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MATHEMATICAL ANALYSIS OF THERMOSTIMULATED PROCESSES THAT OCCUR DURING THE PROCEDURE OF ENDOVENOUS LASER COAGULATION OF DIFFERENT POWER

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Abstract

Varicose veins are a varicose disease of the veins of the lower extremities - dilation of the superficial veins of the lower extremities, accompanied by insufficiency of the valves of the affected veins and impaired venous blood flow. This pathology is experienced by employees who spend their working day in a sitting or standing position, ie almost all employees in the service sector. However, this is not the only cause of the disease.

These causes can also be: heredity, uncomfortable shoes and clothes, pregnancy and excessive sports stress. Information on the choice of the optimal method of surgical treatment of varicose veins associated with undifferentiated connective tissue dysplasia are virtually absent. The aim of our work is to experimentally substantiate the safe parameters of endovenous laser coagulation for the treatment of varicose veins of the lower extremities on the background of undifferentiated connective tissue dysplasia.

The thermal effect of endovenous laser coagulation energy of different power in experimental animals (Vietnamese pigs) was evaluated. Based on the equation of thermal balance, it is shown that an increase in the traction velocity leads to an increase in the energy of laser radiation at which thermal damage occurs. On the basis of mathematical analysis it is shown that the practical results of thermal damage to the walls of dysplasia and varicose vessels can be described taking into account the difference in their absorption coefficients.

Keywords: *varicose, veins, laser coagulation.*

Introduction

At present, varicose veins of the lower extremities affect about 20-50% of the population, which in its prevalence and social significance emphasizes the scale of this problem [1, 2]. The main and contributing factors play an important role in the occurrence of varicose veins of the lower extremities [3, 4]. Among the main factors should be noted the constitutional features of the structure of the connective tissue of the venous wall, namely the violation of the ratio of collagen and elastin in the venous wall [5, 6, 7].

There are almost no data on the choice of the optimal method of surgical treatment of varicose veins associated with undifferentiated connective tissue dysplasia [8, 9]. Modern intravascular obliterating treatment technologies [10, 11]. Of which the most common is endovenous laser coagulation, have become an alternative to "classic" stripping. Its safety directly depends on the minimum energy absorption of laser radiation by surrounding tissues and skin [12, 13]. However, some authors note in their works local discomfort, infiltrates, phlebitis, paresthesias in the area of intervention in the early postoperative period, which can be explained by high and excessive energy regimens of endovenous coagulation, because in most cases their choice is variable. is empirical [14, 15].

The aim of the work is to experimentally substantiate the safe parameters of endovenous laser coagulation for the treatment of varicose veins of the lower extremities on the background of undifferentiated connective tissue dysplasia.

Materials and methods

The thermal effect of endovenous laser coagulation energy of different power in experimental animals (Vietnamese pigs) was estimated. Conditions used in the analysis - optical fiber through which laser radiation is supplied with the following parameters: radiation wavelength 1.47 µm; radiation - continuous; the possibility of adjusting the power of laser radiation (10-15 W) is provided. The procedure is implemented by moving (traction) of the optical fiber in the vessel at a certain speed (mm / sec). In addition, taking into account the condition of the study of two types of vessels: type 1 - varicose veins, type 2 - varicose veins with dysplasia (hereinafter dysplasia). The latter differ in that their walls are characterized by disorganization of tissue layers. They do not have a well-defined connective tissue framework, and the inner and middle layers are thinner. In addition, they are characterized by disorganization in the structure, the violation of the composition of each of the layers, and their density, and hence the density decreases.

When working with animals, the rules of handling experimental animals were observed in accordance with the EU Council Directive 2010/63 / EU on compliance with regulations, laws, administrative regulations of the EU Member States on the protection of animals used for scientific purposes [16].

Results

The interaction of laser radiation with the material (vessel) can be described by three processes: reflection and absorption with a small depth of energy penetration into the material; conversion of radiation into heat in a thin surface layer with the subsequent increase in temperature and heating of deeper zones of material and with the corresponding transformations and reactions of melting, oxidation, etc.; moving the zone of these transformations from the surface to deeper areas of the material.

