

Diagnostics of Layer-by-Layer Biotissue Evaporation in the Process of Two-Coordinate Scanning by a Laser Beam for Precision Surgery

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Abstract. The use of automated and robotic systems for precision low-traumatic surgery is a common trend in modern medicine. One of the promising tools for such operations is an automated laser scalpel based on a scanner with real-time diagnostics of the process of biotissue evaporation. The paper investigates the possibility of operational Doppler diagnostics of layer-by-layer laser evaporation of biomodels. A surgical CO₂ laser with a two-coordinate scanning system was used as a scalpel. The method of autodyne detection of backscattered radiation coming from the laser action zone was used to diagnose the evaporation process. Samples based on Difco agar with different water content and various tissues of pigs *in vitro* were used as biomodels. The depth of evaporation, the zone of thermal damage of the samples, and the dynamics of the autodyne signal were studied depending on the scanning modes and parameters of laser radiation. It has been shown that the autodyne signal arising from the layer-by-layer evaporation of samples is sensitive to the water content of biomodels and the structural features of the tissue. Autodyne diagnostics of layer-by-layer laser scanning makes it possible to control the evaporation process of biotissue of the same type and to determine the boundaries between tissues of different types both in the scanning plane and in the tissue depth. The obtained results can be used in the developing technologies for automated laser layer-by-layer evaporation of biological tissues in relation to the precision low-traumatic surgery tasks. © 2023 Journal of Biomedical Photonics & Engineering.

Keywords: robotic surgery; CO₂ laser; automated feedback; autodyne diagnostics; XY scanner; automated biotissue evaporation.

Paper #3585 received 17 Jan 2023; revised manuscript received 29 May 2023; accepted for publication 29 May 2023; published online 2 Jun 2023. doi: [10.18287/JBPE23.09.020302](https://doi.org/10.18287/JBPE23.09.020302).

1 Introduction

The use of automated and robotic systems in surgery is a modern trend in developing and improving medical technologies [1]. This approach is based on objective monitoring of the surgical intervention process in real time, which reduces the risks of the human factor and enables fast postoperative rehabilitation of patients. Currently, surgical systems of this kind are mainly based on the tactile feedback from the surgeon and various methods of visualizing the surgical field [2].

Laser radiation as a surgical manipulation instrument has such advantages as low invasiveness and traumatization of healthy tissues, high accuracy and fast removal of pathological tissues. These advantages can be fully exhibited when laser radiation is used as part of automated and robotic systems. However, one of the disadvantages that limits the surgical use of lasers is the lack of tactile feedback during laser intervention [3]. When performing laser surgery with penetration deep into the tissue, the surgeon is not able to receive

information about the actual depth of evaporation or about the underlying tissue type. In this regard, some sensors are needed that would allow the surgeon to obtain objective information about the course of laser surgical intervention in real time.

To receive feedback for single-mode surgical CO₂ lasers, we propose to use the self-mixing effect (autodyne effect) that occurs when radiation is exposed to condensed media, in particular, to biological tissues [4]. The effect is that the radiation backscattered from an external moving object enters the laser cavity and initiates modulation of the output power (autodyne signal) at the Doppler frequency. The autodyne signal is a source of operational information about the course of laser biotissue evaporation and thus serves as kind of a “sensor” for organizing feedback in intelligent surgical devices. The proposed operational diagnostics of the processes of laser evaporation of biological tissues consists in identifying differences in the amplitude-frequency characteristics of the autodyne signal that occurs when exposed to tissues of different types. We have shown the potential of this approach for monitoring and controlling the process of biotissue laser evaporation based on commercial single-mode CO₂ lasers with pulsed-periodic (PP) pumping of the active medium [5, 6].

Surgical devices based on PP single-mode CO₂ lasers with scanning systems are widely used for treating various skin lesions and high-precision removal of superficial neoplasms providing automated layered laser evaporation of the affected biological tissue [7, 8]. In general, these devices are used for laser resurfacing, removal of skin lesions and mucous membranes, which is considered the “gold standard” in dermatological surgery [9]. Currently, the quality control of laser operation with scanning systems is carried out both by setting the parameters of automated evaporation (the shape and area of the evaporated tissue, the stepwise depth of its evaporation) visually and by using video control [7, 10]. In particular, when selecting modes for precision laser cuts of a certain depth, it is proposed [11] to use an experimental database containing the results obtained from model biomaterials. Although this approach makes it possible to implement precision low-traumatic and organ-saving laser surgical interventions, at present there is no possibility to obtain objective information on the course of laser surgery in real time, in particular, to determine the boundaries and the depth of the evaporated tissue.

