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Real-time control procedures for laser welding of biological tissues

A. ZAJĄC[1], D. PODNIESIŃSKI[1], D. KĘCIK[2], M. KĘCIK[2], and J. KASPRZAK[2]*

[1] Institute of Optoelectronics, Military University of Technology,
2 Kaliskiego St., 00-908 Warszawa, Poland
[2] Cathedral and Clinic of Ophthalmology, Medical University of Warsaw,
4 Lindley‘a St., 02-091 Warsaw, Poland

Abstract. In this contribution an optical method of controlling the state of soft biological tissues in real time, exposed to laser radiation is discussed. The method is based on the assumption that the change dynamics of the amplitude of the scattered diagnostic radiation ($\lambda = 635$ nm) is compatible with the change dynamics of the tissue inner structure exposed to the Nd:YAG laser radiation ($\lambda = 1064$ nm). In this method the measurement of the tissue temperature is omitted. Exemplary results of the laboratory research on this method and an interpretation of the results are presented.

Key words: laser therapy, medical lasers, tissue welding.

1. Introduction

The main aim of the laser welding process of biological tissues is the advancing of processes connected with a postoperative wound union. Tissue welding relies on obtaining a local coagulation focus on both sides of the tissue incision. Two fundamental phenomena play a very important role here: the union of the tissue heated up and an increase in collagen fibers within a coagulated region. In practice, the union is realized by means of a local temperature change of a tissue region irradiated by laser radiation. This process is very complicated and currently it is not fully described. Obtaining the correct thermal union and not big coagulated region at the same time requires meeting very critical conditions concerning the laser radiation power, the selection of the proper work regime of a device and, what is particularly important, the assurance of a very accurate temperature control of an irradiated tissue. Additionally, the welding process realized correctly requires the control of the tissue temperature in real time and, according to literature [1–5], it should be realized with the accuracy of $\pm (1 \div 3)$°C round the coagulation temperature of the tissue protein. The absolute value of the coagulation temperature depends on the tissue type, the exposure time and equals from 65°C to 95°C (for human tissues) [6].

In medical tests done so far the temperature of the welding process of a specific biological tissue type is estimated experimentally [7]. The developing of models of heat exchange in tissues is very helpful in this case. In order to study a proper model concerning the laser beam interaction with tissues it is necessary:

- to know energetic and spectral parameters of a laser beam – that is: wavelength, power (for continuous work), energy, pulse duration and repetition rate (for pulse generation),
- to know the value of optical parameters of a tissue in the interaction region which is (for the sake of complicated micro- and macroscopic tissue structure) a fundamental difficulty in obtaining correct modelling results,
- to know the parameters of the body fluid flow in an interaction region.

For these reasons, in the laser welding process, the valuations obtained are only the first approximation. The heterogeneity of optical parameters both in case of individual organs and groups of organs chosen from the population very often exceeds 50% of the average value. It makes the suitable selection of laser parameters difficult for the laser welding process.

The welding process control is carried out in practical systems by measuring the tissue temperature during its welding. This measurement can be curried out by means of contact methods (characterized in case of the laser radiation exposition by low accuracy) or non-contact methods (effective but requiring expensive instrumentation).

The contact methods, for the sake of the limited accessibility to a relatively small operating region and the need of measuring probe insertion on a tissue surface near the place of a laser radiation interaction, are inconvenient for medical applications and cause additional problems connected with the probe sterilization. These methods are mainly used in laboratory research on a laser radiation interaction with segments of biological tissues.

The non-contact temperature measurement of a tissue can be done with the use of thermovision cameras, special pyrometer systems or MRI technique [4, 8].

In many literature reports it is emphasized that the effect of a laser radiation interaction with a tissue is supported by the application of activators – the most often ICG (indocyanine green) [3, 5, 9]. The tissue temperature stability assurance during the laser radiation exposure allows performing the appropriate tissues union (suitable union strength, tight-

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*e-mail: kasprzak@amwaw.edu.pl

ness) [3, 10, 11]. To reach this aim, medical laser devices require applying additional devices allowing controlling its output parameters.

All the methods of the tissue state control within an exposure region, for the sake of the narrow range of a temperature change allowing obtaining the correct weld, are used in the feedback system – combine thermal parameters of a tissue with laser beam parameters selected in real time.

