Optical Methods and Devices for Elimination of Carbon Monoxide Toxic Effect on Human Body

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***Abstract* — new approach to carbon monoxide poisoning treatment based on laser-induced photodissociation of the carboxyhemoglobin is proposed. Using the simple model of laser tissue interaction the action spectra of laser radiation on carboxyhemoglobin of cutaneous blood vessels has been calculated. The results of calculations indicate that there is a respectively narrow spectral range in a visible region were one could effectively irradiate carboxyhemoglobin through the tissue not in a deep distances. In the case of deeper penetration the action spectra of laser radiation shifts toward the longer wavelength region. Despite of similarity of carboxyhemoglobin and oxyhemoglobin action spectrum, significant difference on quantum yields of photodissociation makes possible to develop effective method of carbon monoxide poisoning treatment.**

***Key words* — carbon monoxide, intoxication, blood hemoglobin, carboxyhemoglobin, photodissociation.**

I. INTRODUCTION

The problem of effectively eliminating the toxic effect of carbon monoxide is an urgent and socially significant task. Up to the present, the capabilities of modern medicine remain quite limited and therefore losses as a consequence of poisoning are serious. Carbon monoxide (CO) is a product of incomplete burning of hydrocarbons and is a toxic gas without color or odor. The toxicity of CO to the human body is linked to the formation of a complex with hemoglobin (carboxyhemoglobin - HbCO), the stability of which exceeds the stability of oxyhemoglobin (HbO_2) by hundreds of times [1, 2]. Growth in the concentration of blood HbCO leads to a decrease in oxygen transport via hemoglobin (Hb) to cells of vital organs and tissues.

The half-decay rate the complex of CO with Hb is extremely low, and at concentrations of $Hb(CO)_4$ in the blood about 20%, the period of its half decay time takes more than eight hours [3]. In clinical practice usually uses forced ventilation of the lungs with pure oxygen. This methods makes it possible to somewhat shorten decay time, but it does not eliminate the problem of lethality [4] and at concentrations of $Hb(CO)_4$ in the blood higher than 60%, carbon monoxide is the main cause of hypoxia in fire related fatalities.

Currently, the method of hyperbaric oxygenation (HBO) is considered to be the most effective for detoxification; it is based on the action of pure oxygen at a pressure several times exceeding atmospheric [5]. The use of HBO_2 makes it possible to create the maximum possible concentration of oxygen in the blood, but it simultaneously results in a higher risk of oxygen toxemia as a consequence of prolonged O_2 action. Thus, the problem of effectively eliminating the toxic effect of CO remains urgent and solving it requires a new approach to developing modern, highly effective therapeutic methods.

In the present study, we propose and examine an optical method for eliminating the toxic effect of carbon monoxide, which is based on laser induced photodestruction of blood HbCO in cutaneous vessels and capillaries. The key role in development of this method is played the first proposed and earlier developed hypothesis on the role of laser induced photodissociation of oxyhemoglobin (HbO_2) in blood vessels in the mechanism of the biostimulating and therapeutic effect of low intensity laser radiation. The essence of the hypothesis is that during the action of laser radiation through the cutaneous tissue, part of the radiation is absorbed by the HbO_2 in blood vessels. As well, we can expect that with a probability of ~10%, photodissociation releases of molecular oxygen [6] and restore of hemoglobin:

$$HbO_2 \text{ -------}\rightarrow Hb + O_2.$$

This hypothesis was experimentally confirmed and summarized in our previous investigations. Development of this idea allowed examining the possible photodestruction of blood HbCO in vivo in order to effectively eliminating the toxic effect of carbon monoxide. In application to the complex of hemoglobin with oxygen, laser induced photodissociation makes it possible to additionally extract molecular oxygen directly in the zone of irradiation and thus eliminate tissue hypoxia.

In addition to this, photodissociation of carboxyhemoglobin makes it possible to restore hemoglobin's function of transporting oxygen to tissue cells. Despite the fact that the bond in the CO complex with Hb is significantly stronger than in the case of O_2 complex with Hb, the effectiveness of photodissociation of HbCO is almost an order of magnitude higher than HbO_2: 98 and 10% in the visible range of the spectrum, respectively [6]. Such a large difference in the quantum yield of photodissociation opens the possibility of destroying the blood HbCO complex with high selectivity, essentially not touching the useful HbO_2 component. At the same time as the effectiveness of known methods of eliminating the toxic effect of CO is limited by the time of natural decay of the HbCO complex, mandatory destruction of HbCO by photodissociation under simultaneous saturation of the blood plasma by molecular oxygen makes it possible to substantially hasten the removal of CO from the body.

