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Laser-induced hydrodynamics in water-saturated tissue: III. Optoacoustic effects

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Abstract
Studied in this work are specific features of acoustic vibrations generated at the hot blackened tip of an optical fiber (the so-called hot tip) delivering moderate-power (1–10 W) CW laser radiation in contact with water or a water-saturated biotissue. Generated upon such contact is a wideband acoustic signal whose characteristics largely depend on the object exposed and treatment scheme. Placing the hot tip in an acoustic resonator is demonstrated to cause distinct amplitude modulation of the acoustic noise. The formation of laser channels in an intervertebral disc or the intramedullary cavity of a bovine thighbone gives rise to the emission of a quasiperiodic train of pulses associated with the explosive growth and collapse of steam-gas bubbles in the hot-tip-to-biotissue contact region. The resultant pressure pulses, 20 ± 15 MPa in amplitude, cause damage to the adjacent tissue and facilitate the production of a laser channel at a rate of some 0.4–5 mm s^{-1}. During the course of laser treatment the biotissue gradually gets saturated with steam-gas bubbles, which results in the development of low-frequency pressure oscillations in the range 0.1–10 Hz and a gradual pressure rise to around 200 kPa, leading to reduction of the natural frequencies of the resonance modes of the biotissue. The possible effect of these acoustic vibrations on the biotissue is discussed.

Keywords: cw laser, moderate-power, biotissue, acoustic emission, optoacoustic, hydrodynamic, bubble, pressure, channel formation, therapeutic effects, medical technologies

(Some figures may appear in colour only in the online journal)

1. Introduction

This work continues our studies of laser-induced hydrodynamic processes developing in water-saturated biotissues in the vicinity of the heated carbon-coated (blackened) end face (hot tip) of an optical fiber delivering moderate-power (1–10 W) CW laser radiation [1–3]. These processes determine the efficiency of such medical laser technologies as the laser puncture treatment of osteochondrosis and osteomyelitis, laser cartilage engineering, fractal photothermolysis, sclerotization of varicose veins, and others [4–8]. For example, the laser treatment technologies for osteochondrosis [4–6] and osteomyelitis [8] are based on forming laser channels in biotissues by advancing thereinto a silica optical fiber whose tip, preliminarily coated with carbon (blackened), is heated by laser radiation of moderate power.

In our previous works [1–3], we demonstrated that in the neighborhood of the optical fiber tip, heated by continuous-wave laser radiation of moderate power and immersed in water, there developed various intense hydrodynamic processes caused by the explosive boiling of water. Formed in that case were both single steam-gas bubbles moving with velocities of up to 100 m s^{-1} and stable microscopic jets of bubbles from a few microns to a few tens of microns across. The generation of bubbles within a thin water-filled capillary was accompanied by the development therein of stable circulation flows with a circulation period from 0.2 to 1 s. It was also found [2, 3] that the hydrodynamic processes induced by CW laser radiation of not very high intensity (10^3–10^4 W cm^{-2}) caused within a few minutes a noticeable degradation of the optical fiber tip. The degradation of the fiber substantially intensified when in contact with water-saturated tissue. As a result of such a contact the fiber tip became fused and developed micron-sized holes and cracks in the face. It was shown that with the laser radiation power and intensity being moderate the temperature near the tip of the delivery fiber reached a few thousands of degrees centigrade, and on the end face surface there formed a new phase—nanosized diamonds. It was suggested [2] that the characteristic damage of the fiber tip, its fast degradation, and formation of nanosized diamonds were due to the formation of supercritical water and the collapse of cavitation microbubbles, attended upon by the development of high temperatures and pressures [9, 10].

All these laser-induced processes associated with the intense movement, origination, collapse, and vibrations of steam-gas bubbles are accompanied by a characteristic acoustic noise within a wide frequency band from a few fractions of a hertz to a few tens of megahertz [9, 10] that not only has the capacity actively to affect the condition of the exposed biological tissue, but also bears important information about the processes. Acoustic signals are extremely informative; that is why they are being widely used for remote diagnostics of various processes in medicine [11, 12], engineering [13, 14], and experimental physics [13–20]. This is largely thanks to the fact that acoustic signals propagating in various media, biological tissues included, attenuate much less intensively than, for example, the electromagnetic radiation signals of visible and near-infrared wavelengths widely used for diagnostics purposes.

