Characterizing GCLAD as a non-contact detector for biomedical applications

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Photoacoustic (PA) imaging is a rapidly growing field that has the potential to improve non-invasive imaging capabilities. Conventional detectors such as transducers have several disadvantages such as narrow bandwidth, limited sensitivity and the fact that contact with the sample is required. Optical methods provide better bandwidth and resolution but have other limitations. These detection methods often contain complicated optics and depend on the reflectivity of the sample. Since biological tissue is mostly rough and poorly reflective the addition of reflective tape is often required. However, this is not always possible or desired for example when imaging the eye or burned tissue. Therefore GCLAD provides an alternative fully non contact detection method for photoacoustic and ultrasound imaging that does not depend on the reflectivity of the sample. GCLAD is a line detector that measures the deflection of an optical beam propagating parallel to the sample as the refractive index of the air caused by an acoustic wave travelling through the sample is affected. GCLAD was originally developed for materials testing and therefore research needs to be performed to exploit the potential of GCLAD as a detection method for biomedical applications. Underlying principles are outlined and characterizing experiments are performed. Research into the effect of the air gap between the probe beam and the sample surface show that only slight attenuation takes place and that signals can clearly be detected at distances of over 10 cm away from the sample. Furthermore, the results are reproducible and the scans require little time. Possibly the most important advantage of GCLAD as a detector for biomedical applications is being fully non contact. Comparison of GCLAD with line-integrated data of a commercial laser vibrometer point detector shows an 83% agreement. Finally it is demonstrated that GCLAD can be used to image an artery-sized absorber using a detector several centimetres away from the sample.

Keywords: photoacoustic imaging, laser-ultrasound, gas-coupled laser acoustic detection
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Gas-coupled laser acoustic detection (GCLAD) is a non-contact detection method that can be used to detect sound in the frequency range of audio and ultrasonics. GCLAD measures the difference in refractive index of the air caused by an acoustic wave traveling through a sample. A laser beam is directed perpendicular to the acoustic wave. When the wave reaches the sample surface, the refractive index of the surrounding air is slightly changed causing the laser beam to displace. This displacement is measured with a position-sensitive detector. Advantages of this technique are that it is a simple technique without complicated optics, it requires few components, is inexpensive, and independent of the reflectivity of the sample because the probe beam is not reflected from the surface of the sample [2, 3, 4]. Furthermore, no contact with the sample to be imaged is needed. The technique can be used for any application in which (ultra)sound is detected and is especially useful in cases where sample surfaces are rough and poorly reflective. In these cases GCLAD can be used as an alternative to vibrometry, where light needs to reflect directly off the target. When using pulsed laser as a source for generating acoustic waves the technique can be used for remote sensing and non-destructive material evaluation [2]. Moreover, the technique can be used in a wide range of medical applications. GCLAD is especially relevant for imaging when contact with the sample or use of a coupling medium is troublesome. Examples include imaging for surgical interventions, and imaging of the brain, eye, or burned tissue [5, 6]. In medical imaging GCLAD can be used as a detector for photoacoustic imaging.

Photoacoustic (PA) imaging is a rapidly growing field that shows promise in a wide range of clinical applications, such as the detection of cancer and diseased blood vessels. Photoacoustic imaging is based on the photoacoustic effect which arises when a short pulse of laser light is incident on biological
tissue. The tissue being highly scattering causes this beam to diffuse. The energy of the diffused beam is absorbed by chromophores within the tissue when the wavelength of the source matches the absorption wavelength of the chromophore. This energy is then converted into heat which causes thermoelastic expansion resulting in the generation of an acoustic wave [7, 8]. PA imaging combines the high contrast and specificity of optical imaging with the high spatial resolution of ultrasound imaging. PA imaging depends mostly on the optical absorption of the tissue, which creates better contrast than conventional ultrasound because differences in optical absorption are usually bigger than differences in acoustic impedance between different tissues. One of the biggest advantages of PA imaging is that you can selectively enhance the contrast for specific tissue by altering the excitation wavelength of the source. This makes PA imaging very suitable for structural and functional imaging. Vasculature can be visualized with very high contrast due to the absorption of hemoglobin and the contrast provided by lipid absorption gives the possibility to identify vulnerable plaques. PA imaging provides a broad range of potential applications in tumor identification, vascularization, skin pathologies and blood flow measurement [9].

The most commonly used detector for photoacoustic imaging is the piezoelectric transducer. However, these transducers have several disadvantages such as their narrow bandwidth, limited sensitivity and the fact that contact with the sample is required. Other methods, such as optical interferometers provide better bandwidth and resolution compared to the use of transducers. However, these optical methods are based on complicated optics and still have limitations. One of these limitations is the fact that they depend on the reflectivity of the sample, which limits the use for biomedical applications, where surfaces are usually rough and not that reflective. Although reflectivity can be improved by the addition of reflective tape this might not be feasible in some cases. Examples are surgical interventions, imaging of burned skin or imaging of the eye. For these applications it would be beneficial to have a fully non-contact method in order to make the procedure more practical [6]. Furthermore, developing a non-contact method will increase the range of applications for PA imaging. For these reasons research into new non-contact detectors for PA imaging is of great interest [5, 7, 6].