On the basis of the *in vitro* and *in vivo* experiments performed on different types of biological tissues of both animals and humans, we have revealed that the spectral characteristics of the autodyne signal change when the laser beam passes from one type of tissue to another during laser evaporation [12]. These changes are caused by a variance in the characteristics of the Doppler backscatter signal coming from the laser impact zone on different tissues. The Doppler signal is determined by a combination of laser-induced dynamic processes in the zone of laser evaporation of biotissue and depends on both the structural features of the biological tissue and on the parameters of laser action. The use of the autodyne effect

makes it possible to perform real-time differential diagnostics of the evaporated biotissue type for surgical CO₂ lasers, that is, to distinguish the tissues differing from each other by the magnitude of the autodyne signal at the same parameters of laser action.

The use of scanning systems with feedback presents new opportunities for creating robotic surgical laser systems for the tasks of precision low-traumatic surgery. A peculiar characteristic of this approach lies in the fact that during the process of layer-by-layer tissue evaporation using laser beam scanning, it is necessary to identify both the boundary between the tissues in the scanning plane and the boundary between tissues by depth. In this case the laser beam repeatedly passes through the previously evaporated zone with a gradual deepening of the beam. This paper presents the results of the study of the autodyne diagnostics possibility for the process of automated laser layer-by-layer evaporation of tissues using a scanning system.

2 Methods and Materials

For automated surface laser evaporation of biomodels we used a setup consisting of a laser unit, an articulated-mirror manipulator and a JS1105 Galvo Scanner 2-coordinate galvanic scanner (Sino-Galvo Technology Co., China) docked with it (Fig. 1a) [6]. The setup is based on the C20A single-mode pulse-periodic CO₂ laser (Coherent, USA) with a power up to 20 W. It allows precision evaporation and dissection of biotissue with simultaneous real-time recording the autodyne signal generated by the CO₂ laser. The autodyne control scheme of the biotissue evaporation process is shown in Fig. 1b. The backscattered radiation from the laser evaporation zone hits the mirrors of the 2-coordinate scanner, then it is directed through the system of mirrors of the articulated-mirror manipulator to the CO₂ laser resonator and initiates modulation of the output radiation power (the autodyne signal) at the Doppler frequency. Part of laser radiation is diverted by the beam splitter to a fast IR photodetector. The signal from the photodetector routed through the ADC is fed to the computer that processes and retrieves the information component of the autodyne signal and controls the operation of the scanner.

The scanner control unit and the specially developed software make it possible to set any shape of the evaporation area within 20 mm × 20 mm, the speed of the laser beam within 1–50 mm/s, and the required filling density of the evaporated surface by laser hatching. The surface scanning area is a set of parallel lines (hereinafter, hatching lines). The width of these lines corresponds to the diameter of the focal spot. During the experiments the degree of overlap of the hatching lines was varied. To obtain a certain depth of the evaporated area, multiple laser scanning of this area of the biomodel was carried out. The dimensions of the laser beam and the distribution of the laser radiation intensity were determined with a NanoScan2s Pyro/9/5 laser beam profile analyzer (Ophir-Optronics, Israel).