In the process of endovenous laser coagulation, the above three mechanisms are realized, both in the stationary case (the fiber is stationary) and in the traction of the optical fiber in the vessel. It is obvious that the processes that occur in the thickness of the vessel wall are associated with the absorption of energy of laser radiation by the material of the vessel wall. It is also obvious that the process of energy absorption by the vessel walls will be accompanied by the processes of heat transfer and heat dissipation of the absorbed energy by various objects in the area of interaction and near it. Such objects are the blood surrounding the vascular tissue and the optical fiber.

To describe the process that occurs with the wall of the vessel when exposed to laser radiation, you can use a model that is based on the analysis of heat balance between objects in the area of interaction.

The main objects are blood vessels and blood. Then, the equation of heat balance will look like:

$$W = Cm(T - T_0) + HS(T - T_0)$$

where T - is the temperature reached by the vessel wall under the action of laser radiation with power *W*,

T_0 = 36.6 ^{o}C,

C = 4200 J / kg - heat capacity of blood,

S is the surface area of the inner wall of the vessel irradiated for 1 second,

m - mass of blood heated per second.

Physical parameters of biological objects can differ very essentially. Therefore, for clarity in the simulation, the heat transfer coefficient was taken by us equal to:

H = 7500 W × m^{-2} × K^{-1}, and not 2000 W × m^{-2} × K^{-1}. Taking into account that:

$$m = \rho V \frac{\pi\left(d^2 - d_0^2\right)}{4}, \quad S = \pi V d$$

where *V* is the traction speed,

ρ – blood density,

d is the diameter of the vessel,

d_0 is the diameter of the fiber,

we obtain the expression for the temperature to which the vessel wall is heated under the action of laser radiation with power *W*:

$$T = T_0 + \frac{W}{\pi \times V \times \left[H \times d + C \times \rho \times \frac{\left(d^2 - d_0^2\right)}{4} \right]}$$

Assume that the change in the heat transfer coefficient of the vessel wall may be a consequence of the absence of dysplastic vessels with a pronounced connective tissue framework. The absence of a pronounced connective tissue framework in these vessels indicates their porosity, and, accordingly, we can assume that they have poorer thermal conductivity. Figure 1 shows the results of modeling the change in vessel wall temperature depending on the energy of laser radiation with a difference of 20% of the heat transfer coefficients of dysplasia and varicose vessels. It is seen that the increase in traction velocity leads to an increase in the energy of laser radiation, at which thermal damage occurs. In addition, for example, the temperature of 60 ^{o}C (Fig. 1), at which protein denaturation occurs in varicose and dysplasia vessels will be achieved at different laser radiation powers. As the traction velocity increases, the effect of the laser radiation will last less time on a specific part of the vessel, and, obviously, at the same power of the laser radiation, the temperature to which the vessel wall will be heated will be lower. Thus, we can conclude that by increasing the speed of traction, you can avoid unwanted thermal damage to the walls of the vessel.

It is possible to indirectly substantiate the increase in the temperature of the vessel wall based on the laws of radiation propagation in the environment. Consider the process of absorbing the energy of laser radiation by a wall material. It is known that the process of absorption of optical radiation is described by the law of Booger - Lambert - Behr:

$$I_{вих} = I_0 \exp[-\alpha d]$$

Where $I_{вих}$ is the intensity released from the medium,

I_0 –Intensity of incident radiation,

α - absorption coefficient,

d – thickness of the medium.

Taking into account that:

$$I_{погл} + I_{відб} + I_{вих} = I_0$$

where $I_{погл}$ is the absorbed intensity,

$I_{відб}$ - reflected from the environment intensity and assuming that:

$$I_{відб} = I_{вих} = 0$$

we can write the equation for the intensity that is absorbed by the medium:

$$I_{погл} = I_0 - I_0 \exp[-\alpha d]$$

Take into account the fact that in the process of dysplasia there is a change in the size, shape and structure of cells. It can be assumed that such an optical characteristic as the coefficient of absorption of varicose and dysplastic tissues differs. Thus, modeling the absorption process in these tissues, we can find that dysplasia tissues absorb more energy (Fig. 2).