GCLAD is a robust technique that does not require contact with the sample. The detection method was originally developed for materials evaluation and is new to the field of medical imaging [2]. Therefore research needs to be performed to exploit the potential of GCLAD. First a short outline of theory associated with GCLAD will be given. Next, the research includes setting
up GCLAD and characterizing the detector. The detector will first be tested using a transducer source, where the aim is to fully understand both the technique and signals created by GCLAD. In this setup, an air gap between the probe beam and sample surface will be present. The effects of this air gap, such as frequency attenuation and dispersion, will be evaluated. Additionally, the extra time to travel through air should be removed or accounted for. In this research, image processing will be used to account for this delay. Next, the transducer source will be replaced with a laser source for fully non-contacting measurements. Airgap evaluation and delay correction will be repeated with this setup and results will be compared to the transducer source. Furthermore, GCLAD is a line detector where the signal is measured over a straight line perpendicular to the acoustic waves. The dependency of the signal on the horizontal positioning of the sample along this line will be evaluated as well. Two dimensional surface scans using GCLAD will be performed and the research will involve a literature search into reconstruction methods that can be used with GCLAD.
Chapter 2

Theory

Gas-coupled laser acoustic detection (GCLAD) is a technique that detects laser beam deflection caused by ultrasound. Therefore, a probe beam is placed parallel to the sample surface. If acoustic waves are radiated from the sample surface and propagating through air, the slight variations in air density will cause a deflection of this probe beam. These deflections can be detected with the use of a position sensitive detector. For measuring with GCLAD a setup as shown in Figure 2.1 is used. In this figure the acoustic waves are coming from a transducer source, but they can be generated by a pulsed laser source as well. In this section theory of beam deflection caused by acoustic waves will be outlined.

Figure 2.1: Experimental setup for ultrasound measurements with GCLAD. The acoustic wave caused by the ultrasound transducer travels through the sample, propagates through air, modulates the index of refraction transverse to the probe beam and thereby displaces the beam. This displacement is measured by a position-sensitive photo detector.
2.1 Beam deflection

In the setup of Figure 2.1, a transducer source is sending out an ultrasonic pulse. Upon reaching the sample surface this pulse will cause surface motion and an accompanied acoustic wave. This acoustic wave is propagating through the surrounding air. When reaching the probe beam, the beam is deflected by density variations, induced by the acoustic wave causing changes in the index of refraction of air. When an optical beam passes through regions with varying density and index of refraction, it is deflected as described by the eikonal equation [2]. The eikonal equation is a non-linear partial differential equation which links physical wave optics to geometric ray optics.

The index of refraction of a gas can be expressed as follows [2]

\[ n_i - 1 \approx \frac{3}{2} A \rho / M \]  

(2.1)

With:
- \( n_i \), the index of refraction of the gas
- \( A \), the molar refractivity of the gas
- \( \rho \), the mass density of the gas
- \( M \), the molecular mass of the gas

Density variations in an acoustic wave are adiabatic, which means there is no heat exchange with the surroundings. The density variations are related to the acoustic pressure variations by means of the adiabatic derivative [2]

\[ c^2 = \left( \frac{\partial p}{\partial \rho} \right)_s \]  

(2.2)

Where \( c \) is the speed of sound and \( p \) is pressure.

This means that variations in the index of refraction are proportional to variations of the pressure via [2]

\[ \Delta n_i = \frac{3A \Delta p}{2Mc^2} = \frac{(n_i - 1) \Delta p}{\rho c^2} \]  

(2.3)

The path of an optical ray can be described by the eikonal equation. When assuming the beam propagates approximately parallel to the \( z \)-axis, the paraxial approximation can be used which can be expressed as follows [2]

\[ \frac{\partial^2 X}{\partial z^2} \approx \frac{1}{n_i} \frac{\partial n_i}{\partial x} \]  

(2.4)
In this equation X is the deflection of the beam in the x-direction.

The local angle of deflection $\theta$ such as displayed in Figure 2.1 can be written as

$$\theta = \arctan \left( \frac{dX}{dz} \right) \approx \frac{dX}{dz} \quad (2.5)$$

Combining the equations above and substituting Equation (2.5) into Equation (2.4) gives a relationship between the angle of deflection and the index of refraction

$$\frac{\partial \theta}{\partial z} = \frac{1}{n_i} \frac{\partial n_i}{\partial x} \quad (2.6)$$

Integrating this equation over the total beam path gives the total deflection of the beam [2]

$$\theta = \frac{1}{n_i} \int \frac{\partial n_i}{\partial x} dz \quad (2.7)$$

When using Equation (2.3), this can be rewritten to

$$\theta = \frac{n_i - 1}{n_i \rho c^2} \int \frac{\partial p}{\partial x} dz \quad (2.8)$$

This deflection will be converted into an electronic signal by means of the position sensitive detector [2].
Chapter 3

Air gap evaluation

When measuring with GCLAD, an air gap is present between the probe beam and the sample surface. This air gap might influence the GCLAD signal, for example attenuation might take place when the acoustic wave has to travel a bigger distance through air. In this chapter the effect of the air gap will be analyzed for frequencies relevant to PA imaging. Therefore both a transducer source and a laser source will be used to generate acoustic waves. The sources will be compared because the effect might be dependent on the source used. Signal amplitudes, frequency spectra and correlation coefficients will be determined at different air gaps. The first signal arrival will be present at a time equal to the sum of the propagation times through the sample and through the air. The time delay by propagation through air will be accounted for by means of signal processing. The transducer source and the laser source will be treated separately in the methods and results sections, whereafter they are compared in the discussion.