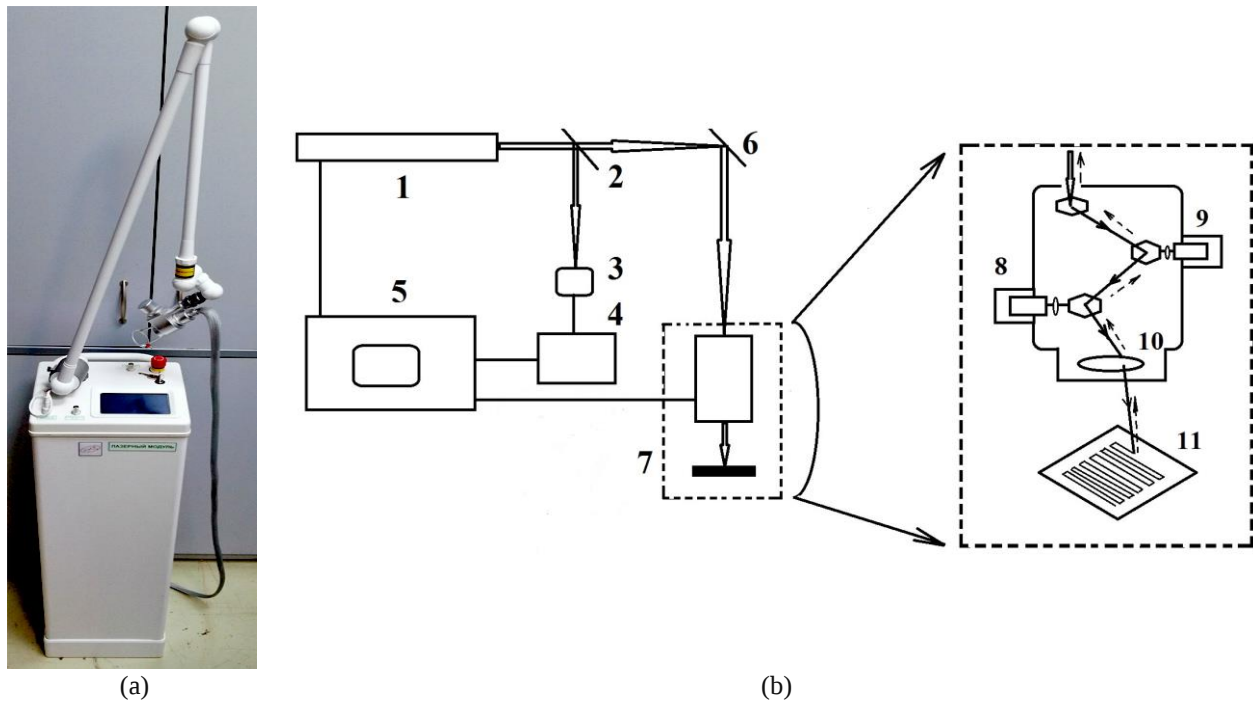


Fig. 1 The setup for automated surface laser evaporation of biomodels (a) and a schematic diagram of autodyne detection of backscattered radiation (b): (1) CO₂ laser, (2) beam splitter, (3) HgCdTe photodetector, (4) ADC, (5) PC, (6) mirror, (7) galvanic scanner, (8) X-axis scanning, (9) Y-axis scanning, (10) lens, and (11) biomodel.

As biomodels, the samples based on Difco agar and various pig tissues *in vitro* were used: cardiac muscle, skin area with fat tissue (obtained from the abdominal part of the animal), and a fragment of the pig auricle. The cardiac muscle is a three-dimensional structure of densely packed muscle fibers [13] with water content of 79% [14]. The “skin-fat” sample consisted of the sequentially arranged skin (including epidermis and dermis) and fat tissue with water content of 69% [14]. Fat is a collection of fat cells with a central fat droplet (globule) surrounded by cytoplasm [13] with water content of 20–40% [15]. The fragment of the auricle contained a cartilaginous plate covered with skin on both sides with no fat tissue under the skin of the auricle. Cartilage is a three-dimensional structure of collagen fibers and proteoglycan molecules [13] with water content of 80% [14]. The size of the samples was 15 × 15 mm. The thicknesses of the biomodel layers are indicated in the description of the experimental results. The studies were carried out on pig tissues obtained from a butchery. Each tissue sample that was used in this study was less than 48 h *post mortem*. The samples were stored at a temperature of 0–4 °C at constant humidity. Samples for experiments utilizing agar were prepared with a mass agar fraction between 5% and 15%. Such samples simulated soft tissues with a high water content. Cross sections of biomodels after scanning were studied under a microscope, for which a sample was cut in a direction perpendicular to the direction of beam motion.

In experiments on automated evaporation of the surface of biomodels, a 8.5 mm × 11.6 mm rectangular area was scanned by means of a lens with a focal length of 50 mm. The radiation was focused on the biomodel surface. The position of the focal spot remained unchanged

during multiple scanning. In the experiments, the exposure and scanning modes were changed: the power of laser radiation (3–5 W), the speed of the laser beam (from 2 mm/s to 30 mm/s), and the density of hatching lines. The evaporation depth of the biomodel surface was several millimeters.