The feedback systems applied allow changing the laser output power, time parameters of generated pulses. They are also responsible for stopping the laser generation when the planned effects are reached. Thanks to such solutions the possibility of obtaining the incorrect weld and (in extreme cases) the permanent thermal tissue damage including carbonization is limited.

The idea of the biological tissue laser welding is known for many years. However, there is still the lack (except the contribution [12]) of reports confirming the implementation of this method in clinical practices. It is commonly known that the basic problem here is to achieve the precise control of physical processes occurring in tissues welded during an operation. To this end some authors propose the use of physical processes occurring in tissues coagulated, which leads to the change of optical characteristics of the tissue heated.

2. Materials a method

The methods of the automation processes of the welding and the coagulation of a biological tissue quoted in [1–4] require using the unique measurement apparatus and carrying out complicated computational processes. However, it is known that a local increase in tissue temperature caused for instance by laser radiation absorption makes the tissue structure change – if the temperature value exceeds the value of the coagulation temperature. The tissue structure changes for constant chemical composition cause crucial changes of the scattering coefficient of the medium whereas the absorption coefficient value is almost constant. The local change of the scattering coefficient of a biological tissue in the region of the laser beam interaction causes a crucial change in the spatial distribution of the backscattered radiation (Fig. 1). Analyzing the data presented in Fig. 1, after exceeding the value of the coagulation temperature, the indicatrix of the radiation backscattered in the tissue changes. To control the current state of the inner tissue structure during the welding process, the changes of spatial distribution of the backscattered radiation flux were accepted [13]. The value changes of optical signals determining the tissue state can be recorded in a wide angle range $\alpha = \pm(5 \div 85)^\circ$, but in practice it is not necessary to record in a full range of the half space over a tissue.

In order to eliminate the optical signal variation connected with the change of the absorption coefficient in the tissue heated, two solutions are applied. A laser used for the tissue heating is a laser generating radiation in the range of $1 \div 1.5$ μm – e.g. Nd:YAG laser. However, the diagnostic of the tissue changes is realized with the use of the radiation of a semiconductor laser emitting in a visible range. For the wavelengths applied, the significant differences of the absorption coefficient value of biological tissues occur. These changes, depending on a tissue type, reach even three orders of magnitude [14]. Thanks to that, it is possible to describe a tissue state objectively – on the basis of the optical parameter changes.

The Nd:YAG laser radiation is used for tissue heating. The Nd:YAG laser generates radiation at the wavelength of 1064 nm and works in pulse mode. Applying the pulse exposure is a very effective way of tissue heating. Here, for the same energy absorbed in a tissue, the temperature change may be several times higher than in case of a continuous exposure [15]. During the experiments conducted the pulsed Nd:YAG laser characterized by the smoothly controlled pulse energy (from the range of $0 \div 9$ J) and pulse duration (from the range of 1 μs to 9999 μs) was applied. The maximum peak power of generated pulses equaled 900 W. A semiconductor laser working in CW regime, generating 5 mW of the output power at the wavelength of 635 nm was used as a source of the diagnostic radiation.

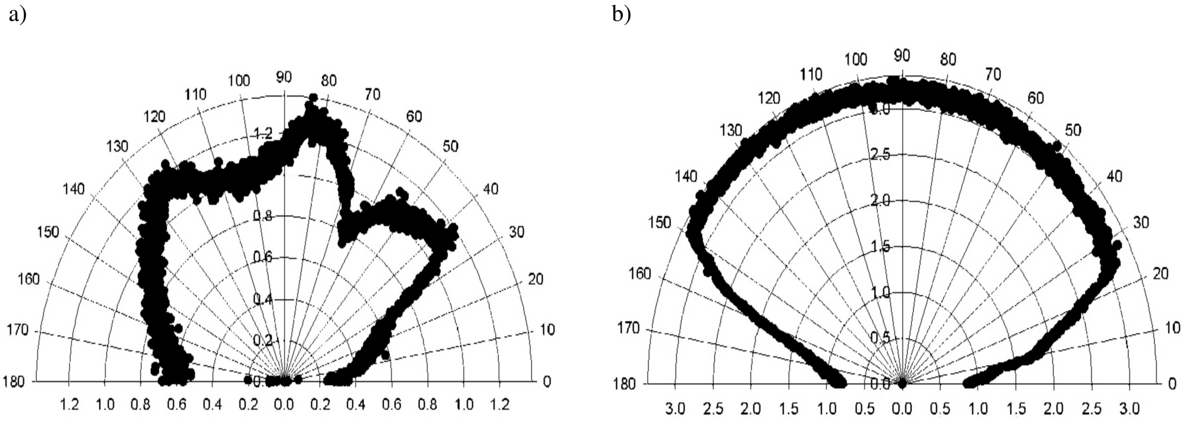

Fig. 1. Change of the indicatrix of the scattered radiation flux for the liver tissue vs. the change of the tissue temperature: (a) below the coagulation temperature, (b) above the coagulation temperature