Zeroing of the curves was performed at thicknesses that correspond to the thicknesses of normal and dysplastic vessels.

The calculations of the absorbed energy were performed in conventional units, because the optical characteristics (absorption, reflection, scattering coefficients) for biological tissues can differ significantly, and to calculate the path of laser radiation propagation in the vessel is extremely problematic.

To model the dependences presented in Figure 2, the absorption coefficient of varicose vessels was taken equal to 15 cm^{-1}, ie commensurate with the corresponding coefficient of human colon tissue. Since there is no information in the literature on the value of the absorption coefficient of dysplastic vessels, based on the experimental fact of burning dysplastic vessels at energies lower by 20% than those at which normal vessels burn, we adopted the absorption coefficient of dysplastic vessels equal to $1.2 \times 15\ cm^{-1} = 18\ cm^{-1}$. The traction speed is considered to be the same.

From the simulation presented in fig. 2, it is seen that with such a change in the absorption coefficient, the amount of energy absorbed by the wall of the dysplasia vessel is greater than the energy absorbed by the wall of the varicose vessel, which, obviously, will increase the temperature of the vessel wall.

In general, a change in the temperature of biological tissue leads not only to histological changes, but there is also a change in the optical parameters of these tissues. Thus, when the temperature changes, the processes of protein denaturation, coagulation, formation of extracellular vacuoles, evaporation of intracellular and interstitial fluid, which are manifested in changes in tissue color, changes in their polarization properties, increased scattering and changes in absorption, with a change (obviously) dynamic increase in the temperature of the vessel wall and, as a consequence, its avalanche destruction. Given this, and taking into account that the amount of absorbed energy will determine the temperature to which the laser radiation heats the vessel wall, we can conclude that the probability of thermal damage to the dysplasia vessel is extremely high (see Fig. 1), which fully correlates with our practice.

Since it is known from practice that at radiation energies of 15 W and 12 W for varicose and dysplastic vessels, respectively, thermal damage does not occur, we performed simulations of optical energy absorption for these cases. Figure 3 presents the results of modeling the absorption of normal and dysplastic vessels at a ratio of incident intensities 15/12 = 1.25.

Figure 3 shows that the walls of the dysplasia vessel will absorb approximately the same energy when introduced into the fiber probe power at the level of 12 W, as the walls of the varicose vessel when introduced into the fiber probe power at the level of 15 W. Taking into account the peculiarities of dysplasia vessels, namely the absence of a pronounced connective tissue framework in these vessels, which leads to a more active increase in the wall temperature of such a vessel (see Fig. 1), it is obvious to reduce power below 12 W to prevent temperature damage to the vessel wall.

Figure 4 shows a simulation of the dependence of the energy absorbed by the vessel walls on their thickness for powers of 15 W, 12 W and 10 W. As can be seen from the figure, reducing the power to 10 W (or less) will further reduce the energy absorbed by the wall of the dysplasia vessel, preventing its thermal damage, which coincides with the positive effect we obtained (when reducing the power to 10 W), which is confirmed by us clinically and morphologically.

Conclusions

Therefore, based on the equation of thermal balance, it is shown that an increase in the traction velocity leads to an increase in the energy of laser radiation at which thermal damage occurs. On the basis of mathematical analysis it is shown that the practical results of thermal damage to the walls of dysplasia and varicose vessels can be described taking into account the difference in their absorption coefficients.