The basis of the suggested method is irradiation of blood vessels and capillaries by optical irradiation of a certain wavelength. As well, the majority of energy absorbed by blood HbCO will be expended on photodissociation. We present here the results of investigation the effect of optical radiation with HbCO in cutaneous blood vessels and capillaries and the method of its effective photodissociation.

II. NUMERICAL SIMULATION FOR THE OPTIMAL PHOTODESTRUCTION OF BLOOD CARBOXYHEMOGLOBIN

Study of the mechanism by which optical radiation interacts with skin tissue is the basis of developing new methods and high technology systems for photomedicine. In our study, we clearly highlight the following three main mechanisms of laser–tissue interaction: photothermal, mechanical, and photo biological. The first two mechanisms are related to the action of high energy laser radiation on tissue, and they are well studied. On the basis of first mechanism high power laser systems are used for surgery, cosmetology, ophthalmology, etc. In the other side the most interesting is the study of features of low intensity laser radiation and its effect on skin tissue chromaforms.

Analysis of the effectiveness of laser radiation interacting with oxyhemoglobin in cutaneous blood vessels shows that it is impossible to directly use the absorption spectra of Hb and its complexes obtained in vitro. The reason for this is the screening effect of the skin tissue. It is necessary to take into account the optical properties of skin in determining the most effective wavelengths for acting on the complex of Hb with gas molecules (action spectra).

Obviously, the features of optical radiation interaction in tissue are primarily determined by skin properties, as well as the wavelength and action energy. These parameters determine the penetration depth of optical radiation into skin tissue, which is important for estimating the action on blood vessels and capillaries located at different depths.

In numerical simulation, the structure of skin tissue is investigated in the form of a medium consisting of three layers, which determine its optical properties.

We perform the calculations with allowance for the following skin tissue parameters. The first is the stratum corneum (~10–200 μm), which partially reflects of incident light. The epidermis (~40–150 fm) contains the pigment melanin, which intensely absorbs light in a wide spectral range.

Melanin in skin tissue serves as a unique optical filter. From the optical standpoint, directly beyond the epidermis, of most interest is the main layer, the dermis, the width of which could reach up to 5 mm.

The dermis contains collagens, which are a source of strong scattering of light, and blood vessels. In a normal state, the rich network of arteries, veins, and capillaries predominately contain Hb and HbO_2. In addition, hemoglobin can form complexes with CO and NO, which hinder oxygen transport. At concentrations of HbCO in the blood of more than 30%, oxygen transport drops to such an extent that there is a high probability of lethality.

Cutaneous blood vessels are mainly situated at two levels: close to the epidermis and deep at the interface with subcutaneous fatty tissue. In addition, a vast network of capillaries almost completely fills the entire bulk of skin tissue, supplying every cell with oxygen. Paying attention to this factor in numerical calculations by the Kubelka–Munk model [7], we assumed a homogenous distribution of the main chromophores over the corresponding layers.

Such an approach makes it possible to simulate and obtain qualitative data on the interaction of light with skin tissue components [9]. Figure 1 shows the typical spectra of Q band absorption of oxyhemoglobin, carboxyhemoglobin, and hemoglobin (Hb) in vitro, which are used in calculating the action spectra of Hb, HbO_2, and HbCO at various depths of the skin tissue.

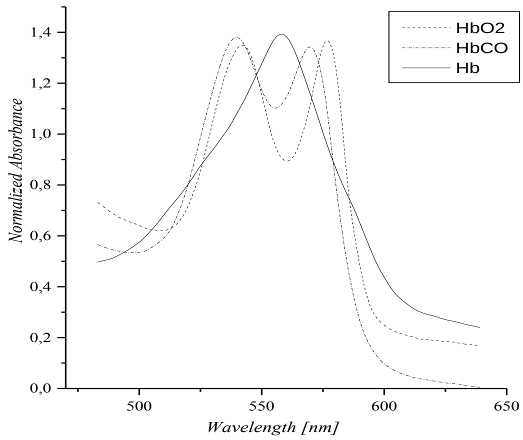

Fig1. Absorbtion spectra of hemoglobin (Hb), oxyhemoglobin (HbO2) and carboxyhemoglobin (HbCO)

In calculations, we chose the Hb, HbO_2, and HbCO absorption bands in the spectral range of 480–650 nm, since in the shortwave region, optical transmission of skin drops sharply and light does not penetrate skin tissue. Figure 3 shows the calculated action spectra of Hb, HbO_2, and HbCO in blood vessels situated at a depth of 1 mm from the surface of the skin.