Acoustic pulses generated in a biological tissue under the effect of laser radiation have been known to be capable of causing their local damage. To illustrate, high-power acoustic pulses generated by intense pulsed laser radiation are being widely used in medical practice [21, 22], for example, in laser lithotripsy. In that case, the exposed biotissue is affected by high-amplitude pressure pulses accompanied by the explosive appearance and cavitation collapse of bubbles [23–26]. Acoustic vibrations developing in a water-saturated biological tissue exposed to a moderate-power CW laser radiation can also actively influence its condition by initiating mechanobiological processes [7], exciting resonance vibrations in bubbles [1, 3], causing its local damage [3], and triggering chains of chemical transformations [2, 27, 28].

Studied in this work are wideband signals of the acoustic emission accompanying the laser-induced hydrodynamic processes that occur near the tip of the delivery optical fiber upon its contact with water or a water-saturated biological tissue.

2. Materials and methods

The laser radiation source used in this work was a fiber laser (IRE-Polyus, Russia) 0–10 W in radiation power and 0.97 μm in wavelength equipped with a silica delivery fiber 400 μm in diameter. The tip of the delivery fiber was preliminarily coated (blackened) with a layer of amorphous carbon by making it contact a lump of wood for a short time (around 1 s) while delivering 3 W of laser radiation power [1].

The experimental materials included bovine thighbones and isolated spinal segments with the intervertebral disc and two vertebras, taken from patients who had died from somatic diseases. An individual experiment was conducted with 5 × 5-mm^2 plates, 2 mm in thickness, cut from the *nucleus pulposus* of the intervertebral disc.

The following two experimental regimes of operation were used in the experiments: (1) a stationary regime in which the optical fiber was kept immovable and (2) a regime of channel formation similar to the one used in the current technologies for treating osteochondrosis [4–6] and osteomyelitis [8], in which the heated end face (hot tip) of the laser delivery fiber was pressed against the tissue to be treated and then pushed into it for a distance from a few millimeters to a few tens of millimeters within a few seconds to a few tens of seconds, thus forming a channel.

Three types of experiment were performed in the stationary regime, wherein the preliminarily blackened fiber tip of the laser delivery fiber was kept (1) immersed in free water, (2) placed in a water-filled glass capillary 1 mm in diameter and 20 mm long, and (3) pressed against the surface of a metal plate immersed in water, either directly, or through the intermediary of a plate cut from the *nucleus pulposus* region of an intervertebral disc.

The regime of channel formation was also used to conduct three types of experiment to record (1) wideband acoustic signals in the intervertebral disc, (2) wideband acoustic signals in bovine thighbones, and (3) low-frequency acoustic signals in the intervertebral disc. To form a laser channel in the intramedullary cavity of a bovine thighbone, a 1-mm-dia hole was drilled beforehand in the wall of the bone to push through the laser delivery fiber. To study the low-frequency region of the acoustic signal generated in an intervertebral disc, several 15–20-mm-long laser channels were successively formed in it in accordance with the procedure described in [4–6], a saline solution being injected into the disc prior to each laser treatment session.

To record acoustic signals, the object under study was placed in a 40 × 40 × 40-cm^3 water-filled container (figure 1(a)). Installed 1 cm distant from the object was a Model 8100 hydrophone (B&K, Denmark) 0–200 kHz in bandwidth and 25 μV Pa^{-1} in sensitivity that was connected to a personal computer via a Model 2650 preamplifier (B&K, Denmark) 0.3–200 kHz in bandwidth, a Model Y7-6 wideband amplifier (Russia), and a Type 873 multichannel 14-bit ADC L-card 2.8 MHz in maximum sampling rate frequency. The amplitude absorption coefficient for water is proportional to the square of the sound frequency, and in the conditions of our experiment such absorption may be neglected.

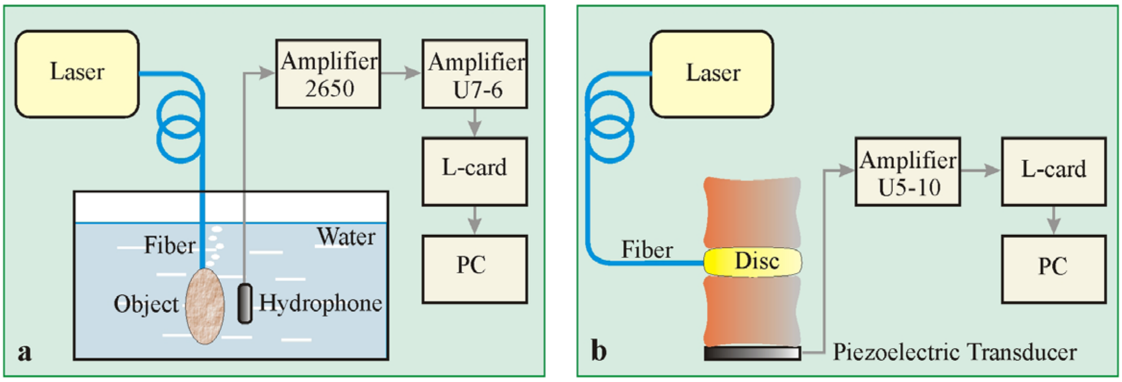

Figure 1. Block diagrams of the experimental setups for recording (a) wideband and (b) low-frequency acoustic signals.

