Photoacoustic blood vessel detection during surgical laser interventions

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Abstract: This paper presents a discussion about the potential of photoacoustics with regard to its application in surgical assistance during minimally invasive, laser assisted interventions. Aim of the work is the detection of obscured large blood vessels in order to prevent unintentional dissection. Based on spectroscopic investigations of the target tissue (liver), a wavelength for the photoacoustic excitation laser was chosen with respect to a high absorption contrast between the vessel and the surrounding liver tissue. An experimental setup featuring a simple liver model is created. Preliminary results show, that vessels with a diameter of 2 mm can be detected up to a distance of 1 mm from the treatment fibre. It is shown, that detection of acoustic waves induced inside liver is feasible over distances higher than 10 cm.

Kewords: Photoacoustics, blood vessel detection, minimally invasive, laparoscopic, partial liver resection, treatment control

1 Introduction

Present-day interventional surgery methods get more and more specific and spatially precise. Advanced treatment lasers allow to perform tissue effects, -sections and -ablation with very high precision. Since a few years, treatment lasers with an adequate performance in the NIR range are available, which allow a flexible energy transport using optical fibres. Thus minimally invasive, laser-assisted interventions become possible. Those interventions are advantageous for the patient. Reduced post-operative pain and lower doses of analgesics lead to a shorter mobilization time which in turn decreases the risk of thrombosis or embolism [1]. Despite these advantages, a minimally invasive intervention also means a higher risk due to the limited view for the surgeon. Particularly in liver and kidney surgery (e.g. laparoscopic, laser-assisted partial resection), unintentional dissection of large blood vessels means an extraordinary risk. If a large blood vessel is dissected, an open emergency operation may be required. To avoid this risk, the availability of a real time treatment control system is demanded. As a first approach, this device would give a feedback to the surgeon before a large blood vessel is damaged during the cutting or stop the treatment laser in a critical case. A conceivable method on which this technique could be based on is photoacoustics.

2 Methods

Photoacoustic methods have become very popular in recent years. Commonly they are used for imaging small structures like subcutaneous vascular networks [2]. However, imaging using photoacoustic techniques requires high investment and significant technical effort. Since the basic technical effort for the generation and detection of photoacoustically induced ultrasound waves is relatively low, a simple and therefore robust real-time photoacoustic feedback system for blood vessel detection is possible.

The photoacoustic principle is shown in figure 1. For the generation of photoacoustic signals, pulsed laser light is brought to the target tissue via an optical fibre. When the pulse energy is partly absorbed e.g. by hemoglobin or melanin in a depth z, a local temperature rise and thermal expansion (and subsequent contraction) is the consequence. Hereby, a pressure wave is induced which is propagating through the surrounding tissue and can be detected by an ultrasound detector.

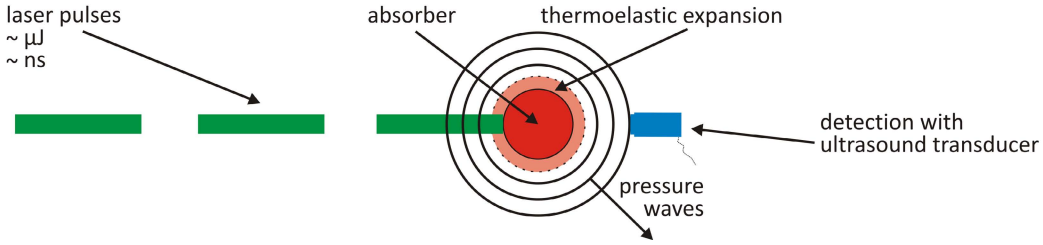

Figure 1: The photoacoustic principle

Besides tissue-specific parameters, the local pressure rise is influenced by the absorbed energy, which depends on the fluence at the location of absorption and the absorption coefficient of the particular tissue [3, 4]:

$$P_0(z) \propto (\beta {c_s}^2/C_p)\mu_a F(z) = \Gamma \mu_a F(z) \quad (2.1)$$

$$\propto \Gamma \mu_a F_0 \; exp(-\mu_{eff} z) \quad (2.2)$$

Here, β is the thermal expansion coefficient, C_p for the heat capacity at constant pressure, c_s is the speed of sound and F_0 represents the fluence at the tissue surface. The Grüneisen parameter Γ combines the expression $(\beta {c_s}^2/C_p)$. The effective attenuation coefficient μ_{eff} is a combination of the absorption coefficient μ_a and the scattering coefficient μ_s: $\mu_{eff} \approx \sqrt{3\mu_a(\mu_a + \mu_s \cdot (1-g))}$ [5]. The anisotropy factor g is about 0.9 for liver tissue and visible light [6]. During one laser pulse, heat diffusion and stress relaxation should be negligible, which is referred to as thermal and stress confinement [4]. For most biological tissues, nanosecond pulses can be used to fulfill these conditions.

When pressure waves are induced, they propagate through the tissue and can be detected at its surface, e.g. by an ultrasound transducer. The shape, amplitude, duration and therefore frequency of the waves depend on the dimensions, geometry, optical and acoustical properties of the absorber [7]. The measured electrical signal is additionally influenced by the acoustic attenuation of the tissue and the transducer itself.

Following the above considerations, aside from a high fluence $F(z)$, a high and selective absorption of the target tissue will improve the signal to noise ratio of photoacoustic measurements. The absorption coefficient μ_a depends on the wavelength. Thus the deposited energy density in the target tissue can be increased by an appropriate choice of the wavelength. Spectroscopic investigations (see fig. 1) show, that due to the high absorption contrast between blood and liver tissue, the wavelength of $\lambda = 532\,\text{nm}$ is an appropriate choice among the available laser sources. Further measurements have shown that black ink (Pelikan 4001, *brilliant-schwarz*), diluted in water in a ratio of 1:5.7, has an absorption coefficient very similar to blood at a wavelength of 532 nm.

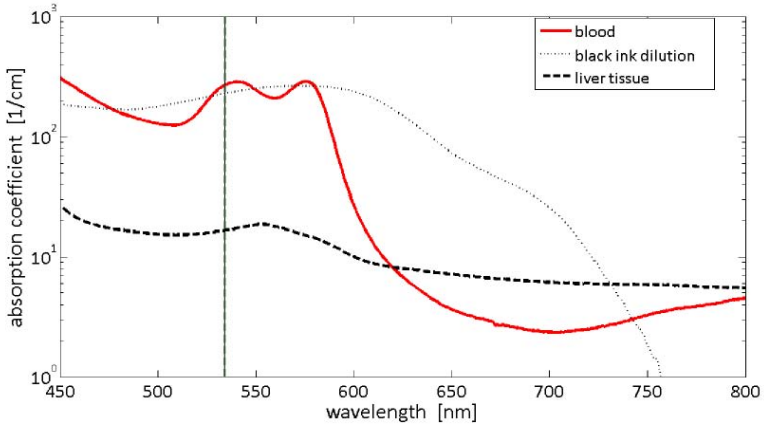

Figure 2: Spectroscopic measured absorption spectra of blood, liver tissue and ink. A wavelength of 532 nm is an appropriate choice with regard to a selective excitation of blood in liver tissue.

For the intended application, it is important to consider the distribution of the exciting laser light within the tissue. Based on equation (2.2) and the spectral data shown in fig. 2, absorption and thus pressure wave sources

are expected throughout the entire liver when irradiated. Within blood vessels, where the absorption coefficient is higher by a factor of approximately 15, the amplitude of the measured transients is expected to be significantly higher (see figure 3). Within this simplified considerations, scattering is not taken into account.