Processing the autodyne signal during laser scanning was carried out using a special algorithm for extracting the informational Doppler component described in Ref. [16]. The signal power P_s in the selected frequency range was used as an information parameter of the autodyne signal.

3 Results and Discussion

The use of autodyne detection of backscattered radiation imposes excessive requirements on the quality of operational laser radiation [5]. The profile of the laser beam was measured directly at the exit from the laser, whereas in the operating field it was measured in the scanning plane. The measurements show that the radiation at an output power of 3–20 W is a single spatial mode with an intensity distribution close to the Gaussian profile. Fig. 2a shows the distribution of radiation intensity at the laser exit at the radiation power of 6 W. The beam diameter (at the level of 13.5% along the X axis) was 2.3 mm, the difference from the Gaussian distribution (calculated using the Least Squares Fit method) along the X axis was 0.955. After passing through the setup optical system, the articulated-mirror manipulator, and the optical path of the scanner with a 50-mm focal length lens, the laser beam in the scanning plane retains the Gaussian profile (Fig. 2b).

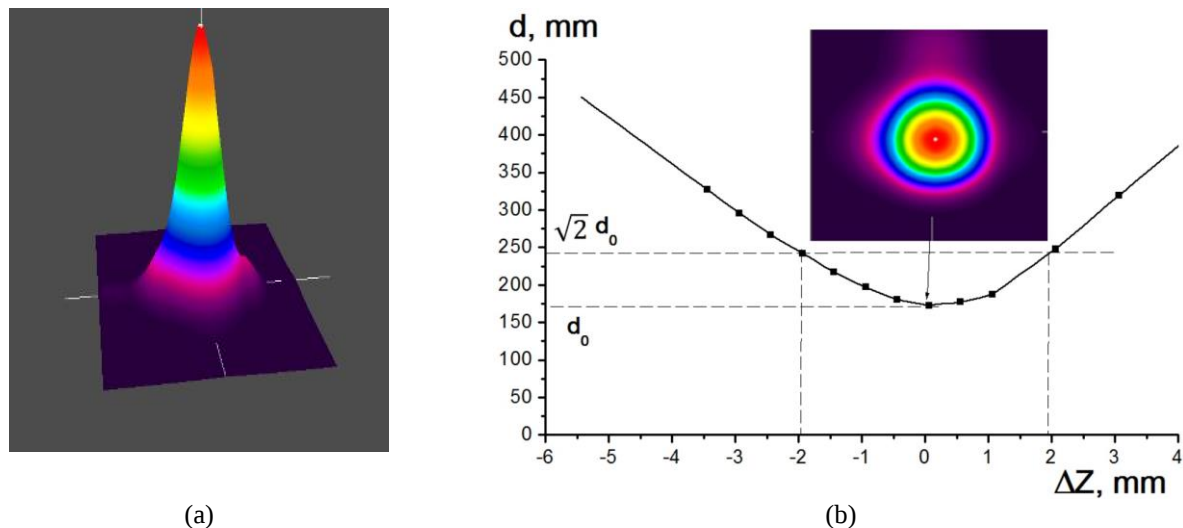


Fig. 2 Distribution of laser radiation intensity in the focal spot in the scanning plane (a) and relationship between the laser beam diameter d and the ΔZ distance from the focal plane of the lens (b). The focal length of the lens is 50 mm.