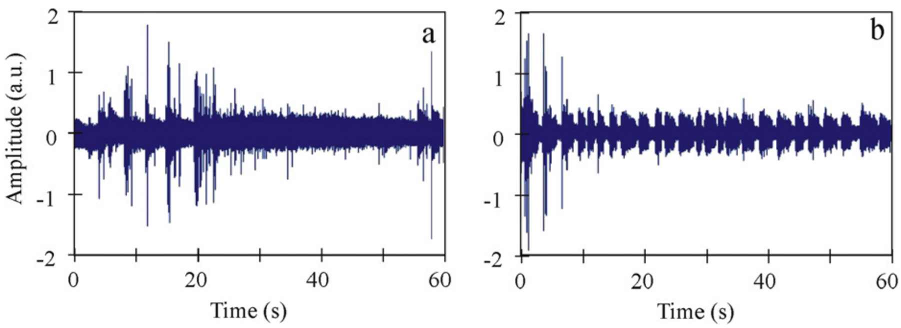

Figure 2. Acoustic signal generated in (a) free water and (b) a capillary. Stationary regime of operation. Laser power 3 W.

Low-frequency acoustic signals generated in the intervertebral disc of spinal segments were recorded with the setup whose block diagram is presented in figure 1(b). The segment under study was rigidly fixed with two wire clamps to a piezoceramic-based piezoelectric transducer 65 mm in diameter, 2 mm in thickness, and 34 μV Pa^{-1} in sensitivity. The transducer signals were fed to a DC amplifier U5-10 (up to 10^4 in gain and 0–60 kHz in operating band), coupled to a personal computer via a Type 783 ADC L-card (12-bit, sampling frequency 3 MHz).

The high-frequency region of the acoustic signal spectrum was recorded with a 30-μm-thick polyvinylidene fluoride film (PVDF) piezoelectric transducer with a 0.2–50 MHz operating band and sensitivity of 75 μV Pa^{-1}. Measurements were taken in a water-filled plastic cell 150 × 100 mm^2 in cross-section and 15 mm high. The piezoelectric transducer was installed in water at a distance of 17 mm from the tip of the laser delivery fiber and connected via a preamplifier to a Model TDS1012 digitizing oscilloscope of 100 MHz in bandwidth.

To investigate the acoustic signals, use was made, in addition to their spectral analysis, of a one-dimensional wavelet transform with the aid of the complex Morlet wavelet [29]. Physically, taking a wavelet transform is similar to passing the initial time series through a system of bandpass filters of the same passband-to-center-frequency ratio, i.e., of the same Q-factor. The processing results are represented in the form of a wavelet diagram, wherein the x-axis indicates time and the y-axis frequency, with the color or intensity gradations in the case of representation in shades of gray indicating the amplitude.

3. Results and discussion

Figure 2 shows the shape of acoustic signals generated at the laser-heated blackened end face (hot tip) of the laser delivery fiber in contact with water. In the case illustrated by figure 2(a), where the hot tip of the optical fiber is in water, the acoustic signal is a time-constant noise chaotically distributed in intensity, whose energy is mostly concentrated in the relatively high frequency spectral range 10–20 kHz. Observed visually on the surface of the hot tip is an intense boiling of water, with steam-gas bubbles gathering momentum in the radiation direction and floating to the surface.

In the case illustrated by figure 2(b), the hot tip is placed in a water-filled glass capillary that plays the part of an acoustic resonator. The acoustic signal here assumes an entirely different shape. It consists of a series of individual pulses of complex shape generated with a period of some 2 s, the acoustic signal energy being concentrated in the ranges 2–20 kHz (high-frequency region) and around 1–10 Hz (low-frequency region). When viewed through a microscope, the capillary is observed to contain a chain of approximately equidistant vibrating bubbles with active water circulation in the spaces between them [1, 3]. We believe that it is precisely this water circulation with a period around 0.1–1 s that is the source of the low-frequency component of the acoustic signal.