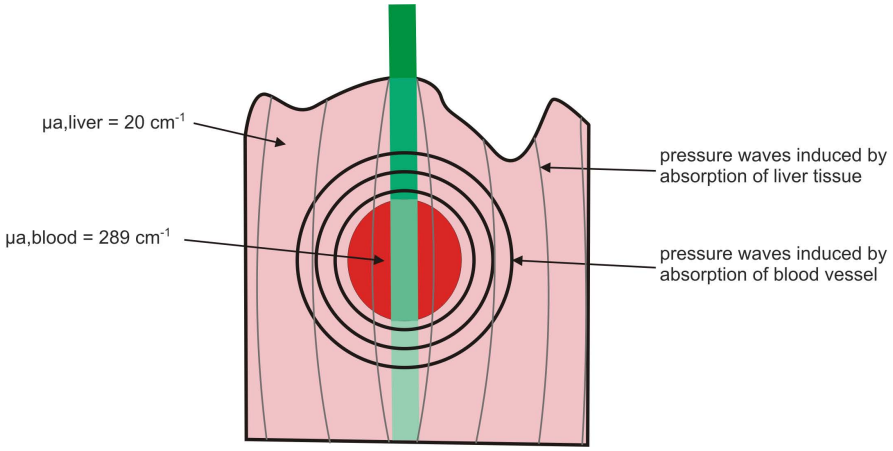

Figure 3: Absorption and photoacoustic signal origins in irradiated liver tissue

Consideration of the intended application brings up the following basic questions: **How deep** can blood vessels be detected inside liver tissue photoacoustically and **up to which distance** from the source the detection of the acoustic waves is feasible?

Experimental setup
For the investigation of the above mentioned basic questions, an experimental setup is created which is shown in figure 4. Using this setup, acoustic waves can be induced optically by irradiating a blood vessel phantom (diluted ink in a polyethylene tube, 2 mm diameter), which is immersed in water. For excitation, a frequency-doubled Q-switched Nd:YAG laser (CryLas Laser Systems, Berlin, Germany, FTSS 355-50, wavelength 532 nm, pulse duration 1 ns, repetition rate 10 Hz) is used. The radiation is coupled into a fiber with a diameter of 200 μm. At the distal fiber end, a waterproof collimating unit (f= 4 mm) is adapted, leading to a collimated beam of about 1mm in diameter. The end-of-fibre energy amounts to 25 μJ. A single element piezoelectric transducer serves as a detector. Both, the excitation fiber and the transducer can be moved independently and reproducibly. The vessel phantom is initially surrounded by water. By adding ink to the surrounding water, the absorption contrast of vessel and surroundings can be tuned to the conditions in liver.