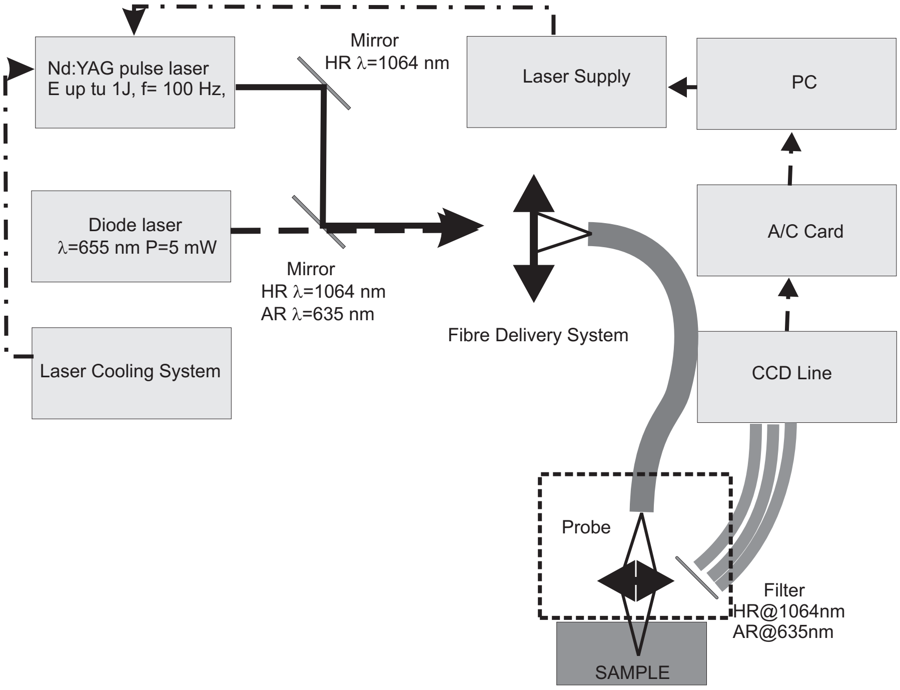

Fig. 2. Diagram of the optical system designed for the real time control of tissue parameters

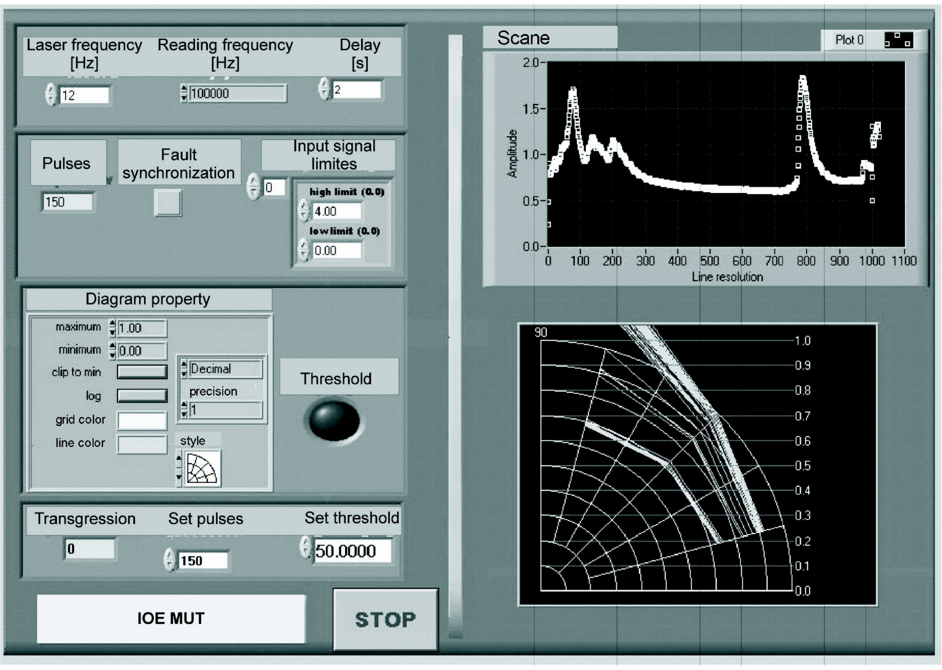
Laser frequency [Hz]: 12
Reading frequency [Hz]: 100000
Delay [s]: 2
Pulses: 150
Input signal limites: 0
high limit (0.0): 4.00
low limit (0.0): 0.00
maximum: 1.00
minimum: 0.00
Decimal
precision: 1
Transgression: 0
Set pulses: 150
Set threshold: 50.0000