Figure 3 presents the dynamics of a wideband acoustic signal and the shape of a single acoustic pulse generated in an

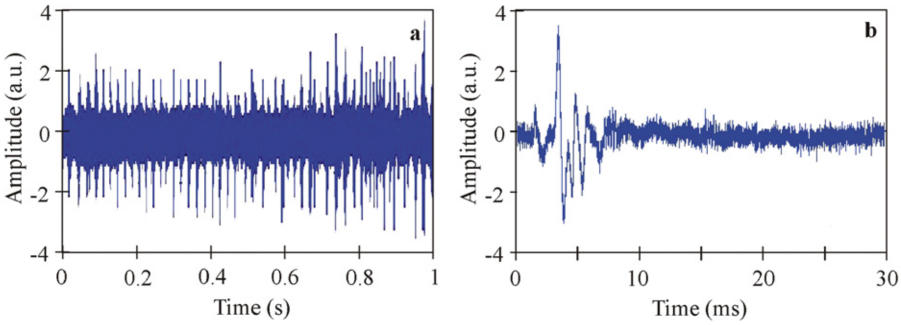

Figure 3. (a) Acoustic signal generated in an intervertebral disc in the regime of channel formation; (b) detailed shape of an individual acoustic pulse. Laser radiation power 4 W.

intervertebral disc in the regime of channel formation. It can be seen from figure 3(a) that as in the case of simple acoustic resonator—the capillary (figure 2(b)—the signal has the shape of a quasiperiodic pulse sequence (frequency around 26 Hz). That is evidence of the resonance character of generation of the acoustic signal, each pulse (figure 3(b)) containing a wave train with a frequency around 1 kHz, wherein the amplitude first sharply rises to its maximum and then gradually drops almost down to the background noise level within 3–5 ms. The energy of this pulse is concentrated in the 0.4–1.7 kHz interval with two separated maxima at 1.0 and 0.5 kHz. The spectral analysis of the acoustic signal generated in the intervertebral disc showed that the energy of the signal is concentrated in the spectral range 0.7–10 kHz, with a local maximum in the region of 1 kHz.

The detailed study of the acoustic noise with the aid of the PVDF piezoelectric transducer showed that when the hot tip of the laser delivery fiber was placed in free water, short high-power pressure pulses were generated on the surface of the tip with an amplitude of 20 ± 15 MPa, followed by a damped wave train (figure 4). The temporal shape of the pulses was only slightly dependent on the distance from the fiber tip. In the experiment, pulses were actually observed at a distance of 17 mm. Pulses of such a shape can result both from the explosive boiling of water and the formation of initially expanding bubble [30] and from the cavitation collapse of the latter [10, 20, 31]. In the former case, the high pressure produced upon the explosion-like growth of the bubble gives rise to a spherically symmetric expanding shock wave that breaks away from the surface of the bubble and propagates deep into the medium. In the case of cavitation collapse of the bubble formed, its potential energy

$$E_B = \frac{4\pi}{3}(p_0 - p_V)R_{max}^3, \qquad (1)$$

which is determined by its maximum radius R_{max} and the difference between the hydrostatic pressure p_0 and the vapor pressure p_V within the bubble [9], is converted upon compression of the bubble to a very small size into the kinetic energy of a high-velocity ($\sim 10^3$ m s^{-1} [31]) cumulative jet and the acoustic energy of an extensively propagating shock wave [32]. When the bubble collapses near a hard wall, this jet is directed towards the wall, but when this happens near an elastic surface (e.g., the surface of a biotissue), two jets

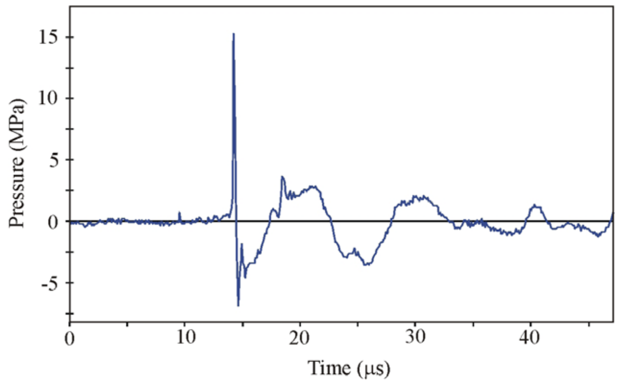

Figure 4. Typical high-frequency pressure pulse generated near the hot tip of the laser delivery fiber in free water. Stationary regime of operation. Laser radiation power 4 W. Pressure is referred to the surface of a sphere with a radius of 3 μm.

are formed, one directed towards the surface and the other away from it [31]. These jets are capable of damaging not only the biotissue, but also the surface of the hot tip of the laser delivery fiber [2, 3].