3.1 Methods

3.1.1 Transducer source

The experimental setup is shown in Figure 3.1, a photo of the setup is shown in Figure 3.2. A rectangular solid phantom of 1% Intralipid®, 1% highly purified agar (A0930-05, USBiological), and deionized water is used to represent biological tissue. A laser diode with a wavelength of 637 nm and a current of 75 mA is focused on a position sensitive photo detector with a frequency bandwidth of 50 kHz to 6 MHz (Dulcian, Quarktet) by means of a convex lens with a 60 mm focal length. This ensures the response to be independent of the acoustic source position. A 500 kHz ultrasound transducer
3.1.2 Laser source

The experimental setup is shown in Figure 3.3, a photo of the setup is shown in Figure 3.4. A cylindrical solid phantom of 1% Intralipid®, 1% highly purified agar (A0930-05, USBiological), and deionized water is used to represent
biological tissue. A Quanta-ray pulsed ND:YAG laser with a wavelength of 1064 nm, energy of 300 mJ and repetition rate of 10 Hz is used to generate acoustic waves. Although an energy of 300 mJ is beyond safe limits for biological tissue, the high signal-to-noise ratio at this energy is beneficial for analysing the performance of GCLAD at this stage. Signals are filtered and amplified by means of a low noise pre-amplifier (SRS SR560) with a high pass filter with cut-off frequency of 100 Hz and a gain of 20. Signal acquisition and GCLAD setup are the same as with the transducer source.

3.2 Results

3.2.1 Transducer source

Figure 3.5 and Figure 3.6 show a wiggle plot of the signals before and after delay correction, respectively. The wiggle plots are created with PLACE [10]. These plots show that the delay increase is proportional to the distance between the probe beam and the sample surface and that all signals become aligned when correcting for this delay with cross correlation. The wiggle plot
after delay correction only contains the 100 µs time window used for correlation analysis. Signals obtained with the transducer source are shown in Figure 3.7 where all signals are plotted in a 100 µs window and the delay is accounted for. The absolute air gap is given in the legend and is determined by interpolation of the first occurrences of the signals. Figure 3.8 shows the first 20 µs of the same signals, which clearly shows the resemblance between the signals with different air gap. Also, clear signals can be obtained with an air gap as big as 147 mm. The mean correlation coefficient between the signals in a 100 µs time window is 0.88, in a 20 µs time window it is 0.97.

Figure 3.9 shows GCLAD signals for three different air gaps. These signals are not normalized to analyze the effect of air gap on amplitude. As this figure shows, the effect of the air gap on amplitude is small when using a transducer source. The amplitude of the traces shown does not differ much even though there is a 35 mm difference in air gap between subsequent traces. Figure 3.10 shows the corresponding frequency spectra of the GCLAD signals, which can be used to evaluate the effect of air gap on frequency. As this figure shows, some frequencies are slightly attenuated when the air gap increases. Higher frequencies seem to be attenuated most, however, all frequencies are attenuated to some extent. Since no frequencies are completely disappearing, no dispersion takes place. The figure also shows that the received frequencies are 500 kHz or lower, which is expected.

Figure 3.5: Wiggle plot of GCLAD signals before delay correction.

Figure 3.6: Wiggle plot of GCLAD signals after delay correction (100 µs time window).
Figure 3.7: Signals of GCLAD measurements on tissue phantom with transducer source and variable air gap.

Figure 3.8: Zoom on first arrival of GCLAD measurements on tissue phantom with transducer source and variable air gap.

Figure 3.9: Amplitude evaluation of GCLAD measurements with variable air gap and transducer source.

Figure 3.10: Frequency evaluation of GCLAD measurements with variable air gap and transducer source.

3.2.2 Laser source

Figure 3.11 and Figure 3.12 show wiggle plots of the signals obtained with the laser source. Figure 3.11 shows that also with the laser source the delay increase is proportional to the distance between the probe beam and the sample surface. When correcting for the delay induced by this air gap, all signals become aligned, as shown in Figure 3.12. Again, the wiggle plot after delay correction only contains the 100 µs time window used for correlation analysis.

Signals obtained with the laser source are shown in Figure 3.13 where all signals are plotted in a 100 µs window and the delay is accounted for.
A bandpass filter with frequencies between 100 kHz and 300 kHz is used to remove noise. It should be noted that this figure shows the first arrival around 70 µs and shows a second event around 130 µs. This second event is caused by a hole in the middle of the phantom. Figure 3.14 shows the first 20 µs of the same signals, which zooms in on the first arrival of the GCLAD signal. Clear signals can be obtained with an air gap as big as 106 mm. The mean correlation coefficient between the signals in a 100 µs time window is 0.86, in a 20 µs time window it is 0.95. It should be noted that the signals look more noisy than with the transducer source and the correlation is lower when taking into account a bigger time window.