Fig. 3. Visualization of the graphical interface of the computer program designed for the measurements and control of the Nd:YAG laser work and its parameters. The oscilloscope pictures of optical signals coming from the CCD line (at the top) and the angular distribution of the changes of the scattered radiation flux (at the bottom) are depicted on the right of the picture

The laser system set-up along with the optical system designed for the control of the tissue parameters in real time is shown in Fig. 2. To control the exposure parameters and the state of tissues irradiated, the PC computer with the suitable software developed was applied. The visualization of the graphical interface of the computer program is presented in Fig. 3. The semiconductor laser generated the diagnostic radiation penetrating deeply into a tissue. It also performed a function of a pointer determining the place of the laser radiation interaction. The radiation of the Nd:YAG laser (with the output parameters regulated smoothly) and the semiconductor laser were transmitted to the biological tissue surface by means of the same optical fiber. The operative probe equipped with an optical system was designed for forming the radiation distribution on the tissue surface. This probe performed two basic functions: it allowed determining the spot diameter on the tissue surface and it made the transmission of the scattered light to the measurement system (thanks to receiving fibers mounted in a special applicator) possible. In the system described the change recording of the amplitude of the spatial scattered radiation was done by means of three optical fibers located at the angles of $\alpha_1 = 30°$, $\alpha_2 = 45°$, $\alpha_3 = 60°$ towards the direction of the incident Nd:YAG laser radiation. The amplitude changes of the optical signals observed were recorded by means of a CCD line. The recorded values of the optical signals measured allowed determining the changes of the spatial distribution of the scattered radiation during the tissue heating. The signal processing was realized by means of a PC computer equipped with LabView 6.0 software (National Instruments). The start, control (repetition rate, number of generated pulses) and the stop of the Nd:YAG laser were carried out by adequate commands given by the user of the software. The amplitude change dynamics of the scattered radiation flux in real time was demonstrated on the monitor display in the form of the polar graph (for three optical fibers used). Additionally, it was recorded in the computer memory as the numerical data (data set of *.txt type). The program also allowed determining the coagulation moment – by the control of the amplitude change dynamics of the signal recorded.

The research connected with the tissue susceptibility to the creation of the coagulation focuses and the laser welding in “in vitro” conditions were carried out. The basic biological tissue examined was a muscular tissue of a chicken and a rabbit.

3. Results

The laboratory research carried out permitted the realization of three main aims:

- determining the moment of a tissue coagulation – on the basis of the characteristics presenting the change dynamics of the scattered radiation amplitude,
- determining the energy dose of the Nd:YAG laser radiation required to achieve the coagulation process of a muscular tissue,
- determining the moment of welding two parts of a muscular tissue – on the basis of the characteristics measured presenting the change dynamics of the scattered radiation amplitude.

To this end, a number of experiments consisting in the muscular tissue exposure with the use of the Nd:YAG laser radiation (characterized by different output parameters) was done (Fig. 4). The energy of output pulses was controlled by the change of the laser pulse duration (within the range of 120÷500 μs) and the change of the output voltage of the laser discharge lamp (within the range of 350÷600 V). The repetition rate, the number of generated pulses and the laser beam diameter on the tissue surface are also very important for the tissue coagulation process (Fig. 5). All the attempts of the tissue coagulation obtained for the Nd:YAG laser working at the repetition rate below 12Hz (independently from the pulse energy and the pulse duration) turned out to be ineffective. The satisfactory effects were achieved at the repetition rate above 15 Hz. However, it required delivering a relatively high dose of energy to a tissue (over 3 J) as well as extending the pulse duration (up to 500 μs) and the voltage (up to 600 V).