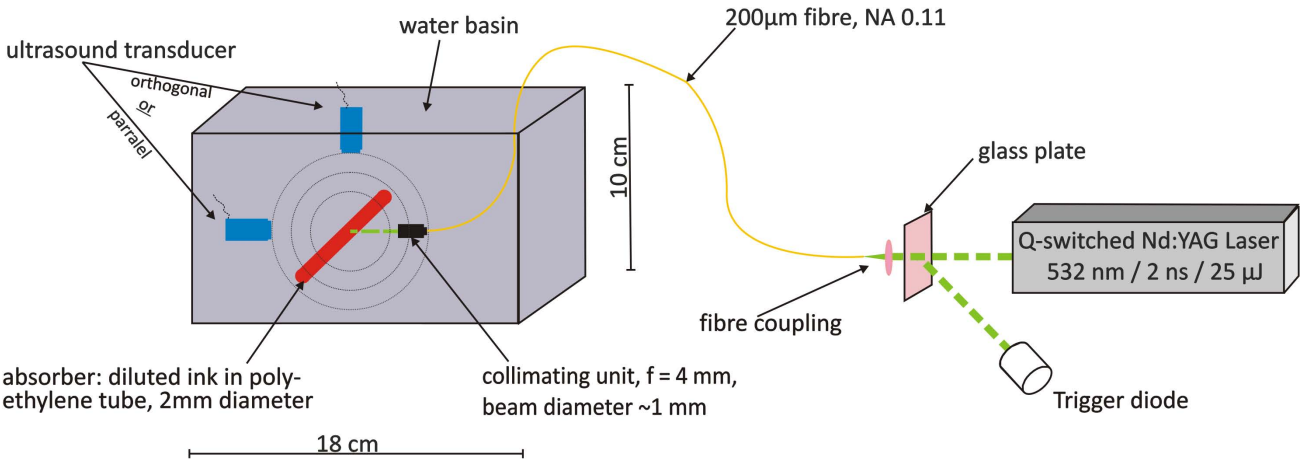

Figure 4: Experimental setup for the generation and detection of photoacoustic signals

Measurements
To demonstrate the general approach to photoacoustical blood vessel detection, the vessel phantom in the basin, immersed in water, is crossed five times within ten seconds by moving the excitation fiber orthogonal to the phantom as shown in figure 5 (left). The measurement is taken at a repetition rate of 10 Hz. The measured transient data is processed and evaluated amplitude-based. Figure 5 (right) shows the result data plotted over time. Each peak represents on vessel crossing.

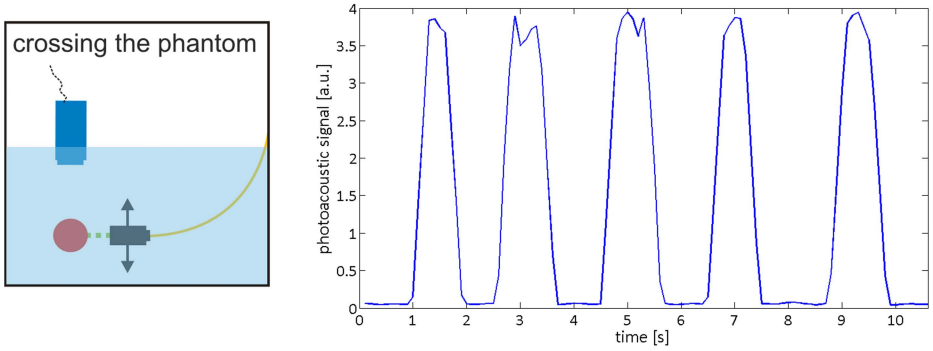

Figure 5: Left: In this measurement, the vessel is crossed five times within ten seconds. The data is processed and plotted over time (right). Each peak represents one vessel crossing.

For the investigation of the maximum vessel detection depth, the absorption contrast within the phantom is tuned to the condition in liver. The excitation fiber is moved towards the vessel phantom (immersed in ink dilution with an absorption coefficient according to the absorption of liver tissue), starting at a distance over 3 mm to a distance of 0.5 mm (measurement A). As a reference, the measurement is repeated without a phantom (measurement B). By dividing the results of measurement A by the results of measurement B, the relative photoacoustic detection contrast is calculated, which is shown in the right part of figure 6.

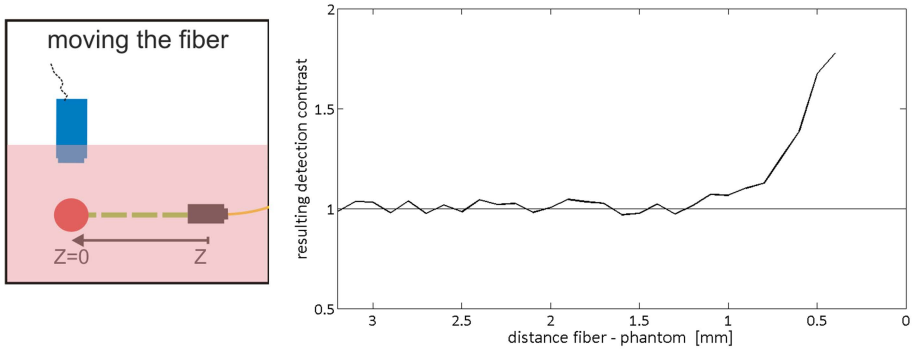

Figure 6: Left: In this measurement, the absorption contrast is tuned to the conditions inside liver. The excitation fiber is moved towards the vessel phantom. In addition, a reference measurement without a phantom is taken. The data is processed and the resulting photoacoustic detection contrast is plotted over distance (right).