Figure 3.15 shows GCLAD signals for three different amplitudes. These signals are not normalized to analyze the effect of air gap on amplitude. As this figure shows, an increase in air gap causes a small decrease in amplitude. Figure 3.16 shows the corresponding frequency spectra of the GCLAD signals, which can be used to evaluate the effect of air gap on frequency. This figure shows the frequency spectra of the GCLAD signals without using any additional filter. As this figure shows, some frequencies are slightly attenuated when the air gap increases. Higher frequencies are attenuated most. However, as with the transducer source, all frequencies are attenuated and no dispersion takes place. The frequency range of the signals is broader than with the transducer source.
3.3 Discussion

The results presented in the previous section show that the air gap has some effect on both the amplitude and the frequency spectrum of the signal. Some frequencies get attenuated with both the transducer source and the laser source but no dispersion takes place. This means the waveform, which is the sum of all frequencies, will stay constant. By means of cross correlation signals with different air gaps can easily be aligned. The mean correlation coefficient between all signals is high. The delay caused by travelling through air can easily be removed before signal acquisition, when the speed of sound...
Comparing the transducer source with the laser source shows that the amplitude of the different sources at about the same air gap (47 mm for the transducer source against 46 mm for the laser source) is approximately equal. With the laser source however, the amplitude gets slightly lower with a bigger air gap, while this happens to a lesser extent with the transducer source. In both cases an increase in air gap corresponds to attenuation of some frequencies in the signals. The frequency range of the signals obtained with a laser source is broader than that of the signals obtained with the transducer source. However, filtering learns that much of the high frequency content obtained with the laser source is noise and that the signal is within the kHz range. This high frequency noise might be caused by interference between the laser source and the GCLAD detector. When the air gap is bigger, this effect gets smaller because the laser source is further from the detector. The attenuation of high frequencies with the laser source might in large part be due to this optical interference. In general, higher frequencies attenuating more rapidly means that imaging small structures with a high frequency content requires a small air gap, while larger structures with lower frequency content can be imaged further away from the sample. Although the signal with the laser source is somewhat more noisy the correlation around an arrival is about as high as with the transducer source, being 0.95 and 0.97, respectively.
Chapter 4

Sample positioning

GCLAD is a line detector, which means that the signal is measured over a straight line parallel to the sample surface. In theory the local angle of deflection of the beam does not depend on the position of the sample. When looking at Equation (2.7) and Equation (2.8), all the variables in these equations are independent of the sample position. Furthermore, since the acoustic waves are caused by the same source and travel through the same medium they should be independent of the sample position and the frequency content will stay the same. The eventual waveform is the sum of all frequencies and will therefore not change with sample position. Although the detected waveform should be exactly the same at a random position along the line, it is possible that a certain position gives a better signal. This might be favourable when measuring very small signals and might mean the difference between detecting these signals or not. This chapter describes the use of GCLAD with a transducer source which will have a variable position along the line, with the goal to find out the effect of the sample position on the signal.

4.1 Methods

An overview of the experimental setup is shown in Figure 4.1. A 500 kHz ultrasound transducer is used to generate acoustic waves. A laser diode with a wavelength of 637 nm and a current of 75 mA is focused on a position sensitive photo detector with a frequency bandwidth of 50 kHz to 6 MHz (SD197-23-21-041-ND) by means of a convex lens with a 60 mm focal length. The transducer source is moved in the direction of the arrow, keeping the air gap constant. Distances are measured with respect to the beginning of the laser beam. Signals are processed with Python.
Figure 4.1: Top view of setup for evaluation of the effect of horizontal position of the sample along the line detector. The transducer source is moved in the direction of the arrow. The acoustic wave caused by the transducer propagates through air and displaces the GCLAD probe beam. This displacement is measured by a position-sensitive photo detector.

4.2 Results

The signals obtained are shown in Figure 4.2 and 4.3, which show results for an air gap of 20 mm and 45 mm, respectively. Both figures show that the amplitude is lower when the sample is positioned further away from the laser diode. It is also clear that the signal amplitude is higher in the first half of the line between the laser diode and the detector. It should be noted that in Figure 4.2 the signal amplitude of the closest horizontal position is lower than the following ones. This might be caused by the laser mount blocking part of the acoustic wave. Figure 4.4 shows a plot of the position on the x-axis against the maximum amplitude on the y-axis. This figure shows that the relation between the sample position and the maximum amplitude seems to be approximately linear.
Figure 4.2: Signals of GCLAD measurements at different horizontal positions along the line detector with a 20 mm air gap.

Figure 4.3: Signals of GCLAD measurements at different horizontal positions along the line detector with a 45 mm air gap.

Figure 4.4: Plot of position against maximum amplitude for GCLAD measurements with variable sample position along the line.
4.3 Discussion

Although it is hard to quantify the best position of the sample along the line detector, Figure 4.2 and 4.3 make clear that the signal amplitude is higher in the first half of the line between the laser diode and the detector. This effect can be explained by the bigger distance between the sample and the detector, allowing for a bigger deflection at the point of the detector. This can easily be seen in Figure 2.1, where a bigger \( z_0 \) and a constant \( \theta \) means a bigger deflection at the point of the detector. This also explains the linear nature of the data shown in Figure 4.4. Looking at Figure 2.1 in the theory section and assuming \( \theta \) to be small, the measured signal should indeed be linearly related to the sample position \( z_0 \). This also shows that if more sensitivity is required, the line between the laser diode and the detector can be elongated.

