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Laser spectroscopy and imaging of gallbladder stones, tissue and bile

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Abstract

Laser spectroscopic study of billary calculi and tissues is described. Fluorescence spectra of human gallbladder stones, bile and tissues were recorded with streak camera in the frequency and time domain. Potential of fluorescence as a diagnostic tool to discriminate between the intended target and the surrounding tissues and bile is evaluated. Initiation of fragmentation process is visualized by high-speed shadowgraphy, interferometry performed during the laser impact and generation of plasma causing growth and collapse of bubbles.

Keywords: Laser lithotripsy; Gallbladder; Fluorescent spectroscopy; Shadowgraphy and interferometry

1. Introduction

Most of the common bile duct stones (CBD) can be extracted by endoscopic sphicterotomy or extracorporeal shockwave lithotripsy (ESLW) as long as the stones are not too large or too hard for mechanical disintegration. Otherwise laser-based lithotripsy of human calculi has become a standard procedure in many of the surgical interventions. A patient can be relieved from acute pain caused by the blockage of the bile duct by inserting a needle-thin optical fiber to impact the stone with a few hundred laser pulses and shattering the stone into sand size particles which can flow out in natural way.

However, a serious complication often reported by the surgeons is the collateral damage to the surrounding tissue due to mispositioning of the fiber tip and injury or puncture of the CBD wall. One way to avoid this situation is to be sure that the fiber is located properly on the target by taking a fluorescence spectrum with a low-power laser of appropriate wavelength and duty cycle. Diagnostics of the stone type and understanding of the fragmentation mechanism is essential to set the proper laser parameters. The fragmentation mechanism and dynamics of the physical processes generated during the laser action is not yet fully understood [1–3].

In this work, we study the optimal condition and possibility to extract an output signal, which can be used as a feedback output to perform a controlled or smart triggering of the laser pulse for the stone destruction. Fluorescence spectroscopy and high-speed imaging and interferometry are the most reliable techniques to study the optimal condition and enable one to reach the best possible output signal to trigger the laser pulsed power and to perform a successful and safe lithotripsy.

Tissue fluorescence has been extensively used for detection, demarcation and localization of malignant tumors and lesions in variety of tissues [1–3]. Optical correlation based on ballistic imaging has been proposed for recognition of the stone and rejection of the tissue during the process of lithotripsy [4–8]. However, fluorescent-based techniques seem to be more reliable compared to correlation-based techniques where a match-spatial filter and relatively complicated optical setup is required [6–8]. Advantage of the fluorescence technique lies in its sensitivity, signal collection by thin fiber and easy discrimination not only between the tissue and stones but also identification of the type of the stone. The study of fluorescence of the stone, tissue and the bile is presented in Section 2 of this paper.

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The fluorescent signal generated on the top of the stone surface during the laser action depends on the environment, at this point and mechanism of the stone destruction. Namely, thermodynamics, phase change, pressure and rapid expansion and collapse of a bubble formed during the laser pulse action is interconnected with the chemical content and concentration of the material releasing the fluorescent radiance. Therefore, study of the dynamics and formation of a bubble is tightly connected with a successful application of laser spectroscopy for a controlled lithotripsy. In many cases the phenomena and the bubble formation above the stone and under the tip of the fiber during the laser pulse action, was not possible to be seen by using ballistic imaging, including conventional photography and shadowgraphy. Here, in Section 3, we propose a shadowgraphy combined with interferometric technique to visualize a bubble which otherwise could not be seen. Conclusion is presented in Section 4.

2. Fluorescent spectroscopy using a streak camera

Freshly extracted stones and bile from human patients were collected from surgical wards of local hospital and the stones were thoroughly washed to remove any blood contamination. The stones were classified into three groups on the basis of visual appearance. Black stones commonly known as pigmented stones composed mainly of calcium bilirubinate are porous and soft, whereas white and slightly tanned known as cholesterol stones are hard and difficult to crush by mechanical force. The third group was intermediate both in appearance and hardness. The gallbladder tissues from the same patients were washed in normal water followed by double-distilled de-ionized (DDDI) water and then stored in formaldehyde solution. A Segura-Dretler basket was used to hold the samples inside the container filled with saline. Experimental setup has a laser system containing two lasers Ho-YAG and Nd-YAG laser. The details of the lasers, optical fibers and streak camera are given in our earlier paper [9]. Here, we describe a simplified version of the experimental procedure. A simplified version of a schematic diagram of the setup is shown in Fig. 1.

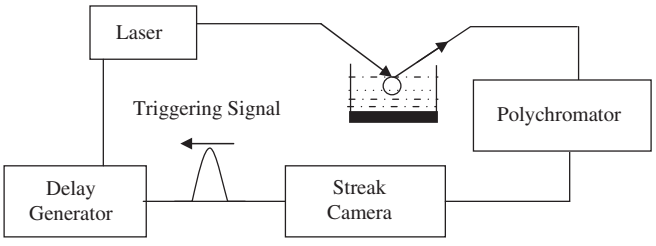

Fig. 1. Block diagram of a setup for the streak camera-based fluorescence detection system.

2.1. Spectroscopy of the plasma

The laser system consisting of a Ho-YAG and a Nd-YAG laser is triggered by a signal coming from a streak camera. The input signal on the streak camera comes from the stone to be destructed. In this way optical information from the stone selected by a streak camera resulting to an output signal and leading to triggering of the laser system, constitutes a feed back controlled system for lithotripsy.

Intense plasma is generated at the surface of it when high power pulse from Nd-YAG laser or Ho-YAG laser is delivered to the target. Due to the short pulse from the Nd-YAG or excimer laser, it is essential to use fiber of large diameter. Minimum fiber diameter used was 600 μm, whereas in the case of Ho-YAG laser with typical pulse width of 250 μs, the optical fiber of 200 μm diameter did not show any damage to the fiber tip. In clinical environment smaller size fibers are more flexible and easier to insert through the endoscope channels.

Bluish plasma visible to naked eye, produced by laser-induced breakdown (LIB) has been analyzed by optical multichannel analyzer. Most prominent plasma fluorescence peaks for the stone at the initial stages are at λ 363 and 400 nm, which appear within the first 50 ns of the laser pulse arrival and by the end of 1 μs there are five additional wavelengths which characterize the stone. These wavelengths and their atomic or ionic origin are shown in Table 1. Plasma fluorescence from the bile and tissue appears as a broader band-like structure with peaks at the λ360 and 460 nm with a typical width of 40 and 60 nm, respectively. Temporal growth of plasma emission from bile and tissue is much delayed and weaker in intensity, which can be useful to discriminate between the stone, tissue and bile which can be used for remote diagnostic purpose.

Threshold for plasma production is strongly dependent on the type of stone and the nature of the target and the angle of the delivery fiber with the surface. Delivery fiber angle with the surface is very critical for the intensity of the plasma and the bubble dynamics. Threshold measurements for the initiation of plasma was typically 10–15 mJ corresponding to laser fluency of 15–20 J/cm^2. The stones which required much higher fluency were the cholesterol stones.

3. Fluorescence studies of the stone, tissue and the bile

Even though the plasma study can be used as a diagnostic tool, it is not free from risk of collateral damage in a clinical environment of in vivo studies. Once the plasma threshold is known for these samples, the

Table 1

Peaks	1	2	3	4	5	6	7
λ (nm)	363	396	421	430	444	525	560
Origin	CaI	CaII	CaI	CaI	CaI	CaI	CaI