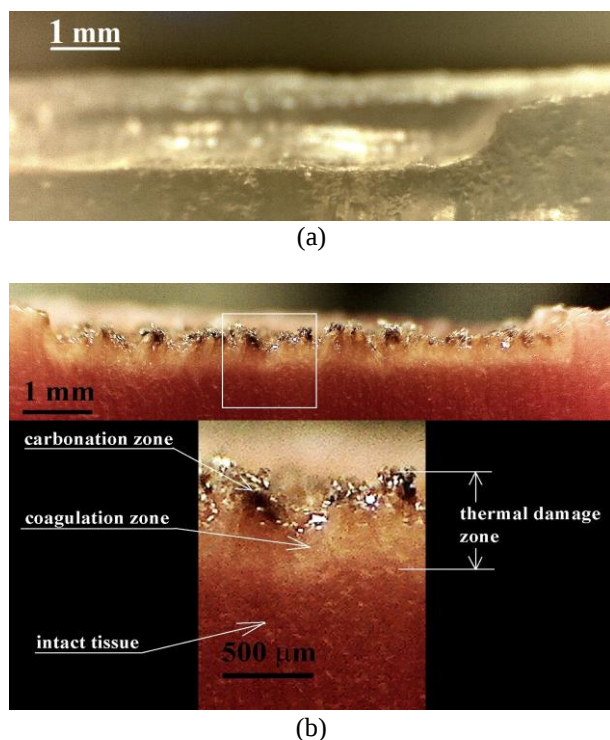


Fig. 3 Cross section of the evaporated zone of biomodels based on agar (a) and *in vitro* pig heart muscle (b) in different modes of a single scanning: a) power is 4 W, scanning speed is 18 mm/s, distance between hatching lines is 160 μm ; b) power is 3.2 W, scanning speed is 12 mm/s, distance between hatching lines is 80 μm .

The beam diameter at the focus (along the X axis) is 175 μm , the difference from the Gaussian distribution along this axis was 0.984. Fig. 2b shows the relationship between the focused beam diameter and the distance from the focal plane of the scanner lens. The diameter of the laser beam at the distance of ± 2 mm from the focal plane of the lens changes by a factor of 1.4

(correspondingly, the radiation power density changes by a factor of 2).

During laser scanning, the biomaterial evaporates to a certain depth, specified by the scanning conditions. In this case, the underlying layer of the sample is heated, which can lead to partial melting of the sample material (in the case of biomodels based on agar), or to thermal damage and changes in the properties of the underlying layer (for the case of biomodels based on the *in vitro* biotissues, see Fig. 3). The thermal damage zone (TDZ) of the tissue includes carbonization and coagulation zones (Fig. 3b). The TDZ depth was measured as the distance between the surface of the evaporated tissue and the boundary of the coagulation zone, which is visually observed as the tissue of a lighter shade. This color is the result of coagulation of tissue proteins when heated to a temperature of 70 $^{\circ}\text{C}$ [17]. With the help of a digital microscope, the TDZ depth of pig myocardial tissue was measured after single and multiple scans. It was found that at the laser radiation power of 3.5 W and the scanning speed of 10 mm/s, even a single scan leads to the tissue thermal damage to a depth of 250–300 μm . After four scans (four successive scans of the same area of the sample surface), the TDZ depth was 650–700 μm .

The peculiarities of the autodyne signal were studied in terms of the scanning speed and the number of scans of the same biomodel surface area (multiple scans). Fig. 4a shows the relationship between the power of the autodyne signal and the scanning speed for a single action to the surface of 5% and 15% agar samples. It can be seen that the power of the autodyne signal differs markedly for samples with different agar content, which allows for biotissue differential diagnostics with different water content. It is quite probable that the greater value of the signal for samples with 15% agar content is due to the fact that larger particles are formed due to microexplosions during laser exposure and are removed from the active surgery zone. During multiple laser scanning of the surface area, the sample surface is displaced relative to the focal plane of the laser beam.