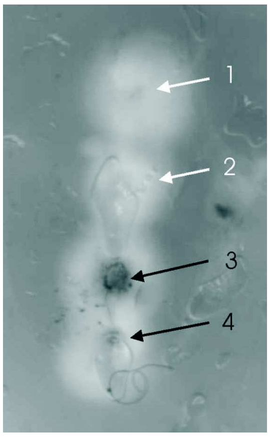

Fig. 4. Interaction effect of the laser beam characterized by different output parameters with the muscular tissue. The digits marked in the picture treat: the correct selection of energetic parameters of the laser beam (1, 2), the incorrect selection of energetic parameters of the laser beam (3, 4)

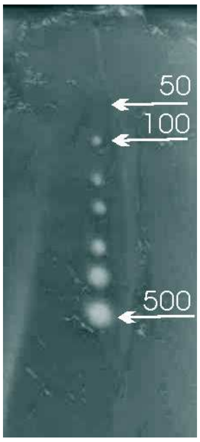

Fig. 5. Influence of the number of generated pulses characterized by stable parameters on the range of the tissue coagulation

During the automatic laser welding process the determination of the limiting changes of the tissue state was possible. Exemplary effects of the effectively controlled interaction of the Nd:YAG laser radiation with the muscular tissue of a rabbit were shown in Fig. 6. The light circle that can be seen in the middle of the photograph points at the coagulation place. The dynamics of the amplitude value changes of the spatially scattered radiation is presented in Fig. 6b. The laser action was automatically stopped when the amplitude of the scattered radiation flux reaches the maximum value. The welding effect of a tissue was observed by applying radiation characterized by pulse energy $E > 200$ mJ, pulse duration $t_i > 300$ μs and repetition rate $f > 20$ Hz. In the welding process the repetition of laser pulses is one of the important factors influencing the quality of the tissue union. This observation is consistent with the condition described in [16]. According to the author of this report, the minimum frequency of the laser work from NIR range should not be lower than 12 Hz (assuming that a suitable energy dose is delivered). The influence of energetic parameters of the laser radiation on the effect of the biological tissue welding is depicted in Fig. 7. Two pictures of the same tissue exposed to an identical energy dose but for a different repetition are presented here. The exposure effect of the tissue at the repetition rate of 10 Hz is depicted in Fig. 7a. As can be seen, the effect of the tissue union is vestigial. The tissue stratification of both parts of the tissue is seen clearly. Too low repetition rate applied did not cause the appearance of the tissue phase change. The gaps between pulses were long enough to distribute the heat in the whole tissue volume. When increasing the repetition up to 25 Hz it was possible to realize the union of two parts of the tissue. The tissue welding effect obtained with the use of the Nd:YAG laser radiation is demonstrated in Fig. 7b. In the middle part of the tissue, the lighter trace of the weld (the lightening effect) is seen clearly. The tissue chromatosis was not observed, which confirms that the tissue is not damaged thermally. The phase change phenomenon occurring in the samples of the muscular tissue covered by the perimysium was observed at the energy level lower than 25% of the value determined for the open muscle. Undoubtedly, it was connected with different thermal parameters of the muscular tissue and the epimysium. When carrying out the welding process, the shrinking of muscular fibers was not observed, which in case of the muscle cut perpendicularly to its run would cause the separation of the weld edge dehiscence. As a result of the experiments conducted for the repetition rate of the laser $f > 50$ Hz, pulse duration $t_i < 200$ μs and average energy $E_{av} < 0.3$ J, the satisfactory effects of the tissue coagulation and welding were achieved. For these conditions of the laser working it is possible to realize a muscular tissue welding process with a very slight influence on the state of the optical fiber end-faces.