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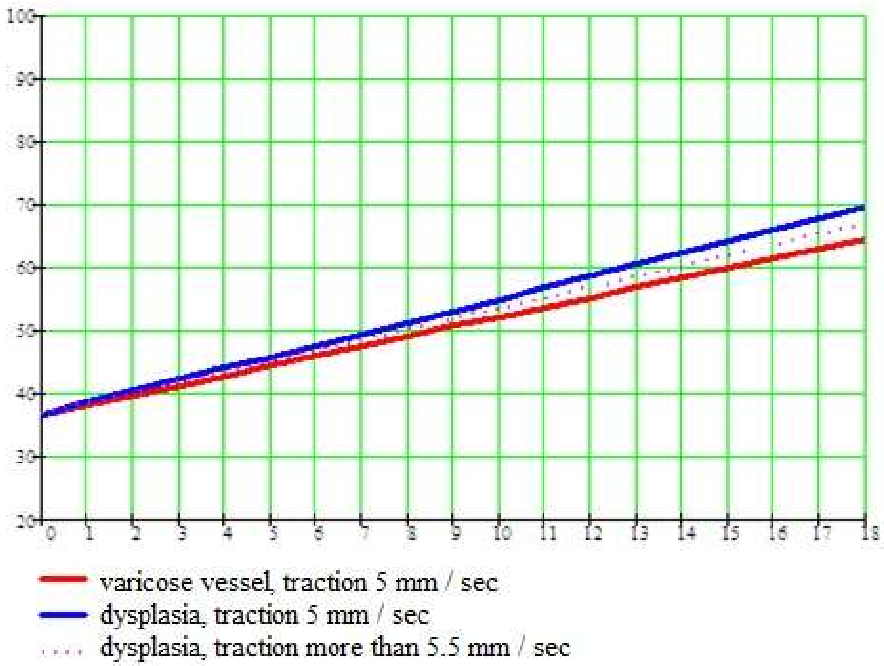

Figure 1. Dependence of the change in vessel temperature on the energy of laser radiation for varicose vessels (red solid line), for dysplasia vessel (blue solid line) and for dysplasia vessel (line marked with dots)

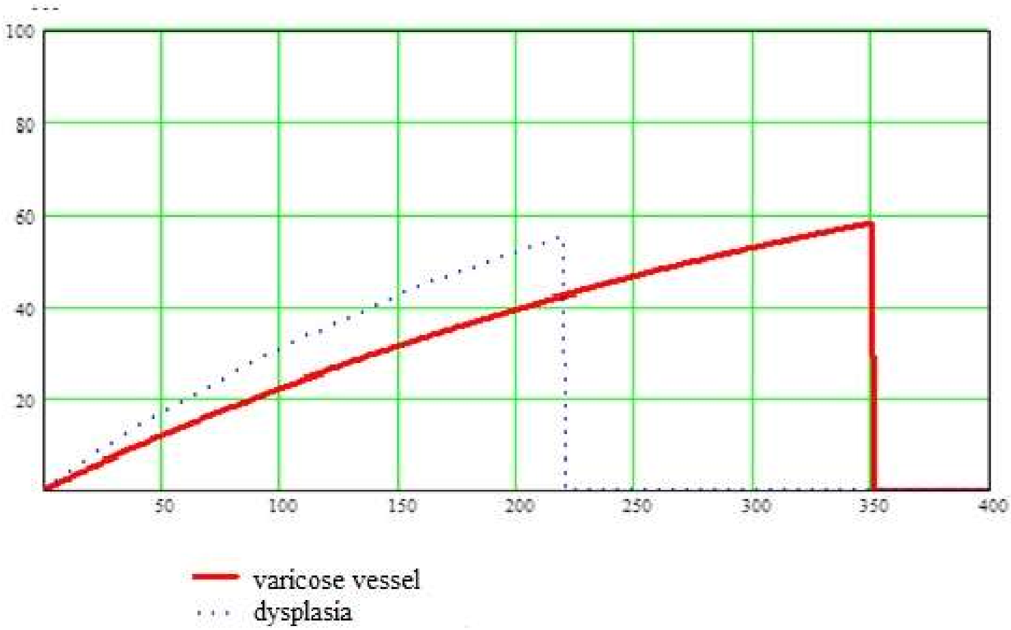

Figure 2. Dependence of absorbed energy (in conventional units) on the wall thickness of the vessel at the same energy of incident radiation: a solid curve corresponds to a varicose vessel, the curve indicated by points - dysplasia.