In placing a sample it should be taken into account that it is unfavorable if the acoustic wave is partly blocked by the laser mount. Therefore it is considered best to place the sample as close to the laser as possible, while making sure the acoustic waves will be able to travel without being blocked.
Chapter 5

Evaluation of GCLAD as an integrating line detector

In this chapter a comparison between a GCLAD signal and a line of point measurements made with a Polytec vibrometer is described. Since the Polytec signal is a point measurement it can only be compared to a GCLAD signal when the Polytec signals are taken along the same line as GCLAD. Averaging a Polytec scan covering multiple signals along the line should be equal to one GCLAD signal along the same line. Another important difference between the Polytec and the GCLAD signal is that the Polytec signal is measured directly on the surface of the sample while GCLAD is not. Therefore the GCLAD signal should be corrected for the delay caused by the air gap between the probe beam and the sample surface in order to compare the signals.

Working principle of Polytec vibrometer

A signal measured with a Polytec vibrometer is based on laser Doppler vibrometry. The Polytec measures back-scattered laser light from a vibrating sample, determining the vibrational speed and displacement. The Polytec laser Doppler vibrometer is based on optical interference. An overview of a Polytec vibrometer is shown in Figure 5.1. In the vibrometer a laser beam is split into a reference beam and a measurement beam by a beam splitter (BS1). The second beam splitter (BS2) directs the measurement beam toward the sample. This measurement beam is reflected at the sample surface and propagates to a photodetector via two beam splitters (BS2 and BS3) where BS3 merges the measurement beam with the reference beam. The path length of the reference beam is constant over time, while the path length of the measurement beam depends on the sample. The change of the
optical path length per unit of time is the Doppler frequency shift of the measurement beam with respect to the reference beam, which is measured at the detector. This frequency shift is directly proportional to the velocity of the sample. With laser Doppler vibrometry it is also possible to directly measure displacement by counting the bright-dark interference fringes on the detector [12, 13]. In the experiment described in this section the Polytec vibrometer is calibrated to displacement.

Figure 5.1: Working principle of a Polytec Laser Doppler Vibrometer [1].

5.1 Methods

The experimental setup is shown in Figure 5.2. A rectangular solid phantom of 1% Intralipid®, 1% highly purified agar (A0930-05, USBiological), 0.16 mL India ink and deionized water is used to represent biological tissue. India ink is added to increase absorption of the phantom. Polytec tape is applied to the phantom. This tape is not necessary to measure GCLAD, but it is also applied in GCLAD measurements to compare equal circumstances. A Quanta-ray pulsed ND:YAG laser with a wavelength of 1064 nm, energy of 100 mJ and repetition rate of 10 Hz is used to generate acoustic waves. In both modalities 100 averages are taken per signal. It should be noted that the laser source is positioned slightly off center of the phantom.

For the GCLAD measurement a laser diode with a wavelength of 637 nm
Figure 5.2: Top view of setup for comparison of GCLAD signals with a line of Polytec signals. The laser source generates acoustic waves in the phantom. When reaching the GCLAD probe beam the acoustic waves displace the probe beam which can be measured with a position sensitive detector. Polytec is using Laser Doppler Vibrometry measuring vibrational displacement directly at the phantom surface. The Polytec sensorhead is moved in the direction of the arrow by means of a linear stage. When GCLAD is measured Polytec is switched off and the other way around.
and a current of 85 mA is focused on a position sensitive photo detector with a frequency bandwidth of 50 kHz to 6 MHz (Dulcian, Quarktet) by means of a convex lens with a 60 mm focal length. A laser line filter (Newport 05LF10-633) with a center wavelength of 633 nm is used to make sure any interfering light is filtered out. The GCLAD signal is filtered and amplified by means of a low noise pre-amplifier (SRS SR560) with a highpass filter with cutoff frequency of 300 Hz and a gain of 20. The GCLAD measurement is taken when the Polytec is switched off.

For Polytec measurements a Polytec vibrometer is used with a OFV-505 sensorhead. The Polytec sensorhead is aligned with the line formed by GCLAD. This ensures that Polytec and GCLAD are measured along the same line. Polytec signals are taken every 0.25 mm along a line of 83 mm taking 333 traces in total. These traces are averaged to form the Polytec signal along the line. Polytec measurements are taken when GCLAD is switched off.

Signals are processed and normalized with Python, normalization is necessary since the two systems use different scales. Polytec is calibrated to displacement while GCLAD is not. Signals are aligned by means of cross correlation and the correlation coefficient between the GCLAD and Polytec signal is determined.

5.2 Results

Figure 5.3 shows the normalized GCLAD and Polytec signals. In this figure no correction has been performed for the delay due to air gap between the sample surface and the probe beam of GCLAD. This figure clearly shows the difference in Polytec and GCLAD signals, where Polytec is measured directly at the sample surface, while GCLAD has travel time through air. The time difference between the first arrivals of GCLAD and Polytec is 52.6 µs, which corresponds to an air gap of 18 mm. This air gap matches the initial air gap estimated based on the known speed of sound in the phantom and the air, and the arrival time of the GCLAD signal. In Figure 5.4 correction for this time delay has taken place by means of cross correlation between the signals. This figure shows that the GCLAD and Polytec signals are quite alike. Figure 5.5 shows the same signal in a 50 µs window. The correlation coefficient between the GCLAD signal and the averaged Polytec signal is 0.83 in the first 50 µs after the first arrival.
Figure 5.3: GCLAD and Polytec signal of tissue phantom taken along the same line. GCLAD signal is not corrected for delay caused by air gap between probe beam and sample surface.

Figure 5.4: GCLAD and Polytec signal of tissue phantom taken along the same line. GCLAD signal is corrected for air gap delay.