As can be seen from figure 4, the positive pressure pulse half-cycle is followed by a negative half-cycle with an amplitude of some 7 MPa. This is important, because biotissues are well known to be much more susceptible to tensile rather than compressive stresses [33]. Inasmuch as the peak pressures injurious to various biotissues fall within the range 0.3–2 MPa [26], one can expect that each high-frequency pulse similar to the one presented in figure 4 will destroy the exposed tissue at a distance of 20–50 μm from the tip of the laser delivery fiber. When such high-power pulses are generated at a frequency around 30 Hz (figure 3(a)), the fiber in contact with various water-saturated tissues will be capable of being advanced, thanks to the destruction of the tissue near its hot tip, at a rate of 0.6–1.5 mm s^{-1}, which agrees well with the rate of formation of a laser channel in an intervertebral disc (around 1 mm s^{-1}). Note that when recording acoustic emission signals with the setup of figure 1(a), such high-frequency pulses cannot be seen (figure 3(b)), as their characteristic frequencies substantially exceed the upper limiting frequency of this setup.

As one can see from figure 4, the short high-power pulse is immediately followed by a train of damped waves with a

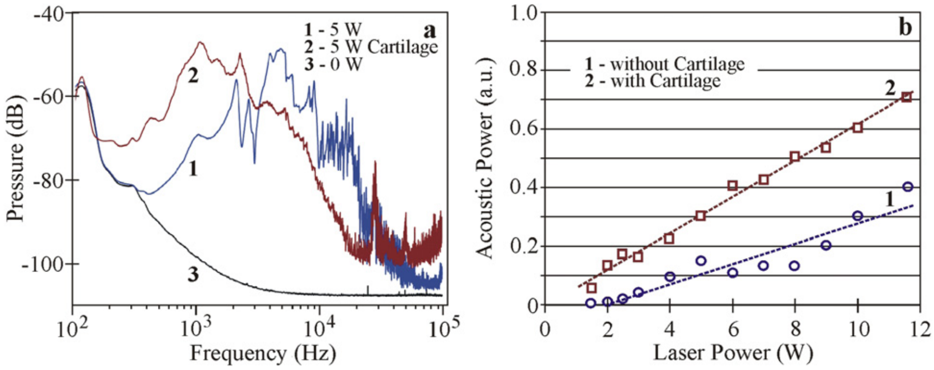

Figure 5. (a) Characteristic acoustic emission spectra; (b) acoustic emission power as a function of the laser radiation power in the cases where the hot tip of the laser delivery fiber is pressed against the surface of (1) a metal plate and (2) a cartilage plate. Stationary regime. The dashed lines indicate linear trends.

frequency around 100 kHz. Many investigators believe that this train is due to the fact that, on collapsing, the bubble pulsates at a frequency close to its natural vibration frequency, which according to [34] is given by the following expression, with the surface tension for free water being disregarded:

$$F \approx \frac{1}{2\pi R}\left(\frac{3\gamma P_0}{\rho}\right)^{1/2}, \qquad (2)$$

where γ stands for the ratio between the specific heat capacities of the bubble, ρ is the density of water, and P_0 is hydrostatic pressure. Setting $\gamma = 1.4$, $\rho = 10^3$ kg m^{-3}, and $P_0 = 10^5$ Pa, we get $R \approx 33\ \mu$m for the radius of the resonant bubble, which falls within the range of the visually observed values [1, 3].

