

Photoacoustic Image Guidance for Laser Tonsil Ablation: Approach and Initial Results

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ABSTRACT

Tonsillectomy, one of the most common surgical procedures worldwide, is often associated with postoperative complications, particularly bleeding. Tonsil laser ablation has been proposed as a safer alternative; however, its adoption has been limited because it can be difficult for a surgeon to visually control the thermal interactions that occur between the laser and the tissue. In this study, we propose to monitor the ablation caused by a CO₂ laser on ex-vivo tonsil tissue using photoacoustic imaging. Soft tissue’s unique photoacoustic spectra were used to distinguish between ablated and non-ablated tissue. Our results suggest that photoacoustic imaging is able to visualize necrosis formation and calculate the necrotic extent, offering the potential for improved tonsil laser ablation outcomes.

Keywords: Photoacoustic Imaging, Laser Ablation, Tonsil Surgery

1. INTRODUCTION

Tonsillectomy is one of the most frequently performed procedures worldwide, with over 500,000 annual procedures in the United States alone.¹ The standard surgical technique involves dissecting the tonsils and the surrounding capsule (refer to Fig. 1), creating bilateral wounds that normally heal over 1-3 weeks. Despite being routinely performed, tonsillectomy is not without risks: A significant number of patients (up to 15% according to data reported in the literature²) experience postoperative hemorrhage (PTH), which can obstruct breathing and be fatal if not controlled promptly. PTH is the leading cause of emergency hospital readmission among tonsillectomy recipients, and it creates a substantial financial burden on patients and healthcare systems alike.³

A potentially safer alternative to tonsillectomy was proposed by Volk et al. in Ref. 4. In this procedure, the tonsils are thermally coagulated with a fiber-based diode laser, setting off an involution process that leads to complete tonsil regression (i.e., disappearance) in 3-6 weeks. The viability of this approach was demonstrated in an in vivo canine model (n=5). Because no tissue is excised and no wounds are created, laser tonsil ablation virtually eliminates the risk for PTH and its associated morbidity and mortality. Despite these benefits, Volk and colleagues’ approach was never translated to practice due to challenges in the control of the heat penetration into the tissue, and the potential risk for thermal injury to the anatomy surrounding the tonsils.⁵ We hypothesize that if physicians had access to a technology capable of monitoring the state of the tissue during the procedure, this would enable them to prevent tissue overheating; furthermore, it would also provide them with an objective endpoint to halt the procedure, i.e., laser application would be stopped once a sufficient level of tissue coagulation were detected.

In this paper, we propose a method to intraoperatively monitor laser tonsil ablation. Our approach is based on photoacoustic (PA) imaging, a hybrid imaging modality that combines the high penetration of ultrasound (US) imaging with high optical contrast.⁶ PA imaging uses nanosecond laser pulses to create pressure waves inside the tissue – these pressure waves are then picked up by a US transducer, enabling centimeter-depth imaging. One

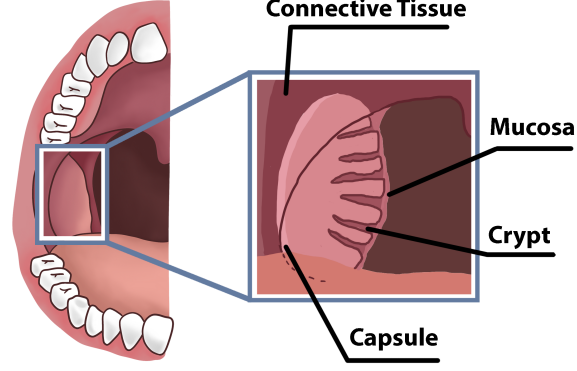


Figure 1. The palatine tonsils are masses of lymphoid tissue located at the back of the oral cavity. When infected, these lymph nodes can grow considerably in size, restricting the upper airway and making it problematic to eat and breathe normally. Traditional surgical approaches to remove the tonsils involve resecting the tonsils and their surrounding capsule.

of the benefits of PA imaging is that it can be used to characterize the absorption spectrum of biological tissue within a prescribed range of wavelengths. In previous work, Gao *et al.*⁷ have shown that by tracking changes in the tissue absorption it is possible to estimate the degree of coagulation of soft tissue subject to radiofrequency (RF) ablation. The goal of our research is to develop a similar technology for laser tonsil ablation. Unlike this previous work, where laser excitation and acoustic sensing were performed from the same side of the tissue, the new approach we propose herein is to detect acoustic signals from the opposite side. Clinically, this approach would be implemented by placing an ultrasound probe on the neck.

2. METHODS

Fig. 2 illustrates the envisioned technology and clinical setup. Following the approach described in Ref. 4, tonsil ablation is performed by irradiating the tissue with a laser beam delivered by means of a flexible optical fiber. The fiber is scanned over the tonsil tissue in noncontact mode. PA imaging is implemented using (a) an ultrasound transducer positioned over the neck of the patient and (b) a laser beam (separate from the one used for treatment).