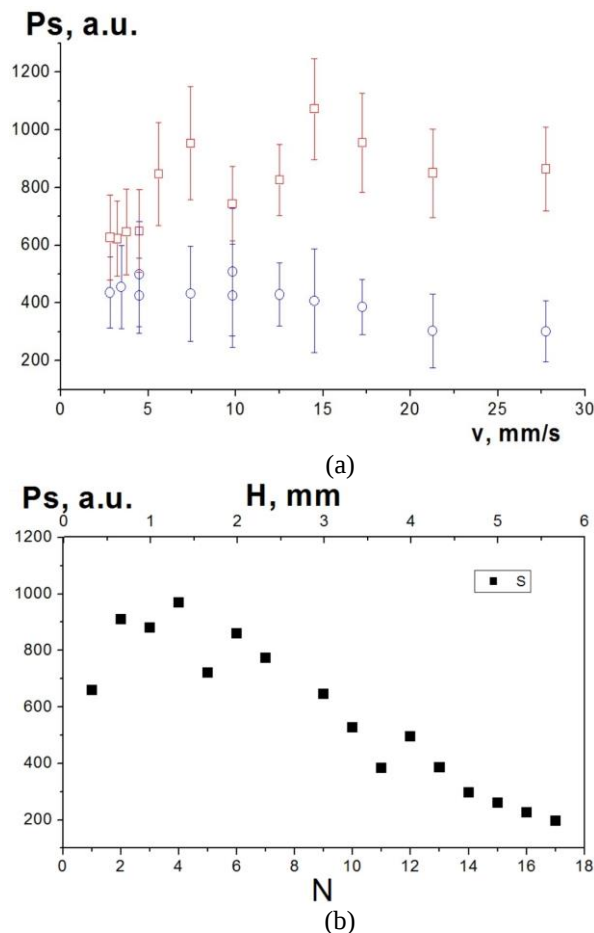


Fig. 4 Relationship between the power of the autodyne signal and the scanning speed (a) and the number of scans during evaporation of the surface of agar samples; a) blue circle $\circ$ is 5% agar; red square $\square$ is 15% agar; b) scanning speed 10 mm/s, black filled square $\blacksquare$ is 15% agar. Radiation power $P = 3.5$ W, the distance between hatching lines is $480\ \mu\text{m}$.

Therefore, the autodyne signal may vary depending on the number of scans. Fig. 4b shows the relationship between the power of the autodyne signal, the N number of scans and evaporation of the sample surface of 15% agar. This figure also shows the distance scale H from the focal plane (or from the initial sample surface) to the sample surface after scanning. The scale was calculated assuming that a $450\ \mu\text{m}$ thick layer is removed in one scan under the given action conditions. As follows from the figure, during multiple scans, a gradual decrease in the power of the autodyne signal occurs. This is due to the fact that the surface leaves the focal plane of the scanner lens. This is in agreement with the size of the caustic at the focus of the scanner lens (see Fig. 2b).

Fig. 5 shows the change in the average value of the autodyne signal power during multiple laser scans of the surface of the heart muscle sample. An increase in the autodyne signal is observed during the transition from a “fresh” tissue area (Scan 1) to subsequent scanning of the surface areas subjected to thermal effects of laser radiation and containing TDZ (see Fig. 3b).

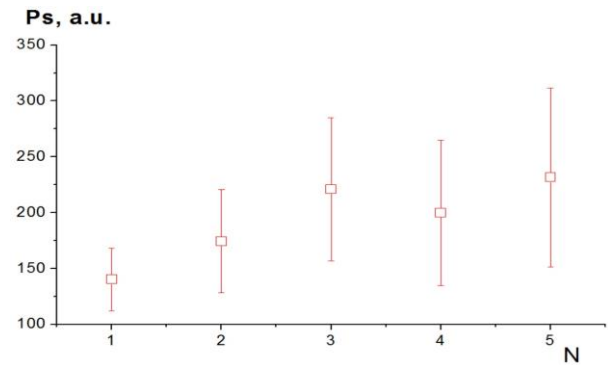


Fig. 5 The power of the autodyne signal during the evaporation of the surface of pig heart muscle *in vitro* depending on the number of scans. $P = 3.5$ W, $v = 10$ mm/s, the distance between hatching lines is $480\ \mu\text{m}$.

The possibility of diagnosing both the lateral boundary and the depth boundary between different tissues was investigated using two-layer biomodels based on agar. The samples with 5% and 15% agar content were used for modeling soft biotissues with different water content. In the first case, the samples connected in series were used. The samples were arranged in such a way that the direction of the hatching lines during scanning and the boundary between the samples were close to parallel. Fig. 6a shows the dynamics of the autodyne signal power during the evaporation of the combined sample.

It can be seen that when the laser radiation passes from 5% to 15% of the sample (from left to right), the signal increases. Moreover, transition from one signal level to another occurs in the form of oscillations. This is due to the fact that the direction of the hatching lines does not completely coincide with the boundary line between the samples, and the laser beam passes several times from one sample to another.

Fig. 6b shows the simulation of layer-by-layer laser evaporation of a two-layer 1.4 mm thick structure consisting of 5% agar located on a 15% agar sample. As follows from the Fig. 6b, the level of the autodyne signal in Scan 2 is greater than that in Scan 1 and smaller than that in Scan 3 because Scan 2 evaporates the remainder of the first layer and captures the underlying second layer of the sample with 15% agar content.