In the up-to-date puncture technologies for treating locomotor system diseases with the aid of moderate-power lasers [4–6, 8], the hot tip of the laser delivery fiber directly contacts the water-saturated biotissue under treatment. In that case, steam-gas bubbles are generated whose evolution dynamics depends not only on the boiling of water, but also on the pyrolysis and burning of the tissue in contact with the hot tip of the advancing fiber. The specific features of the sound produced during this process were studied using a cartilage plate cut from the *nucleus pulposus* of an intervertebral disc. In our experiments, the hot tip of the fiber was pressed against the surface of a metal sheet or a cartilage plate fixed on a metal sheet immersed in water. Contact with the cartilage plate resulted in the exothermic burning and pyrolysis of the biotissue and a more intense boiling of water. Presented in figure 5(a) are the acoustic emission spectra recorded at a laser power of 5 W with and without the cartilage plate. The energy of the wideband acoustic signal is mainly concentrated in the spectral range 0.5–20 kHz, the introduction of the cartilage plate being conducive to an increase in the energy of the acoustic emission and shifting of its spectrum towards the low-frequency region. It follows from figure 5(b), which shows the acoustic emission power as a function of the laser radiation power, that on the average the acoustic emission power grows linearly with the laser radiation power (see the trends in figure 5(b)). While trend 2, which refers to the case where the cartilage plate is present, intersects the *x*-axis approximately at the point 0 W, trend 1 crosses the axis at the point 2 W. The former fact means that the optoacoustic conversion efficiency (which is determined by the ratio between the acoustic emission and laser radiation powers) in the case of cartilage plate (trend 2 in figure 5(b)) remains constant throughout the laser radiation power range used. The latter is because almost no bubble generation takes place at laser radiation powers below 2 W when the hot tip of the laser delivery fiber is pressed against the metal surface (trend 1 in figure 5(b)). One can see from figure 5(b) that when the cartilage plate is placed on the metal surface the optoacoustic conversion efficiency increases substantially (by 2–16 times), the maximum increase being observed to occur at relatively low laser radiation powers (1.5–3 W).

The increase of the optoacoustic conversion efficiency in the case where the hot tip of the laser delivery fiber contacts the biological sample can be explained as due to several reasons. Firstly, the cooling of the tip decreases as a result of a reduction in the convective heat transfer by water, for the tip is immersed in the cartilaginous tissue. Secondly, at sufficiently high temperatures (around 500 °C), the disintegration of collagen is an exothermic process, i.e., it is accompanied by heat liberation [35]. And thirdly, the thermal disintegration of the tissue causes additional gas evolution. All this adds to the generation of steam-gas bubbles and intensifies acoustic emission.

The experiments conducted in the regime of channel formation with isolated spinal segments, complete with the intervertebral disc, and bovine thighbones are the most akin to the up-to-date medical laser technologies for treating osteochondrosis and osteomyelitis, respectively. In the experiments where the spinal segment was fixed on the piezoelectric transducer in accordance with the scheme of figure 1(b), four 15–20-mm-long laser channels were successively formed in the intervertebral disc proper by means of an optical fiber delivering CW laser radiation of moderate power. One can see from figure 6(a) that during the course of laser manipulations the pressure within the cartilage experiences substantial low-frequency fluctuations and gradually grows higher on the average, reaching its maximum at around 180 kPa. Figure 6(b) presents a detailed shape of a wave train (retained are frequencies ≥1 Hz)

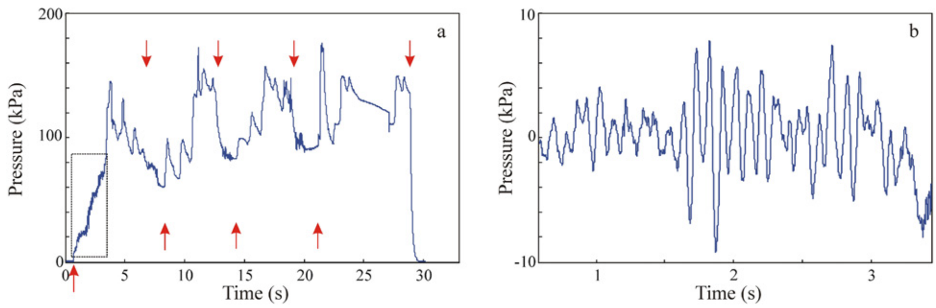

Figure 6. (a) Pressure variations within the intervertebral disc during the course of successive formation of four laser channels therein; (b) low-frequency wave train (the rectangle in (a), frequencies below <1 Hz were removed). Laser radiation power 3 W. The arrows in (a) indicate the instants the laser is switched ON (up arrows, beginning of the channel-forming process) and OFF (down arrows, end of the channel-forming process).

recorded at the initial period corresponding to the active phase of the channel-forming process. Prominent here is a spectral component with a frequency of approximately 10 Hz, whose pressure amplitude falls within the range 2–9 kPa.

