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LASERS AND THEIR APPLICATIONS

A Physical Model of Laser-Assisted Blocking of Blood Flow: II. Pulse Modulation of Radiation

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Abstract—A method for the calculation of blocking of blood flow upon treatment of vessel pathologies by laser irradiation at a wavelength of 530 nm are considered. The model is based on the assumption that blood-vessel occlusion is a consequence of preceding photothermal coagulation of internal layers of the vessel wall. The irradiation regimes are determined that provide homogeneous and highly efficient coagulation of the vessel wall under irradiation of tissues by series of short radiation pulses.

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INTRODUCTION

This study is a continuation of our preceding investigation [1], where we considered the mechanism of blocking blood flow under laser irradiation and assumed that the experimentally observed contraction of blood vessels [2] is a consequence of photothermal coagulation of their internal near-surface structural elements. In this case, a vessel will be contracted if the temperature T of along the perimeter satisfies the following condition [1]:

$$T_{\mathrm{thr}} \le T < T_{\mathrm{vap}}, \quad (1)$$

where T_{thr} is the threshold coagulation temperature of tissues surrounding the vessel, and T_{vap} is the temperature of the vaporization phase transition.

In [1], we numerically determined the conditions of homogeneous coagulation of vessel walls upon irradiation of a model structure of skin by smooth laser pulses at the wavelength 530 nm. In particular, we showed that the coagulation of vessel walls is most efficient and selective if the exposure time is in the range $t \approx (1\text{–}3)\tau_z$, where τ_z is the thermal relaxation time. We also showed that the irradiation of skin by smooth pulses can be accompanied by a higher risk of mechanical damage of tissues near the outer boundary of the blood vessel due to the vaporization phase transition and formation of gas–vapor bubbles. As an alternative, we will consider below a possible way to reduce this risk by using irradiation with a regular series (train) of short pulses. The total duration of the train t_Σ satisfies the condition indicated above. The model structure of a biological medium and method of calculation are the same as in [1]. The same is true for the parameter notation.

RESULTS AND DISCUSSION

A possible way to reduce the risk of mechanical damage of vessel walls can be an artificial inhibition of the formation conditions of boiling centers. In particular, the heating of the vessel walls by series (trains) of short laser pulses seems to be promising. The formation of microbubbles under pulsed heating has a threshold character: upon reaching some critical temperature T_{expl}, which is determined by the thermal pulse duration t, microbubbles are formed in a cascade. For water, at $t \le 10$ μs, T_{expl} exceeds 300°C [3]. At temperatures lower than T_{expl}, the native structure of the medium can be considered to be distorted insignificantly. Therefore, the main problem of the use of the irradiation regime by series of short pulses is the creation of heating conditions at the outer surface of the absorbing layer that would correspond to or approach the conditions for explosive vaporization. Then, in (1), the maximum possible heating temperature of the medium T_{vap} will approach T_{expl}, i.e., considerably exceed the temperature of the stationary phase transition.

To protect tissues from mechanical damage due to generation of a photoinduced acoustic wave in the medium [4, 5], the maximal duration of an individual pulse in a series should be of the order of 5–10 μs. Below, we will consider the particular features for the formation of the temperature field and denaturation conditions of tissues at the boundaries of the blood layer upon interaction with a regular series of triangle pulses of the above-indicated duration. The total irradiation time t_Σ in the examples in the figures is equal to 4×10^{-2} s, which exceeds the thermal relaxation time approximately by a factor of 1.5 ($t_\Sigma \approx 1.5\tau_z$).

Figures 1 and 2 show the kinetics of heating of the outer (o) and inner (i) surfaces of the blood layer by a

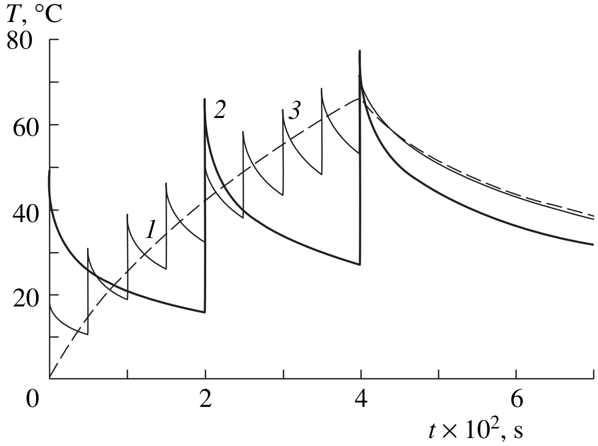

Fig. 1. Heating kinetics at points located on the axis of a laser beam on the outer boundary of a blood layer for (*2*) three and (*3*) nine pulses per series. Curve *1* shows the same dependence for a rectangular pulse with a duration of 0.04 s.