2.1 Mapping of the Ablated Region Based on Photoacoustic Imaging

In general, biological tissues exhibit unique PA spectra based on their optical absorption characteristics. Previous work by Gao *et al.*⁷ has shown that fresh, non-ablated soft tissue presents a characteristic “peak” in the PA spectrum between 700 and 850 nm (see Fig. 2(c)) and that this peak disappears after ablation. Let us define the (known) absorption spectrum of non-ablated tissue at wavelength w as $\mu_{a,(N-Ab,w)}$. Analogously, $\mu_{a,(Ab,w)}$ denotes the absorption of ablated tissue. With these definitions, we can estimate the concentrations of ablated and non-ablated material at any location within the tissue by solving the following minimization problem:

$$\arg \min_{m_{1,2,\dots,M}} = \left\| \sum_{w=1}^W (p_w - (m_{Ab}\mu_{a,(Ab,w)} + m_{N-Ab}\mu_{a,(N-Ab,w)})) \right\|^2 \quad (1)$$

where p_w is the PA signal measured at wavelength w , and m_{Ab} and m_{N-Ab} are the estimated concentrations of ablated and non-ablated tissue, respectively. Finally, W is the total number of wavelengths used to “probe” the tissue. To quantify the degree of coagulation at any location within the tissue, it is convenient to calculate the Necrotic Extent (NE), which is defined as $NE = \frac{m_{Ab}}{m_{Ab} + m_{N-Ab}}$. NE ranges between 0 and 1, with 0 denoting non-ablated tissue, and 1 indicating complete ablation.

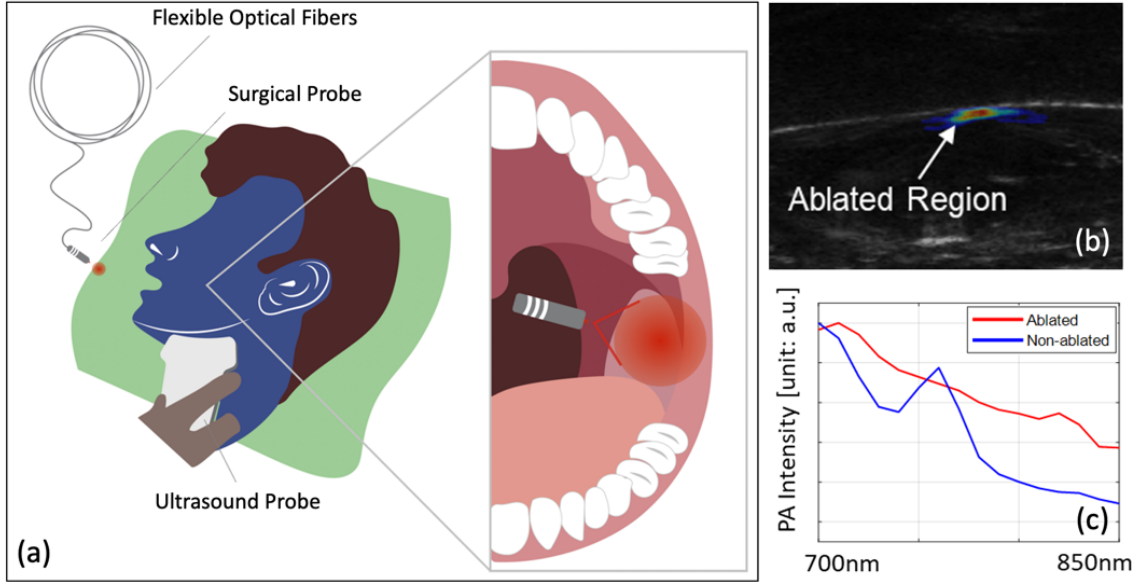


Figure 2. Technology concept: (a) Laser tonsil ablation is performed with a surgical probe carrying optical fibers. An ultrasound probe (US) is positioned on the neck to enable photoacoustic (PA) imaging. (b) Sample tomographic PA image showing the extent of the ablated tissue; Intraoperatively, images like this one will enable physicians to monitor the progression of the procedure and prevent overtreatment. (c) Difference in absorption spectrum between ablated and non-ablated tissue (reproduced from Ref. 7); such a difference can be captured with PA imaging, enabling us to build ablated region maps like the one shown in (b).

2.2 Experiments

To verify the viability of monitoring the ablated region using acoustic and laser probes on opposite sides, we performed a benchtop experiment as illustrated in Fig. 3. An ex vivo tissue specimen was irradiated by a CO₂ laser, the Sharplan 30C (Lumenis Ltd., Israel) – the beam was delivered by means of a flexible waveguide. For this initial proof-of-concept study, we used porcine liver tissue. For the sake of repeatability, scanning of the laser fiber was performed with a Panda robotic arm (Franka Emika GmbH, Germany). We performed a total of 3 scans, each lasting 72 seconds, heating the tissue to about 80 °C.