Figure 5.5: First arrivals of GCLAD and Polytec signal taken along the same line.
5.3 Discussion

Comparing GCLAD with a line of Polytec signals shows that the signals are in good agreement with a correlation coefficient of 0.83. Differences between the GCLAD and the Polytec signal might arise from the fact that with Polytec a finite line with the size of the phantom is measured, while GCLAD might pick up signal from other places along its line. Furthermore, the accuracy of the Polytec signal is determined by the sample density. A denser sampling might give results that better resemble GCLAD. These factors might also affect the correlation between the obtained signals.
Chapter 6

Surface scanning

With GCLAD being a line detector the scanning of an entire surface can easily be performed by moving the detector along the surface. Multiple lines can be detected after each other covering the entire surface. In this way a 2D scan of the surface is obtained when all the lines are taken into account. Ideally, these signals can be reconstructed into a 2D image with image reconstruction methods. This section describes two surface scans performed with GCLAD, where the two scans measure different orientations of the object placed in a phantom. Image reconstruction methods will be discussed in Chapter 7.

6.1 Methods

A top view of the experimental setup is shown in Figure 6.1, a front view of the setup is shown in Figure 6.2. The GCLAD setup is placed on the bench in vertical position making it possible to scan the surface by moving the object on a linear stage from left to right. A rectangular solid phantom of 1% Intralipid®, 1% highly purified agar (A0930-05, USBiological), and deionized water is used to represent biological tissue. A tube with a wall thickness of 0.56 mm and a diameter of 5.6 mm is filled with Epolight 2057 dye, which is designed to absorb infrared. A laser diode with a wavelength of 637 nm and a current of 85 mA is focused on a position sensitive photo detector with a frequency bandwidth of 50 kHz to 6 MHz (Dulcian, Quarktet) by means of a convex lens with a 60 mm focal length. A laser line filter (Newport 05LF10-633) with a center wavelength of 633 nm is used to make sure any interfering light is filtered out. The GCLAD signal is filtered and amplified by means of a low noise pre-amplifier (SRS SR560) with a highpass filter with cut-off frequency of 300 Hz and a gain of 20. A Quanta-ray pulsed
ND:YAG laser with a wavelength of 1064 nm, energy of 300 mJ and repetition rate of 10 Hz is used to generate acoustic waves. A tissue phantom will be scanned along the surface by moving it in the direction of the arrow. By only moving the tissue phantom the alignment between the laser source and the GCLAD receiver remains constant. The experiment is controlled, and signal processing is performed, with PLACE [10]. Two different arrangements are scanned; a phantom with a horizontally positioned tube and a phantom with a vertically positioned tube.

**Figure 6.1:** Top view of setup used for 2D surface scan with GCLAD. The laser source generates acoustic waves in the phantom. These waves displace the GCLAD beam which is measured with a position sensitive detector. The surface is scanned by moving the phantom in the direction of the arrow.

**Figure 6.2:** Front view of setup used for 2D surface scan with GCLAD. The laser source coming from behind the phantom generates acoustic waves in the phantom. These waves displace the GCLAD beam which is measured with a position sensitive detector. The surface is scanned by moving the phantom in the direction of the arrow.

### 6.1.1 Horizontal tube

The horizontal tube is placed \( \sim 22 \) mm under the surface, as shown in Figure 6.3. The tube is placed closest to the laser source side. The surface is scanned by detecting a line every 0.25 mm taking a total of 282 traces, scanning a total distance of 70.25 mm. The air gap between the GCLAD probe beam and the phantom surface is \( \sim 7 \) mm. For each trace 64 averages are taken.
6.1.2 Vertical tube

The vertical tube is placed \(\sim 17\) mm under the surface, as shown in Figure 6.4. The tube is placed closest to the laser source side. The surface is scanned by detecting a line every 0.25 mm taking a total of 294 traces, scanning a total distance of 73 mm. The air gap between the GCLAD probe beam and the phantom surface is \(\sim 17\) mm. For each trace 200 averages are taken.

![Figure 6.3: Placement of horizontal tube, \(\sim 22\) mm below surface. Top: top view, bottom: front view.](image1)

![Figure 6.4: Placement of vertical tube \(\sim 17\) mm below surface. Top: top view, bottom: front view.](image2)

6.2 Results

The results of the surface scan with the horizontally positioned tube are shown in Figure 6.5 and 6.6. These figures show a contour plot showing the amplitude of all traces and a single trace, respectively. In these figures the delay caused by air gap is removed, so the figures display the signals as if they were taken at the phantom surface. The contour plot shows three visible events. The photoacoustic wave of the tube is the first to arrive, after that the laser ultrasound wave of the phantom surface comes in. The third wave is caused by an acoustic wave arising at the tube surface, then bouncing backwards to the phantom surface, to bounce towards the receiver after that. These three events are annotated in the figure. The single trace shown in Figure 6.6 also shows these three events. The laser ultrasound wave is hard to see in a single trace, but it clearly shows in a contour plot. It should be noted that a strong signal is observed in the first 20 \(\mu s\) of the plots, this is part of the trigger noise that is not trimmed of when correcting for the air gap.
Figure 6.5: Contour plot of surface scan with GCLAD, horizontal tube.