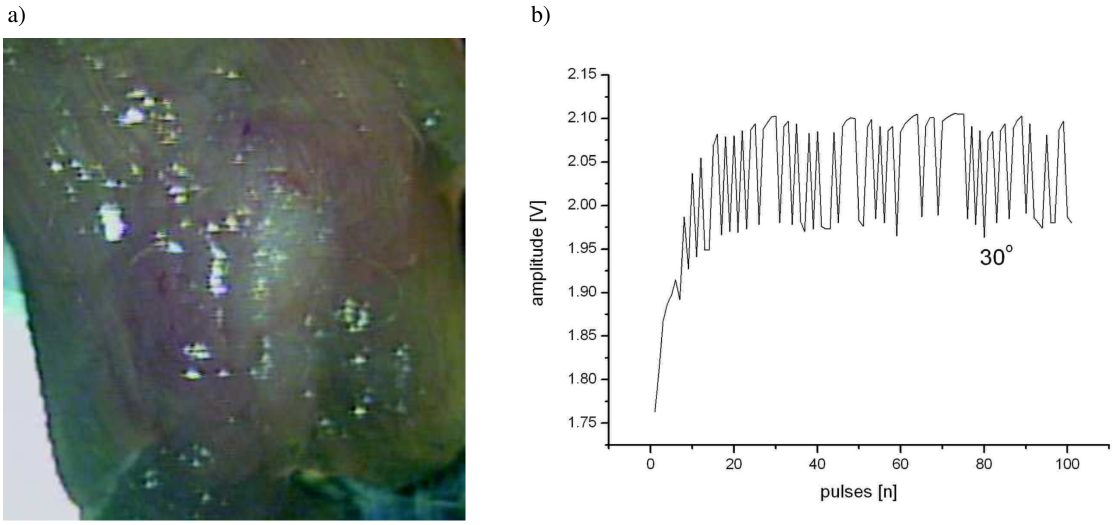

Fig. 6. Effect of the interaction of the Nd:YAG laser radiation with muscular tissue of a rabbit. The fragment of the muscle exposed to photocoagulation (a). The dynamics of the value changes of the amplitude of the spatial scattered diagnostic radiation ($\lambda = 635$ nm) for the optical signal of the feedback (at the angle of $\alpha = 30°$) (b)

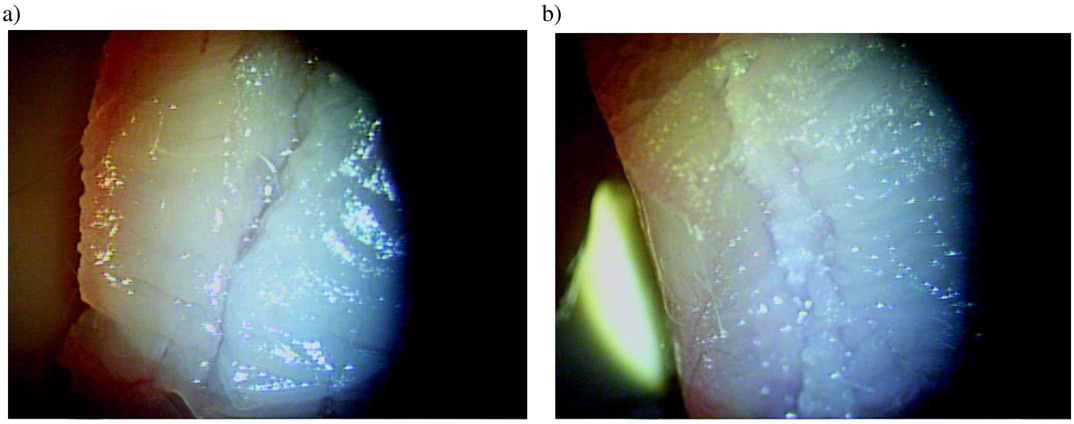

Fig. 7. Comparison of the laser welding of the muscular tissue of a rabbit depending on the frequency of pulses generated for the pulse energy of 300 mJ, the pulse duration of 400 μs, the focus diameter of 800 μm, the exposure frequency of 10 Hz (a) and 25 Hz (b)

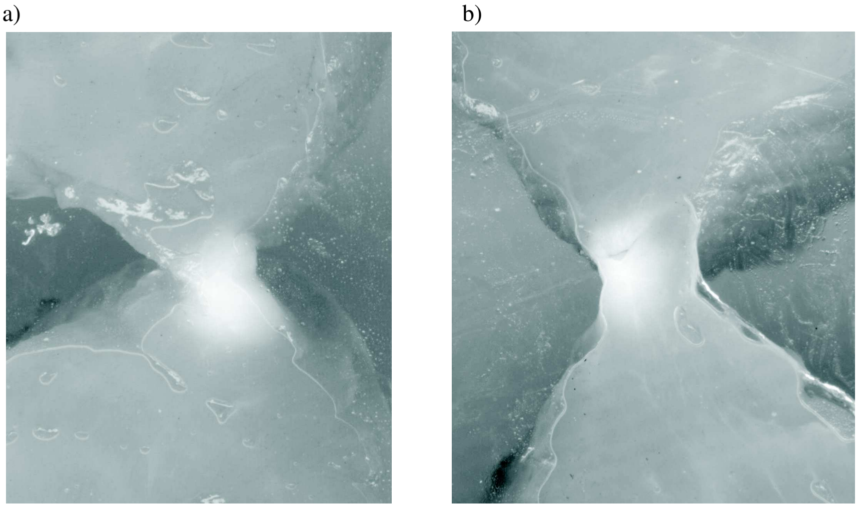

Fig. 8. Quality control of the two chicken muscular tissues done by means of hand stretching. (a) the tissue before stretching, (b) the tissue during stretching (the crack is seen in the middle part of the picture)