To simulate a situation close to a real surgical intervention, *in vitro* pig tissue samples were used. Fig. 7 shows the change of the autodyne signal during layer-by-layer scanning of a sample containing the 1–1.5 mm thick upper layer of the skin, under which the fat tissue was located. A noticeable increase in the autodyne signal occurs at the transition from the skin (Scan 1) to the layer of fat tissue (Scan 2). During Scan 1, the skin layer was not completely removed in some areas. The next pass captures both areas of exclusively fat tissue and areas with the skin remnants, which is reflected in the autodyne signal power.

Another example is layer-by-layer laser evaporation of the biomodel surface based on pig auricle.

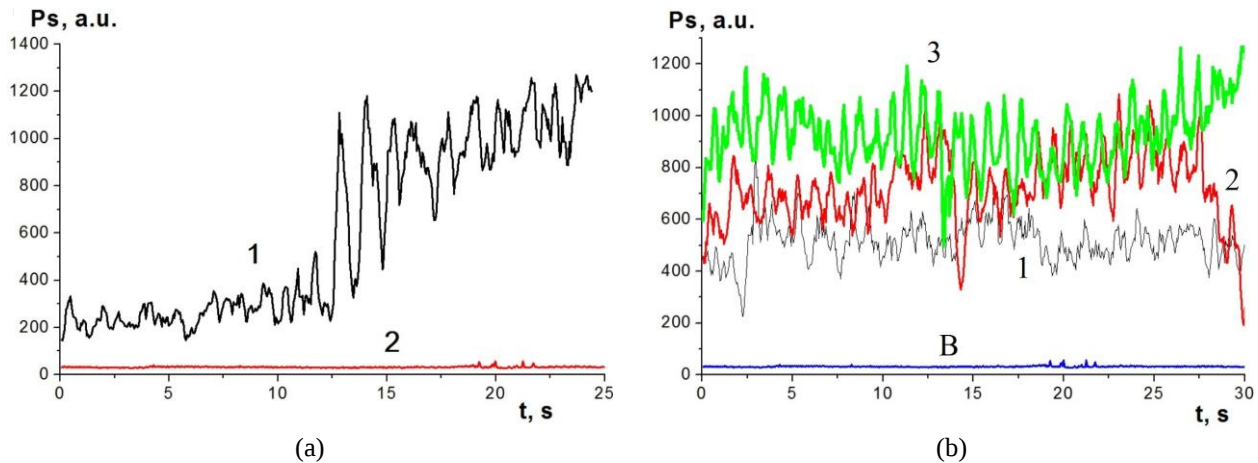


Fig. 6 Dynamics of the autodyne signal power during laser scanning of combined agar samples. $P = 3.0$ W, the distance between hatching lines is $325 \mu\text{m}$. (a) Single scanning of serially connected (from left to right) 5% and 15% agar samples. Scanning speed is 12.5 mm/s . (1) Autodyne signal power, (2) noise. (b) Layered scanning of a 5% agar sample located on a 15% sample. The scanning speed is 10 mm/s . (1) – (3) are scan numbers; (B) is noise.