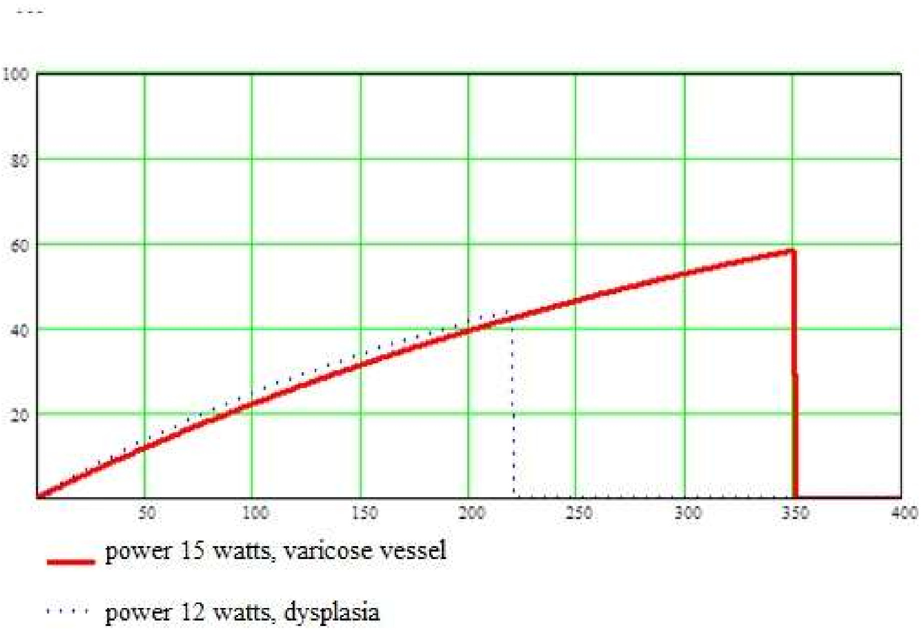

Figure 3. Dependence of the absorbed energy (in conventional units) by the vessel walls on the wall thickness of the vessel. Solid curve - for radiation power, for varicose vessels 15 W; the curve indicated by points - for power, for a dysplasia vessel of 12 W.

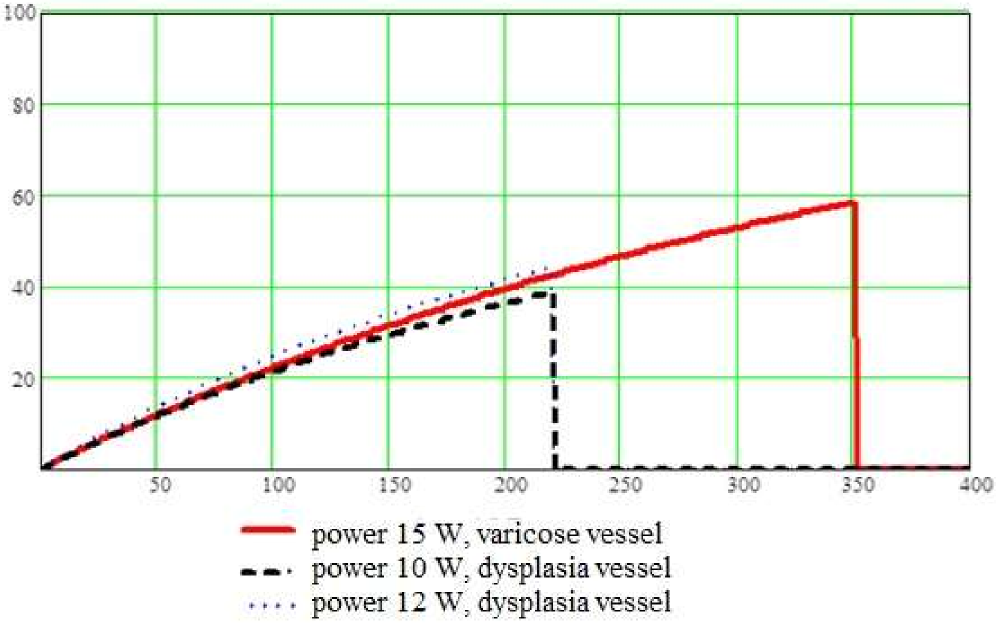

Figure 4. Dependence of absorbed energies (in conventional units) by vessel walls on vessel wall thickness. Solid curve - for radiation power introduced into the probe for varicose vessels 15 W; the curve indicated by the points - for the power wound in the probe for the dysplasia vessel 12 W; the curve indicated by a dotted line - for the power entered in a probe for a dysplasia vessel of 10 W