The example of the point welding of two parts of the muscular tissue of a chicken is shown in Fig. 8a. For the example demonstrated the following laser radiation parameters were used: $E_{av} = 0.13$ J, $t_i = 120$ μs, $f = 70$ Hz, $n = 400$. After the realization of the tissue welding the separation of this tissue edges was carried out (Fig. 8b). The correct tissue union for samples with epimysium and without epimysium as well as for a muscle cut perpendicularly to the fiber run was stated. During the laboratory examinations, for determining the strength causing breaking the welds obtained, the tensometric measurements were not applied. The satisfactory effect was to achieve the union of two parts of the tissue and the subjective evaluation of the strength causing the weld separation. Exceeding the acceptable energy dose by increasing the number of generated pulses caused the muscle shrinking and thereby causing the tissue welding effect ineffective. In order to determine the optimal parameters of the Nd:YAG laser used in the muscular tissue welding process many additional laboratory experiments were performed. For the "in vitro" muscular tissue, the influence of the changes of the repetition rate, pulse duration, pulse energy and the number of the pulses generated on was observed.

The phenomena occurring during the realization of the muscular tissue coagulation process were examined and the measurement of the scattered laser radiation was done. The exemplary changes of the scattered radiation amplitude (recorded when the observation was carried out at the angle of 30°) during the coagulation process of the muscular tissue for different parameters of the Nd:YAG laser were depicted in Fig. 9. The change of the scattering coefficient of the tissue (caused as a result of the interaction of the Nd:YAG laser radiation) is very clear and it causes a significant increase in the optical signal amplitude (for both signals). The tissue exposure with the use of the radiation of higher energy and lower repetition gives higher values of the changes recorded but simultaneously the unfavourable signal fluctuations occur. The changes of the scattered radiation amplitude in real time for different samples and different tissue exposure regions have a similar character. The non-contact method of a state control of the tissue parameters consisting in the change observation of the scattered radiation flux is possible almost in the whole range of the half space. To realize the control process of the tissue coagulation, the change observation of the optical signal coming out from one to three optical lines is sufficient. The analysis of the scattered radiation amplitude changes performed showed that the optimal solution is the location of the optical fibers at small angles with respect to the axis of the Nd:YAG laser beam. For the case presented in Fig. 10 the highest change dynamics of the optical signal amplitude is recorded for the signals received from the optical fiber located at the angle of 30° with respect to the laser beam axis. The signals coming from other receiving optical fibers situated at the angles of 45° and 60° have lower dynamics of the signal changes.

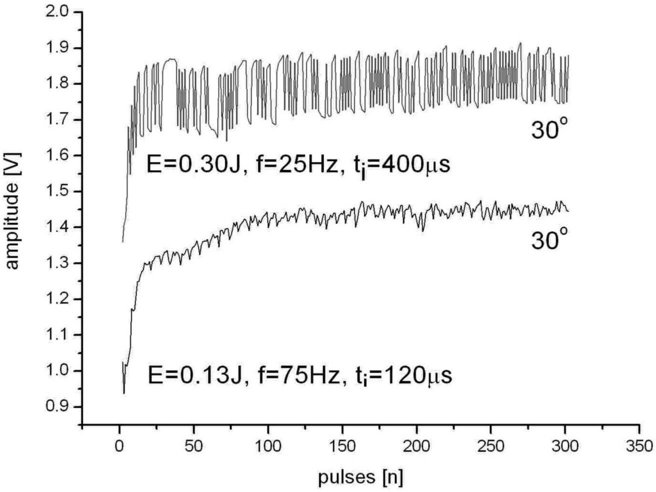

Fig. 9. Exemplary record of the amplitude change of the scattered radiation flux for two different output parameters of the Nd:YAG laser radiation