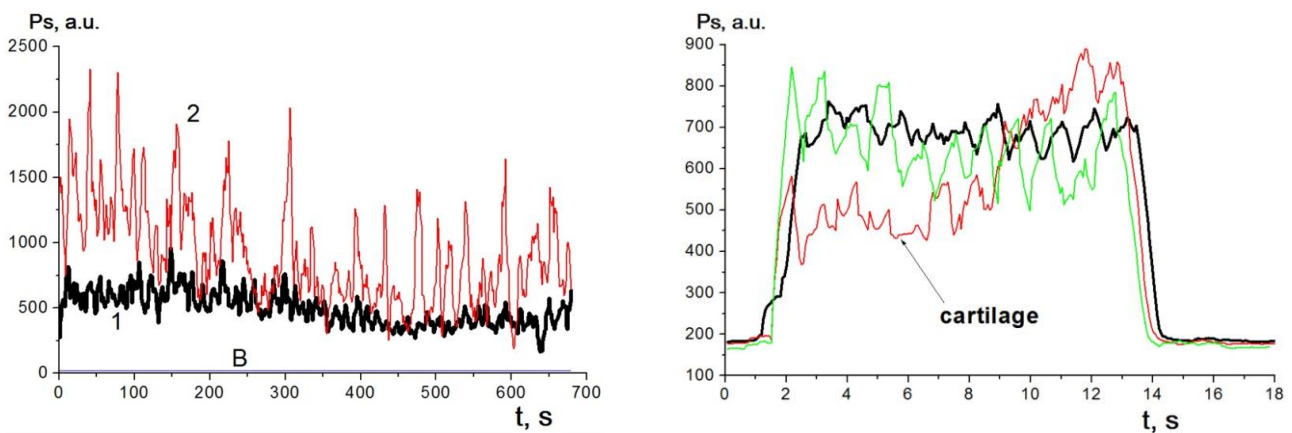


Fig. 7 Relationship between the autodyne signal power and time during layer-by-layer laser scanning of the "skin-fat tissue" biomodel. $P = 4.5$ W, scanning speed is 10 mm/s . Scan 1 is skin, Scan 2 is fat tissue, B is noise.

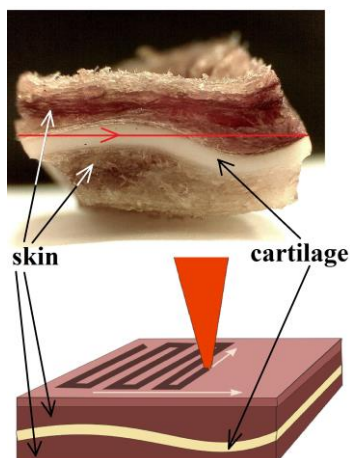


Fig. 8 Biomodel based on pig auricle. (a) Photo of pig auricle section. The red line shows the scanning plane (Scan 4, Fig. 9), the scanning direction is from left to right. (b) Schematic diagram of the process of scanning the laser beam on the biomodel surface.

Fig. 9 Relationship between the power of the autodyne signal and the scanning time (the pig auricle segment in Fig. 8). $P = 5$ W, the scanning speed is 10 mm/s . Scan 1 (black) is skin, Scan 4 (red) is skin and cartilage tissue, Scan 8 (green) is skin.

The model consists of several consecutive layers (Fig. 8): skin ($1.0\text{--}1.8 \text{ mm}$ thickness), cartilage ($0.7\text{--}0.8 \text{ mm}$) and skin ($1.2\text{--}1.8 \text{ mm}$). The change in the autodyne signal power as a function of time during layer-by-layer scanning of this biomodel is shown in Fig. 9. This model is characterized by a curvature of the cartilage tissue layer. Scan 1 captures only the superficial area of the skin. The level of the autodyne signal determines the process of skin evaporation. Scan 4 captures both the skin and the cartilage areas. Accordingly, the area of cartilage evaporation is characterized by a significantly lower level of the autodyne signal. During Pass 8, the laser beam again vaporizes only the skin and the level of the autodyne signal becomes high as in Pass 1.

Previously [12], we showed that the differences in the nature of laser evaporation of biotissues are due to their structural peculiarities, content and distribution of interstitial water. The specificity of the Doppler spectra depends on the type of biotissue which is largely due to

the characteristics of the tissue destruction products. The size, shape, and other characteristics of the destruction products arising from the laser impact zone are largely determined by the structure features of the original biological tissue, in particular, when exposed to fat tissue, the destruction products consist of relatively large fat drops, whereas when exposed to the muscle tissue, they contain fibers. The combination of these factors and the difference in the optical and physical characteristics of different tissues lead to the differences in the Doppler backscatter signal, which makes it possible to carry out differential diagnosis of the evaporated tissue types in real time.

4 Conclusions

The study has demonstrated the possibilities of autodyne diagnosing for automated laser layer-by-layer evaporation of various biomodels based on a scanning system. The specific features of the autodyne signal were examined according to the following characteristics: the

CO₂ laser radiation power, the scanning speed during single and multiple surface scans of the biomodels based on agar with different water content and biotissues of pigs *in vitro*. It has been shown that in the process of layer-by-layer laser scanning, autodyne diagnostics makes it possible to control the evaporation process of the same type of biotissue and to determine the boundaries between biotissues of different types both in the scanning plane and in the depth of the biotissue. The obtained results can be used for developing new technologies for automated laser layer-by-layer tissue evaporation as applied to the tasks of high-precision low-traumatic surgery.

This work was performed within the State assignment of Federal Scientific Research Center “Crystallography and Photonics” of Russian Academy of Sciences.

Disclosures

The authors have no relevant financial interest in this article and no conflict of interest to disclose.

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