The dynamics of pressure variations (figure 6(a)) occurring inside of the intervertebral disc under the effect of laser radiation is conditioned by the formation of steam-gas bubbles within the confined space of the intervertebral disc. The total evaluation of the volume of these bubbles produced at a maximum pressure of $\Delta P = 180$ kPa attained experimentally is

$$V_B = \Delta P V \beta \approx 0.9\ \text{mm}^3, \tag{3}$$

where V is the size of the confined space of the intervertebral disc ($\sim 10\ \text{cm}^3$), β is the isothermal compressibility coefficient of the biotissue (for water at room temperature, $\beta \approx 4.75 \times 10^{-10}\ \text{Pa}^{-1}$). To reach this high a pressure rise in actual circumstances, it is necessary that the volume of the bubbles formed should be greater, because of the presence of bubbles and pores in the cartilaginous tissue, the increase in the volume of the cartilage proper, and directional filtration of the interstitial fluid through the closing plates of the disc under the effect of the increased internal pressure.

If the intervertebral disc is considered as an acoustic resonator, the emergence of steam-gas bubbles with a total volume of V_B in the disc body will result in a change of the natural frequencies of the acoustic modes of the resonator, which are proportional to the effective velocity of sound, c_e. It is well known that in a liquid–bubble mixture the velocity of sound of frequencies much below the bubble resonance frequency (2) is defined in terms of the effective density ρ_e and effective compressibility β_e [36] of the mixture as $c_e = 1/\sqrt{\rho_e \beta_e}$. This approximation agrees well with experiment, provided that the gas volume concentration $\varphi = V_B/V < 1\%$ [37], which is satisfied well enough in our case ($\varphi \approx 10^{-4}$). Therefore, we may take it that [36, 38]

$$\begin{aligned} \rho_e &= \rho_L(1-\varphi) + \rho_B\varphi \approx \rho_L, \\ \beta_e &= \beta_L(1-\varphi) + \beta_B\varphi \approx \beta_L + \beta_B\varphi, \end{aligned} \tag{4}$$

where the subscript L refers to the liquid and B to the bubbles. Finally, we get the following expression for the effective velocity of sound:

$$c_e \approx c_L(1 + \varphi\beta_B/\beta_L)^{-1/2} \approx 0.32 c_L. \tag{5}$$

Consider how the natural frequencies $f_n(\varphi)$ of the acoustic modes ($n = 1, 2, \ldots$) localized in the acoustic resonator change upon the emergence of steam-gas bubbles within the disc body. These frequencies are determined by the geometric resonance conditions, due consideration being given for the characteristic size L of the resonator and effective velocity of sound, c_e:

$$f_n(\varphi) = \frac{c_e(\varphi)n}{2L} = f_n(\varphi = 0)(1 + \varphi\beta'/\beta)^{-1/2}. \tag{6}$$

According to expressions (5) and (6), the laser-induced generation of steam-gas bubbles with a volume concentration of $\varphi \approx 10^{-4}$ within the bulk of the disc will result in a three-fold reduction of the velocity of sound and natural frequencies of the acoustic modes therein. For this reason, one should expect that the frequencies of the acoustic signals generated in a biological tissue under the effect of laser radiation would shift towards the low-frequency region, in line with the progress of the hot tip of the laser delivery fiber.

Such shifting of the frequencies of the generated sound was recorded when moving the laser delivery fiber into the biotissue of the intramedullary cavity of a bovine thighbone placed in a water-filled container. Figure 7 presents the wavelet diagram of the acoustic signal generated in this case. It follows from the figure that the position of the local frequency maximum periodically changes (at a period around 26 s) from $\sim$3.7 to $\sim$1.7 kHz and then returns to its initial position in a stepwise fashion. We associate the periodic lowering of the natural frequencies of the resonator (the intramedullary cavity) with the emergence of bubbles in the region of contact between the hot tip of the laser delivery fiber and the water-saturated tissue.

The return of the sound frequency to its initial value is explained by the periodic escape of the bubbles from the volume of the intramedullary cavity and bone, which was visually observed to occur in the experiment. One can readily find from expression (6) that the lowering of the natural frequency of the resonator from $\sim$3.7 to $\sim$1.7 kHz can be due to the increase of the volume concentration of the bubbles to $\sim 2.7 \times 10^{-4}\ \text{mm}^3$ (additional bubble volume $\sim 1.7\ \text{mm}^3$).