Figure 6.6: Single trace of surface scan with GCLAD, horizontal tube.
For the vertically positioned tube figures are obtained in the same way. The contour plot in Figure 6.7 shows the same three events as were observed with the horizontally positioned tube. These events are annotated in the figures. The crossing stripes at the bottom of the figure are caused by reflections of the edges of the phantom. This figure shows that the photoacoustic wave of the tube has a hyperbolic nature. This is caused by the fact that the vertical tube is further away from the receiver when closer to the phantom edges. Figure 6.8 shows a single trace taken from the middle of the stream to make sure all three events are clearly visible. Also in this figure the three events are visible, however they are difficult to distinguish because they are closer to each other. Again, in the contour plot they can be distinguished quite well.

![Contour plot of surface scan with GCLAD, vertical tube.](image)

**Figure 6.7:** Contour plot of surface scan with GCLAD, vertical tube.
6.3 Discussion

The results presented in the previous section show that GCLAD has good potential for 2D scanning of biological objects. Both in the horizontal arrangement and the vertical arrangement the expected signals are clearly visible. The photoacoustic wave of the tube is more clearly in the vertical arrangement. This is explained by the vertical tube being positioned shallower below the surface. Therefore more source laser light is reaching the tube, leading to a stronger signal. The laser ultrasound wave of the phantom is less clear in the horizontal arrangement. However, it is more clear at the left side of the contour plot of Figure 6.5. It is possible that an air crack is present around the portion of the tube that has lower amplitude. This air crack can be the result of placing the tube in the phantom after the phantom was set. Because of the size of the tubes and the fragility of the phantoms, cracks arise quite easily. This can be prevented when the tube is embedded in the phantom while it is setting. The contour plot of the horizontally positioned tube shows some reverberations after the phantom LU wave as well. These might have been caused by reflections between the tube and the surface or within an air crack.
In addition, Figure 6.5 shows some events that are not completely horizontal. This might be caused by the tube not being placed exactly straight into the phantom or the phantom not being exactly perpendicular to the GCLAD receiver. In future research, more attention should be paid to that.

The contour plot of the vertically positioned tube looks cleaner than the one of the horizontally positioned tube. This is due to the higher amount of averages taken in the vertical arrangement. This higher amount of averages will have a positive effect on the signal to noise ratio, giving a cleaner signal. The results also show that a contour plot gives more insight in the occurring events than a single trace. Although some events are hardly distinguished in a single trace, they are very clear in a contour plot because of their continuous presence.
Chapter 7

Reconstruction

Detection and reconstruction play an important role in photoacoustic imaging. The image quality and imaging speed are mainly determined by the detector geometry and the reconstruction algorithm [14]. Reconstruction for photoacoustic imaging is based on the photoacoustic inverse problem. In this approach it is aimed to get the absorption density inside the sample by measuring the acoustic pressure signals outside of the sample [15]. This chapter will outline a literature search on reconstruction methods using line detection.

7.1 Why use line detectors

Most reconstruction algorithms are based on the assumption that point-like detectors are used. While these reconstruction algorithms assume a point detector, in practice the detector has a finite size. This limits the spatial resolution of the images by the size of the detector and creates a blurring of the reconstructed image. Moreover, it is difficult to manufacture small detectors and they generally have poor sensitivity [16]. Resolution and blurring problems might be overcome by the use of large, integrating detectors such as proposed by Burgholzer et al [17]. These detectors have dimensions larger than the maximum dimension of the object which gives a signal that is an integral of the energy density distribution over an area defined by the shape of the detector. In that case the spatial resolution is only limited by the bandwidth of the detector in the direction of the line. The advantages of using an integrating detector include a constant, high resolution and the possibility to use standard reconstruction algorithms based on the Radon transform [16]. Integrating detectors can be one- or two dimensional, for example, planar- or line detectors. Planar detectors as proposed by Burgholzer
et al. show promise, however in order to obtain a 3D image, a complicated scanning motion is required [18]. To avoid complicated scanning motions it is easier to implement line detectors. With line detection rotation about a single axis only is required to create a full 3D reconstruction.

### 7.2 3D reconstruction with line detectors

Although the use of integrating line detectors makes it easier to acquire signals for a 3D image, the reconstruction becomes somewhat more complicated [19]. A 3D reconstruction using line detectors can be divided into two parts. In the first part 2D projection images are obtained and in the second part a 3D pressure distribution is calculated. The 2D projection images can be obtained by scanning across the surface of the object, reconstructing the initial pressure distribution [18]. Algorithms which can be used for this purpose include frequency domain algorithms such as shown in [20] and [21], time domain algorithms such as backprojection, as shown in [20] and [22], iterative algorithms as shown in [20] or time reversal algorithms such as shown in [15]. Paltauf et al. evaluated 2D reconstruction algorithms (frequency domain algorithms, time domain algorithms and iterative algorithms) and concluded that image quality is similar for all algorithms. However, frequency domain algorithms offer faster reconstruction speed while time domain algorithms allow for correction procedures [20].

The 2D projection reconstruction can be repeated for multiple directions, forming a 3D array of initial pressure distributions which can be reconstructed to the initial 3D pressure distribution, for example by an inverse Radon transform [18, 23]. The first 3D images created with a line detector are published by Grün et al. and show 3D images of a bristle knot and an ant. This research shows promising results for the use of line detectors in biomedical imaging [23].