To implement PA imaging, we used a side-shooting US probe (Philips ATL Lap L9-5, Philips, Netherlands). This probe provides 128 channels, with a central frequency of 7 MHz (bandwidth: 5 MHz to 9 MHz). To generate PA signals, a multimode optical fiber (FT600EMT, Thorlabs, USA) was coupled to a laser system (Phocus MOBILE, OPOTEK, USA) capable of emitting wavelength-tunable laser beams. PA signals were acquired and processed, and ablation-induced lesions were detected using a Verasonics system (Vantage 128, Verasonics, USA). To monitor the ablation process, four wavelengths (700 nm, 740 nm, 760 nm, and 780 nm) were repetitively selected for PA excitation at 20 Hz, without any wavelength tuning delay.

3. RESULTS

Results are shown in Fig. 4. The Necrotic Extent (NE) for each pixel is displayed at the tissue surface where the ablation occurs. Initially, the regions exhibit a blue color, indicating non-ablation. As the ablation time increases, brighter pixels appear and gradually develop into a dark red color, representing complete ablation.

4. CONCLUSIONS

The results suggest that PA imaging can be used to observe and measure the ablation caused by irradiating tissue with laser light, using an acoustic probe positioned on the opposite side of the tissue specimen. While

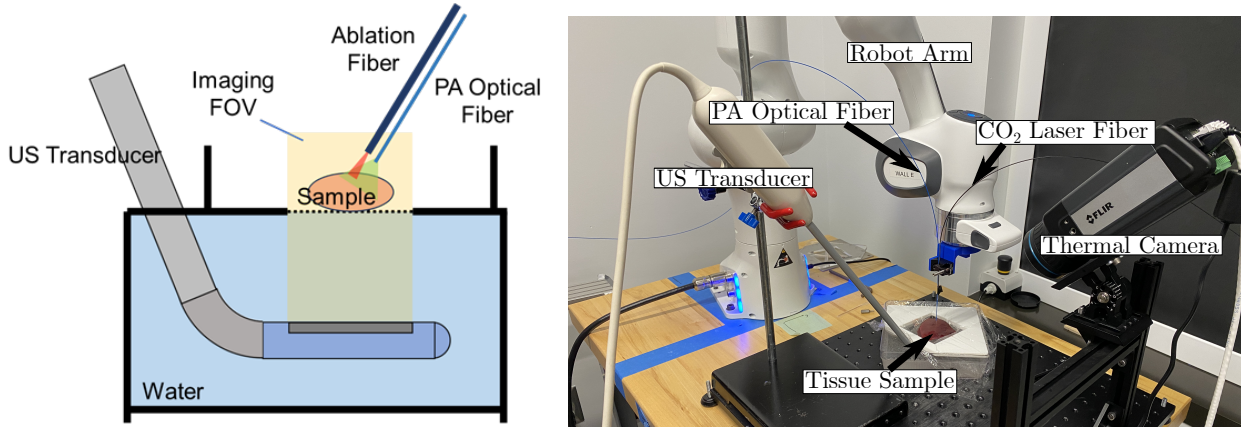


Figure 3. Laser ablation experimental setup. The ablation fiber and the photoacoustic (PA) excitation fiber approach the tissue from the top to simulate an approach through the oral cavity and an ultrasound transducer receiving the acoustic signals from the bottom, with a water coupling layer simulating the neck tissue. The tissue sample was placed on top of a plastic membrane.

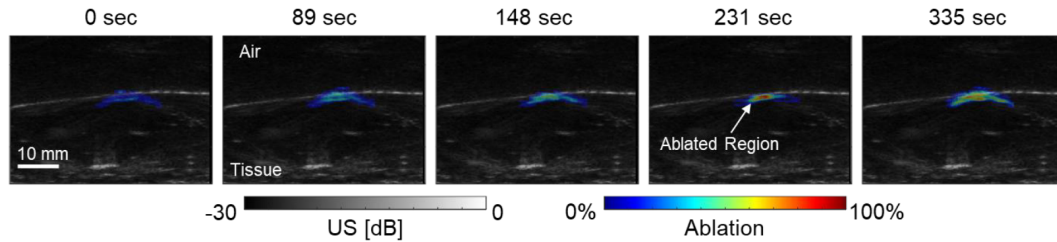


Figure 4. Experimental results. The necrotic Extent (NE) map is overlaid with an ultrasound image.

these results provide an early proof of concept, additional validation of our approach will have to be performed on actual tonsil specimens. By enabling surgeons to visualize the coagulated region, we hope to better equip them to control laser tonsil ablation while minimizing damage to surrounding healthy tissue.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation (NSF) under grant numbers 2237011 and 2038257. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

The authors would like to thank Carla Dipasquale for creating the tonsil anatomy illustration in Fig. 1.

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