This can be attributed to the influence of the directivity of the piezoelectric film [11,12] and of the flat, disc-like source. In the measurement the directivity reduces the effective numerical aperture. This effect is more pronounced for shallow depths, where the incident angle is quite large for the outer rings of the array. In the simulation the directivity effect was not fully taken into account.
4.2. Sensitivity

We compare the sensitivity $S_{\text{sphere}}$ of a spherical lens transducer with an annular array. For a spherical detector area (or a spherical lens in front of a planar detector) the wave front coming from a point at the focus arrives at normal incidence and at the same time on the transducer surface. To calculate the sensitivity for a ring detector array $S_{\text{ring}}$ the incident waves coming from a point on the axis are summed, taking the incident angles into account. Here, a simplified directivity ($\cos \phi$) is considered.

\begin{equation}
S_{\text{sphere}} \propto \frac{P_0 \cdot A_{\text{sphere}}}{f_{\text{sphere}}} \quad \text{and} \quad S_{\text{ring}} \propto P_0 \sum_{i=1}^{\infty} \frac{A_i \cos \phi \cdot a}{c \cdot t_i}.
\end{equation}

$P_0$ is the pressure at $t = 0$ and $a$ is the radius of the spherical photoacoustic source, $c$ represents the speed of sound, $A_i$ is the area of the $i^{\text{th}}$ ring and $A_{\text{sphere}}$ of the spherical detector, $f$ is the focal length of the spherical detector, $\phi$ is the incident angle for the $i^{\text{th}}$ ring, and $t_i$ is the time of flight to the $i^{\text{th}}$ ring. Using these formulas, we can estimate that the sensitivity for a spherical detector with an apert ure of $NA = 0.72$ is higher by a factor of 18.3 than the sensitivity of the annular array. This was expected due to the larger area and normal incidence in the case of the spherical lens.

5. Phantom experiments

To investigate the performance of the ring array with a tissue like sample we built a phantom containing three black horse hairs embedded at different depths in gelatin. The gelatin was prepared with five parts water (by weight), 5% Intralipid solution and one part gelatin powder. Again the sample was illuminated from below with a free beam of 532 nm Nd:YAG laser pulses with 10 ns duration. To obtain a cross section image the phantom was scanned in 50 µm steps across the transducer axis. This experiment is also used to demonstrate the benefits of the chosen signal processing steps. Figure 7(a) shows the cross section image without coherence factor correction and without performing the Hilbert transform. From the resulting image only the positive signal values are displayed. Strong artifacts due to side lobes are visible. In Fig. 7(b) the Hilbert transformed and coherence factor weighted signals are used.
are used to form an image. The artifacts are suppressed and the centers of the sources are slightly shifted away from the detector plane. Due to the phase shifting property of the Hilbert transform, the bright areas most likely indicate the true positions of the hairs.

For a full 3D scan we used a phantom consisting of three black plastisol spheres with a diameter of 1.5 mm and a black plastisol cylindrical source with a length of 3 mm and a diameter of 1.2 mm. They were embedded in transparent plastisol at different depths. The scanning was performed over an area perpendicular to the transducer axis in step sizes of 100 µm in x- and y-directions. The sample was again illuminated from below. Figure 8 shows maximum amplitude projections in z-direction for different sections perpendicular to the z-axis. Figure 8(a) shows the full projection in z-direction, hence all four sources are visualized. Figures 8(b)-(d) visualize the projections for each source separately.

6. Discussion

A concentric ring detector array provides large depth of field photoacoustic imaging using dynamic focusing. The annular array built for this study allowed imaging at almost constant lateral resolution (~ 200µm for a 100 µm photoacoustic source) over a range of 16 mm. For spherical transducers with fixed focus the depth of field is much smaller, as demonstrated in a simulation that used a similar NA as the ring array. Although there have been efforts to increase the depth of field for a spherically focusing transducer by employing a synthetic aperture focusing algorithm (SAFT) [9], scanning in depth would be necessary to obtain an image with comparable depth range. Furthermore, the SAFT algorithm requires a relatively long scan distance, since many neighboring A-scans have to be processed in order to achieve the desired effect. By contrast, dynamic focusing with a ring array already works within a single A-scan.

In general, single ring detectors with a large radius to distance ratio give good lateral but poor axial resolution. Dividing a circular area with a given diameter into a high number of detector rings gives a good suppression of the typical X-shaped artifacts obtained with a single ring. As the sensitivity scales with the integrating area of the detector, the device shown here with its relatively low coverage of the area yielded a much lower sensitivity than a spherical transducer with the same diameter. The practical depth range of the array depends therefore not only on the achievable depth of field but primarily on the signal to noise ratio.
(SNR), which is related to the sensitivity. As it was demonstrated in Fig. 3, there are two ways to maximize the sensitivity of the device: the width of the individual rings has an optimum for a certain size of a source and a certain depth range, given by Eq. (4). Smaller and larger ring widths reduce the amplitude of the source in the image. Larger widths also deteriorate the resolution. Additionally, the sensitivity increases with the number of rings for a given maximum aperture of the array. Our current data acquisition card limited the number of rings to eight, but a larger number of rings would be possible.

We recently introduced a dual mode scanning acoustic microscope (DSAM). This device combines ultrasound pulse echo imaging (image contrast based on acoustic impedance variations of observed targets) and photoacoustic imaging (image contrast is based on the optical absorption of short laser pulses) in one single device [13–15]. For ultrasound generation we use a passive axicon element, formed by a black absorbing layer on a conical surface. When irradiated by short laser pulses, this device generates an acoustic field focused onto the axis of the cone [14]. For taking advantage of this extended focal range, the design presented in the current study will be used for receiving the scattered ultrasound from the sample. Ultimately, the DSAM will therefore provide a large depth of field for both, the photoacoustic and ultrasound imaging modes.

7. Conclusion

An annular array detection system provides large depth of field photoacoustic imaging at almost constant resolution. Hence scanning in depth is not necessary in comparison to a spherical detector. For medical applications the detector array can be used if shallow and deep tissue structures have to be imaged simultaneously. An example is photoacoustic imaging of skin and underlying vessels and lymph nodes.

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