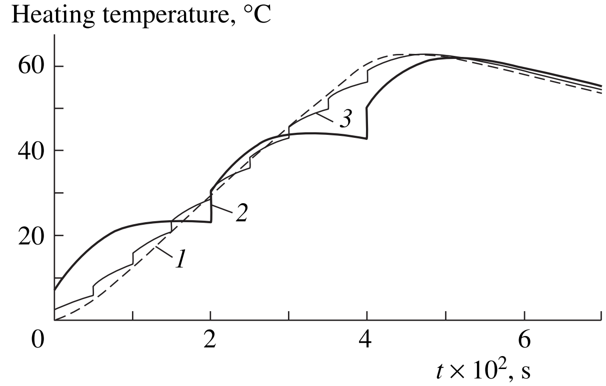

Fig. 2. Heating kinetics at points located on the axis of a laser beam on the inner boundary of a blood layer for (*2*) three and (*3*) nine pulses per series. Curve *1* shows the same dependence for a rectangular pulse with a duration of 0.04 s.

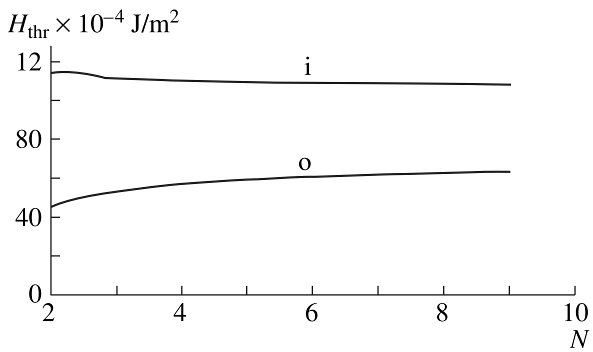

Fig. 3. Threshold radiant exposures for the inner (i) and outer (o) surfaces of a blood layer in relation to the number *N* of laser pulses per series. The total irradiation time t_Σ = 0.04 s.

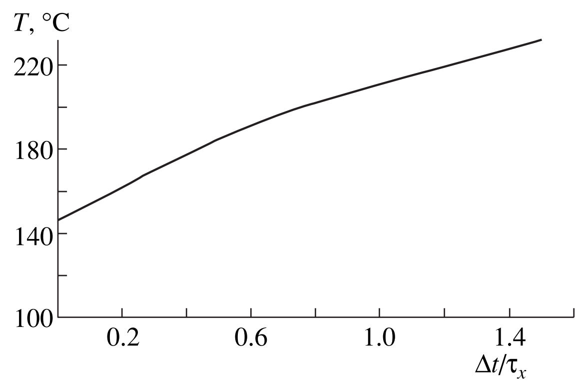

Fig. 4. Maximal temperature (°C) of the outer surface of an absorbing layer corresponding to the threshold coagulation conditions on the inner surface as a function of the pulse repetition period in the series. The calculation performed taking into account the temperature of the medium (36.7°C).