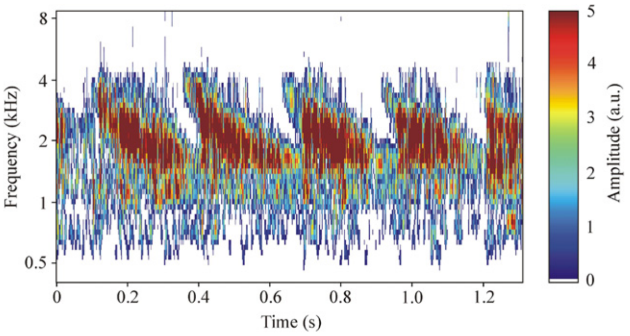

Figure 7. Wavelet diagram of the signal generated in the intramedullary cavity of a bovine thighbone under the effect of laser radiation in the regime of channel formation. The laser radiation power is 3 W.

The recorded periodic saw-toothed variation of the position of the local frequency maximum of the acoustic signal over the range 1.7–3.7 kHz can apparently be explained by the periodic gradual increase and stepwise reduction of the volume concentration of bubbles in the intramedullary cavity of the bone. Within the scope of this approximation, one can easily find from expression (6) that the natural frequency of the acoustic mode of the intramedullary cavity being observed, which amounted to ∼11.5 kHz in the absence of bubbles, decreased to 3.7 kHz, when the volume concentration φ of bubbles reached some 10^{-4}, and then dropped further down to 1.7 kHz each time the volume concentration of bubbles increased periodically to $\sim 2.7 \times 10^{-4}$ mm^3 (additional bubble volume ~ 1.7 mm^3).

4. Conclusion

In this work, we studied specific features of acoustic signals generated at the hot blackened end face of an optical fiber (the so-called hot tip) delivering moderate-power (1–10 W) 0.97-μm CW laser radiation in contact with water or a water-saturated biotissue. The experimental materials included bovine thighbones and isolated human spinal segments, complete with the intervertebral disc. The experiments showed that near the hot tip of the laser delivery fiber a wideband acoustic signal was generated as a result of the formation and collapse of steam-gas bubbles [1, 3]. The characteristics of this signal were found to depend substantially on the object under treatment and the actual treatment scheme used. For example, placing the hot tip of the laser delivery fiber in a resonator in the form of a water-filled glass capillary results in the development of a distinct amplitude modulation (with a period around 0.1–1 s) of the high-frequency noise produced. Such a resonant character of the acoustic signal generation, which consists in the emission of a quasiperiodic (with a frequency of 20–100 Hz) train of pulses, is also observed when pushing the hot tip of the laser delivery fiber under the regime of channel formation conditions through a human intervertebral disc or the intramedullary cavity of a bovine thighbone. Each of such pulses develops as a result of an explosive growth and collapse of a steam-gas bubble in the contact region between the hot tip of the laser delivery fiber and the water-saturated tissue. The efficiency of generation of the steam-gas bubbles was demonstrated to grow substantially higher because of the exothermal disintegration and pyrolysis of the biotissue. The resultant short (≤ 1 μs) pressure pulses 20 ± 15 MPa in amplitude destroy the tissue at a distance of 20–50 μm from the tip of the laser delivery fiber, which facilitates the further parting of the biological tissue and its saturation with steam-gas bubbles and results in the formation of a laser channel at a rate of some 0.4–5 mm s^{-1}. Recorded immediately following a high-power short pulse are damped vibrations resulting from the excitation of the resonance frequencies of the steam-gas bubbles and the natural vibrations of the acoustic modes of the biotissue. When forming laser channels in an intervertebral disc in accordance with the up-to-date medical technologies for treating osteochondrosis, the pressure within the cartilage experiences considerable low-frequency fluctuations in the range 0.1–10 Hz and gradually rises on the average up to around 200 kPa. A similar picture is also observed when forming laser channels in a bovine thighbone (in accordance with the osteomyelitis treatment technology). Such a pressure variation dynamics is conditioned by the laser-induced development of steam-gas bubbles in the confined space of an intervertebral disc or the intramedullary cavity of a bovine thighbone, whose emergence makes the biotissue more compressible and thus lowers the natural frequencies of its resonance modes. Such an energy transfer from the high- to the low-frequency region was experimentally verified. It should be noted that such optoacoustic effects should occur when using not only continuous wave, but also pulsed laser radiation, and of different wavelengths at that [6, 39]. Incidentally, where the exposed biotissue features a high absorption coefficient for laser radiation, so that practically all of the laser energy is absorbed near the hot tip of the laser delivery fiber, the fiber tip need not necessarily be blackened.

As regards their frequency and amplitude characteristics, laser-induced acoustic vibrations are quite capable of exerting effects on biotissues by triggering various mechanobiological [7, 40–42] and acoustobiological [43, 44] processes. The results of investigations into the effect of optoacoustic phenomena on biological tissues will be presented in our next work of this cycle.

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