The results show, that the photoacoustic detection contrast is rising at a distance of 1 mm, when approaching a blood vessel phantom. This can be taken as criterion for a detected blood vessel.

Concerning the intended application, it is important to measure the acoustic attenuation in the tissue. In the first part of the measurement (see figure 7, left), the vessel phantom immersed in water is excited at a fixed certain distance from the fiber. The transducer is placed in line with the phantom and is moved away from it, starting at 0.5 cm up to a distance of 10.5 cm. In the second part of the measurement (see figure 7, right), a

phantom is put on the right side of a piece of bovine liver and is irradiated. The induced acoustic waves are detected on the opposite side of the liver. The liver is then cut slice by slice for decreasing the propagation distance. The data of both measurements are processed and normalized to the lowest distance. Accordingly, the result of this measurement show the relative acoustic attenuations of both water and bovine liver tissue. The results are shown in figure 8.

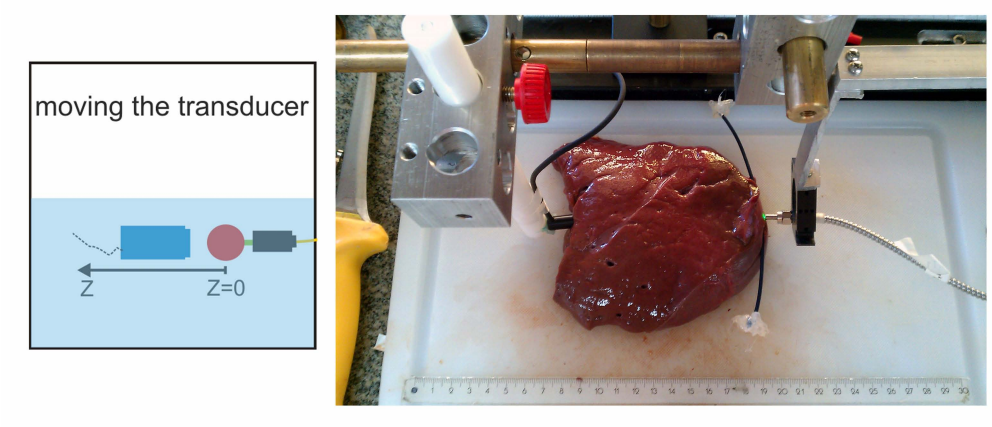

Figure 7: Left: The transducer, parallel to the irradiated vessel phantom, is moved away from it. Right: A vessel phantom is added to to a piece of bovine liver. The acoustic waves are detected on the opposite side. The liver is then cut slice by slice in order to make the propagation distance shorter.

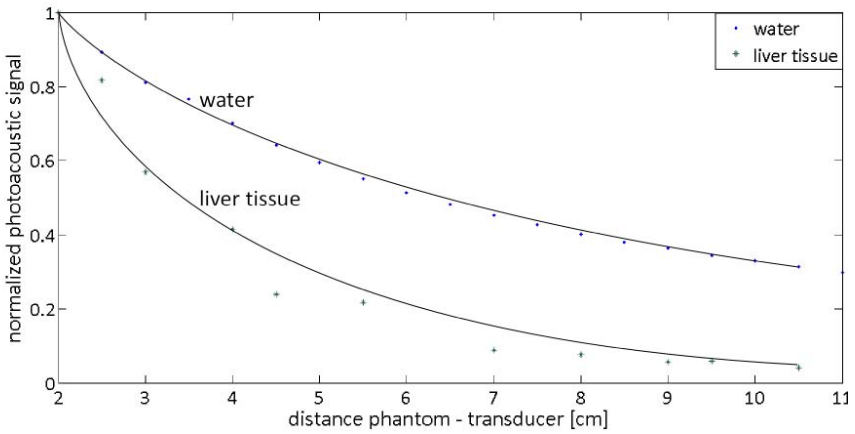

Figure 8: Results of this measurement: The relative acoustic attenuation of both water and liver tissue

The results of this measurement show that the acoustic attenuation of liver tissue is much higher than in water. Nevertheless, acoustic waves could be detected from a distance higher than 10 cm. The signal to noise ratio is still greater than 5 at the highest distance, regardless of the relatively low excitation energy of 25 μJ.