The characteristic depicted in Fig. 10 (illustrating the changes of the optical signal, obtained by means of three optical fibers, for the one coagulation point of the muscular tissue) was split into four time intervals determined by the number of generated pulses. The first interval shows the change dynamics of the radiation scattered in the tissue with the lack of energetic radiation exposure. The second interval shows the initial exposure effect using the Nd:YAG laser radiation. A strong increase in the amplitude value of the optical signal is seen here. The successive changes of the tissue parameters being the result of the thermal changes induced by the laser radiation have an impermanent character. The discontinuation of the exposure before reaching the maximum value of the signal amplitude in this range permits the withdrawal of changes in a tissue structure. This effect is impossible to observe visually. The third interval includes the preservation of changes in the tissue. The laser radiation absorption continues at a constant level. This time the tissue surface (as a result of the local temperature increase in the tissue volume caused by the laser radiation) becomes drained within the small depth causing the time decrease of the optical signal value. In this interval, the visible evaluation of the magnitude of the coagulation focus is possible. The amount of the energy absorbed in the tissue depends on the focus magnitude. The fourth interval presents a slow increase in the radiation absorption (an increase in the tissue temperature) allowing for instance carrying out the procedure of the tissue laser welding. Above this range the out-of-control phenomena in the tissue manifesting in its damage (including a carbonization) may occur.

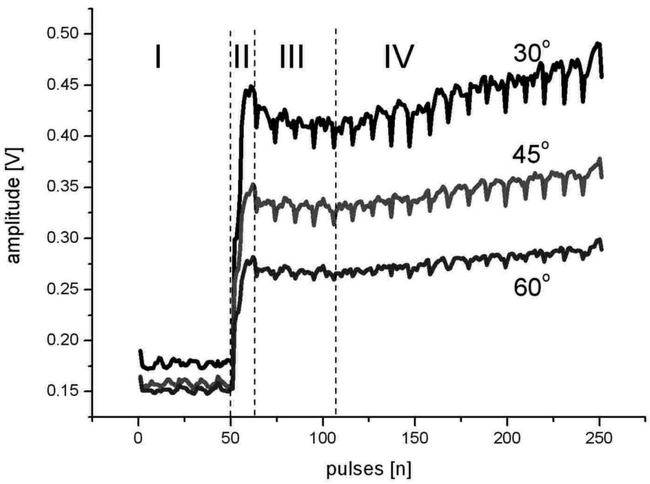

Fig. 10. Dynamics of the amplitude changes of the radiation flux scattered in the tissue for the temperature change – for the range corresponding its coagulation and recorded in real time during the laser treatment (in three optical fibers of the probe)

4. Conclusions

The fundamental disadvantages of the method of the biological tissue state control with the use of the apparatus designed for temperature measurements are connected with the temperature measurement on the tissue surface. The differences occurring as a result of the heat diffusion inside the tissue and close to its surface cause the distortion of the real value of the temperature measured. A number of factors (e.g. the ratio of the tissue volume characterized by the temperature increased as a result of the exposure to the tissue volume being in the normal temperature, the tissue surface, the quantity and rapidity of a body fluid flow, the ambient temperature) has a great impact on the value of the temperature measured. The temperature measured is lower than the real tissue temperature which leads to the necessity of the correction of the control processes – on the basis of the suitable model. The overflow of the acceptable tissue temperature and its keeping in time can cause significant and irreversible thermal tissue damages. Additionally, measurement devices applied require the location close to the field of operation – which has a negative influence on the possibility of visual observation.

The disadvantages mentioned above do not occur in the presented control method based on the optical signal recording. The probe applied is relatively small and combine sending-receiving functions. The change of the amplitude of the diagnostic scattered radiation recorded has a character of the average value (from the volume of the tissue exposed). In the aftermath of that, the optical feedback system analyzing the changes of the optical signal recorded allows determining (in real time) the moment of the tissue coagulation and controlling laser parameters.

The results of the research on the application of the measurement method developed are very promising. The relatively simple principle of operation and the universality of the method permit the application of this method in the automation of the process of the laser coagulation and in the welding of biological soft tissues. In comparison with methods based on the tissue temperature control the method proposed is characterized by the following features determining its superiority with relation to other methods:

- the recording of the scattered optical radiation as a source of information about the state of the biological tissue exposed by the laser radiation is faster and more reliable than the temperature measurement,
- the dynamics of amplitude changes of the scattered radiation recorded in real time allows the minimization of thermal damages of a tissue – by stopping the laser action exactly at the moment of the start of a phase change.
- the method utilization does not require the knowledge of optical parameters of a tissue.

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