In summary, in order to reconstruct a full three-dimensional GCLAD image the following steps have to be performed:

1. Measure multiple GCLAD signals, scanning a surface
2. Use 2D algorithm to determine initial pressure distribution of surface
3. Measure surfaces 360 degrees around the object
4. Create 3D array of all initial pressure distributions
5. Apply preferred inverse reconstruction algorithm on 3D array
Chapter 8
Discussion and Conclusion

In this section the most important points of the research will be outlined and discussed. After that a conclusion will be drawn in order to answer the question whether GCLAD has potential of being a detector for biomedical applications.

8.1 Discussion

Research into the effect of the air gap between the probe beam and the sample surface showed that only slight attenuation took place. Moreover, signals could clearly be detected with an air gap of over 10 cm. This gives GCLAD great potential for being a detector in biomedical applications, where the detector can be placed several centimeters away from the sample surface. Being a fully non-contact detection method, GCLAD shows great potential for medical imaging in situations where contact is troublesome. Furthermore, the delay caused by traveling through air can easily be predicted when the air gap is known. This creates the possibility to remove the delay before signal acquisition, acquiring the signals as if they were measured on the sample surface. It should be noted that the air gap must be determined very precise for this to work. A small error in the air gap will create a big error in the arrival times, because of the relatively low speed of sound in air. The frequency content of GCLAD signals is within the kHz range and no dispersion is observed. The waveform is constant no matter what the air gap or the position of the sample along the detection line.

Placement of the sample is an important aspect of measuring with GCLAD. The results showed that the closer sample is to the laser side, the higher the
signal. Also, sensitivity can easily be increased by elongating the line between the laser and the detector, thereby creating a longer length over which the probe beam can deflect. This might mean the difference between detecting or not detecting certain objects, which can be an important aspect in biomedical imaging as well. Experiments performed with objects mimicking the properties of biological tissue showed that these can very well be detected with GCLAD. Furthermore, the results are reproducible and scans require little time.

A surface scan with GCLAD can easily be performed, without much data points needed and in relatively little time. When measuring the same surface with a point detector, signal acquisition would be a lot more complex and would take longer. A comparison between GCLAD and Polytec also points out that the GCLAD line detector gives about the same result as a line of point detectors, but in a shorter amount of time. Results of the surface scans show that GCLAD has great potential for 2D imaging of biological tissue. Although a contour plot gives good insight in the events happening within the sample, an image reconstruction will better point out how big the potential of GCLAD is. The data acquired with the surface scans should be suitable for reconstruction.

The energy of the laser source currently used is quite high. The laser source used for these experiments can become suitable for biomedical applications when the energy is kept sufficiently low, however it is made for high energy applications. Furthermore, for photoacoustic imaging, other excitation wavelengths might be required in order to pick out specific molecules of interest.

8.2 Conclusion

Overall it can be concluded that GCLAD shows potential for being a detector for biomedical applications. It shows only slight attenuation with a big air gap, sensitivity can be increased if needed and signal acquisition is easy. Comparison of GCLAD with line-integrated data of a commercial laser vibrometer point detector shows an 83% agreement. One of the biggest advantages is the option to detect in a fully non-contact way. Nevertheless, future research is required to fully exploit the potential of GCLAD as a biomedical imaging modality.
Chapter 9
Recommendations

GCLAD shows potential for being a detector for biomedical applications. However, further research is required to find out the strengths and weaknesses of GCLAD as a detector for biomedical imaging. Therefore, some recommendations for future research are proposed in this section.

As mentioned in the previous chapter a small error in air gap creates a big error in arrival time because of the relatively low speed of sound in air. Therefore, it would be recommended to do a short air gap scan before each surface scan to determine the absolute air gap with help of the air gap scan. This could be performed as soon as two translational stages are available to the lab. After that it is also recommended to incorporate the removal of the delay due to air gap in the signal acquisition program. In this way, no trimming is required, trigger noise is eliminated and signal processing can be performed as if signals were measured at the phantom surface.

In addition, it might be convenient to know the actual speed of sound in the phantom to be measured. In the current approach an assumption about this speed of sound has been made. When knowing the real speed of sound, waves can be annotated more easily. Therefore, it is recommended to determine the speed of sound of the phantom after making it.

Another way to make it easier to annotate the waves in the data is to make sure the phantom as well as the tubes within it are positioned exactly straight. To be able to position the tubes straight into the phantom without causing cracks it is recommended to design a phantom mold where the tubes can be embedded in the phantom while it is setting. After that, more attention should be paid to placing the phantom straight with respect to GCLAD.
To get more insight in the absolute displacement of the probe beam it might be possible to link the Polytec amplitudes, which are absolute displacements, to the GCLAD amplitudes, which are measured in Volts. However, it should be taken into account that the amplitude of the GCLAD signal is dependent on the air gap and the positioning of the sample. Although attenuation is small, the air gap can be a factor in determining the absolute displacement. Therefore, it might be necessary to find a relationship between the amplitude and the air gap and to make sure the exact position of the sample is known.

Due to time limitations no actual reconstruction of the 2D data could be performed. However, this will surely give good insight in the capabilities of GCLAD as an imaging modality for biomedical applications. Therefore it is strongly recommended to try a reconstruction on the surface data obtained.

Finally, to really exploit the potential of GCLAD for being a detector for biomedical applications it is recommended to switch to a laser that is specially suitable for this type of imaging.
Bibliography