As a last measurement, a vessel phantom is placed about 0.5 mm underneath the surface of a piece of bovine liver. The liver tissue is irradiated at three different spots: At the spot, where the phantom is located behind and at two spots above and below as a reference. Detector data is acquired for five seconds. A picture of the measurement and the results are shown in figure 9.

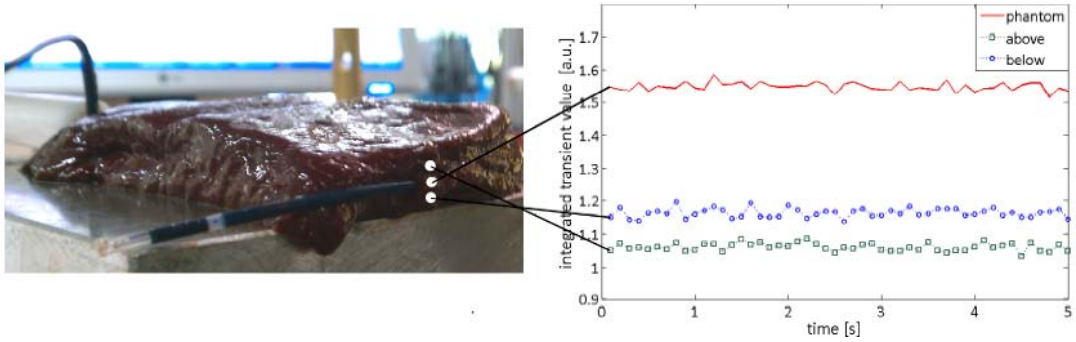

Figure 9: Left: picture of the measurement. Right: the amplitude of the photoacoustic signal is significantly higher, in case there is a vessel phantom underneath the irradiated liver surface spot. This proofs the applicability of photoacoustic blood vessel detection under laboratory conditions.

3 Discussion

As a preliminary result, the feasibility of photoacoustic blood vessel detection inside different liver models could be verified. Spectroscopic investigations have shown a high absorption contrast of about factor 15 between full blood and full liver tissue. Due to the higher absorption of blood, the photoacoustic signal rises when the distance of the excitation fiber to the vessel phantom is <1 mm. This can be taken as a criterion for blood vessel detection. Since the absorption condition is fixed at the used wavelength of 532 nm, this limitation is systematic.

Furthermore, it was shown that detection of acoustic waves induced inside liver tissue is feasible over distances greater than 10 cm. The SNR was still > 5 at the highest distance, using a piece of bovine liver. This result shows the general feasibility of detection of acoustic waves generated inside the liver at a remote location. The excitation energy was about 25 μJ in that case, which is relatively low. The measurement will be repeated using a stronger laser and a bigger piece of liver, in order to concretize the upper detection distance.

In an ex vivo experiment, the practicability of photoacoustic blood vessel detection under laboratory condition was shown. It is possible to find the location of a vessel phantom which is about 0.5 mm underneath the irradiated surface due to the higher photoacoustic signal, compared to the irradiated surface spots without a phantom underneath.

Future measurements will be focused towards a better understanding of the acoustic responses of irradiated blood and liver tissue. The use of a broadband transducer will enable investigations of the frequency spectra of the photoacoustic signals. Potentially, there will be more criterions for differentiating between blood vessels and liver tissue in the frequency domain of the photoacoustic signals. In future experiments, scattering will be taken into account. Numerical simulations will be created in order to improve the used components.

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