regular series of short pulses. The number of pulses per series *N* is three or nine. In all the cases shown in these figures, the radiant exposure is equal to that corresponding to the threshold denaturation conditions, H_{thr}. The dependences of the threshold radiant exposures H_{thr}(o) and H_{thr}(i) on the number of pulses per series *N* are shown in Fig. 3. It is seen from this figure that, for the complex of conditions chosen (the absorbing layer thickness ΔZ is close to the characteristic size Δz_0; the total exposure time t_Σ is of the order of $(1–3)\tau_z$), the processes of heating the inner and outer surfaces differ in a number of features. In particular, the heating of the outer surface has a pronounced pulsed character (Fig. 1). The radiant exposure H_{thr}(o) required for primary coagulation of tissues in the boundary region (Fig. 3, curve o) increases as *N* increases from two to five, which corresponds to a decrease in the pulse repetition period Δt from $1.5\tau_z$ to $0.4\tau_z$. As the pulse repetition period decreases (*N* increases), the heating conditions of the medium become more and more similar to the conditions of its heating by the rectangular radiation pulse with the duration $t = t_\Sigma$. The pulsed action on the inner surface is smoothed due to the specifics of heat exchange processes (Figs. 2 and 3). Here, the character of heating depends to a considerably smaller extent on the pulse repetition period; it is close to the heating conditions by unmodulated radiation. Therefore, the threshold radiant exposure of the inner surface of the blood vessel H_{thr}(i) virtually does not depend on the character of modulation of radiation.

The table presents the threshold temperatures T_{thr}(o) and T_{thr}(i) (calculated without taking into account the temperature of the medium) that are necessary for

Threshold heating temperature T_{thr} (°C) for the coagulation of tissues near the outer (o) and inner (i) boundaries of the blood layer

Number of pulses N per series	2	3	5	9
T_{thr}(o)	78.6	77.6	75.6	73.0
T_{thr}(i)	63.0	63.0	63.0	63.0

coagulation of tissues near the outer and inner surfaces of the blood vessel.

Two conflicting requirements should be taken into account in choosing an optimal pulse repetition rate. On the one hand, a minimal difference between the threshold radiant exposures $H_{thr}(i) - H_{thr}(o)$ is the most favorable condition for simultaneous and homogeneous coagulation of tissues near the outer and inner surfaces of the blood vessel. This difference decreases with increasing pulse repetition rate (Fig. 3). On the other hand, for the heating regime at the outer boundary to be adequately close to the explosive vaporization regime, the modulation depth of the function $T(t)$ should be the maximum possible (Fig. 1). This parameter increases with increasing pulse repetition period Δt. A compromise solution satisfying both above requirements is the choice of Δt in the range $\Delta t \cong (0.4–0.5)\tau_z$, which corresponds to values of N in Fig. 3 equal to four or five.

Let us estimate the maximal temperature of the outer surface of the blood layer for the radiant exposure corresponding to the coagulation threshold of the inner, weakly illuminated, surface (formula (8) in [1]). This dependence is shown in Fig. 4 taking into account the physiological temperature of the medium. It is seen from this plot that the maximal calculated heating temperature achieved at the outer surface of the blood vessel for the last pulse in the series is 180°C for $\Delta t \cong (0.4–0.5)\tau_z$. In this case, for the model of the medium with the properties of water, requirement (1) is formally satisfied with an assurance factor exceeding 1.5.

CONCLUSIONS

(i) The approach developed for the solution of the problem and the results presented above and in our preceding study [1] implicitly deny the expediency of attempts of some authors to find some universal radiation wavelength λ optimal for treating vessel pathologies (see, e.g., [6]). The sought value of λ in the case under consideration is determined by the characteristic size of the blood vessel Δz_0 (from the condition $\Delta z \approx \Delta z_0$),

$$\Delta z_0 = \frac{2}{k + (1-g)s}. \quad (2)$$

Here, k is the spectral absorption coefficient of blood; g is the anisotropy factor of the scattering indicatrix; s is the scattering coefficient; and Δz is the minimal linear size of the blood vessel or capillary layer to be blocked.

(ii) Under condition (2), the vessel walls efficiently and homogeneously coagulate (which, in terms of the concept of this study, means blocking the blood flow) under irradiation by rectangular laser pulses with the duration

$$t \approx (1–3)\tau_z. \quad (3)$$

However, in this case, a finite probability exists of mechanically damaging the outer surface of the vessel wall as a result of the vaporization phase transition.

(iii) The degree of this risk can be reduced using the irradiation regime of tissues by series of short (of the order of several microseconds) pulses, whose parameters are determined by the following conditions:

$$\Delta z \approx \Delta z_0, \quad t_\Sigma = (1–3)\tau_z, \quad \Delta t \cong (0.4–0.5)\tau_z. \quad (4)$$

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