As is seen, the maxima of effective Hb, HbO_2, and HbCO absorption bands are shifted to the long wave spectral region, and the bandwidth narrows significantly. It is noteworthy that HbCO, in contrast to Hb and HbO_2 (see Fig. 2), does not absorb in the near IR and IR regions of the spectrum.

Absorption spectra of Hb and HbO_2 have respectively strong bands in the near and IR spectral regions.

Note that the optical properties of actual skin strongly depend on the concentration of melanin in the epidermis and hemoglobin in the dermis, which substantially change from individual to individual. Thus, the results of numerical simulation allow us to determine only the qualitative characteristics of the interaction of optical radiation with tissue.

The results of investigations clearly show the possibilities of solving the urgent problem of neutralizing the toxic effect of CO by photodissociation of blood HbCO.

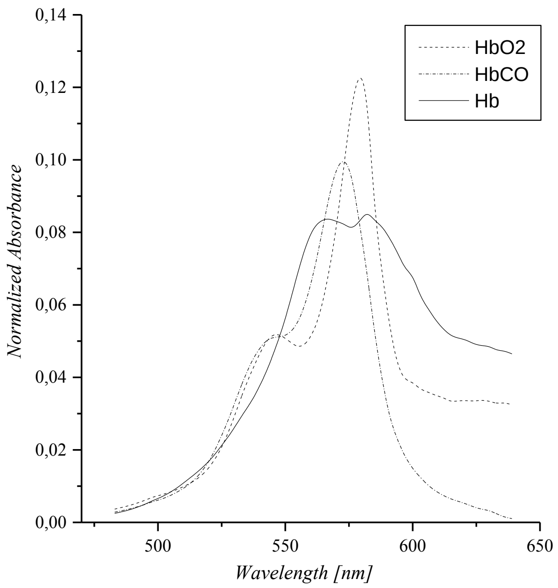

Fig2. Absorbtion spectra of hemoglobin (Hb), oxyhemoglobin (HbO2) and carboxyhemoglobin (HbCO) in the depth of 1mm

The results show that the effective Hb, HbO_2, and HbCO absorption bands in cutaneous blood vessels differ from the absorption spectra obtained in the absence of the screening effect of skin tissue. So, the maxima of the obtained spectra are shifted to the long wave spectral region and depending on the depth of the skin tissue, they significantly narrow.

The shapes of the HbO_2 and HbCO absorption bands in the investigated spectral region at a depth of 1 mm are very similar and have two clearly expressed maxima at λ = 545 and 580 nm, and λ = 540 and 570 nm, respectively.

It should be noted that the action on blood HbCO through cutaneous blood vessels and capillaries is one possible way for use in clinical practice. As well, it is necessary to bear in mind the optical properties of skin for choosing the optimal parameters of optical radiation in order to effectively influence not only surface capillaries, but also deeply situated ones. We examine in more detail ways of effectively destructing of blood HbCO complexes.

IV. EXPERIMENTAL IN VITRO STUDY THE EFFECTIVENESS OF PHOTODISSOCIATION OF BLOOD CARBOXYHEMOGLOBIN

Experimental investigation the effectiveness of blood HbCO photodissociation in vitro by optical radiation with varying wavelength using the numerical simulation results was carried out [10]. In experiments, we used venous blood, stabilized by an anticoagulant heparin, EDTA. Then, this blood was saturated with pure carbon monoxide in order to transform all of the Hb into HbCO. Concentrations blood Hb and HbCO was measured by spectrophotometer [11]. Optical density of blood HbCO was measured with the spectrophotometer SF-16. Carbon monoxide was obtained by reaction of concentrated sulfuric and formic acid under heating (boiling) in an open flask with a breather tube. Concentrated sulfuric and formic acid were mixed in a 1: 1 ratio:

$$HCOOH\ (t,\ H_2SO_4)\ \text{-----}\rightarrow H_2O + CO\uparrow.$$

Blood was saturated with pure CO for 10 min., and then it was subjected to optical radiation at the wavelength of 514.5 nm with the output power of 5.5 mW.

The result of this experiment shows that only 10 min irradiation reduces the concentration of blood HbCO by 15% in comparison to the initial one. In should be noted that in analogous conditions during saturation of blood by oxygen and irradiation by wavelength of 632.8 nm at the power of 5.5 MW, no decreases in the concentration of blood HbCO is observed.

The concentration of blood HbCO is the indicator of the degree of organism intoxication that determine what the above three methods of optical irradiation is the most effective for use in clinical practice. So, at HbCO blood concentrations is less that 10% (in medical practice this is classified as weak intoxication), it is quite sufficiently to use noninvasive transcutaneous method irradiating blood vessels and capillary with optical radiation at the wavelength of 564 nm.

At concentration of blood HbCO far more than 10% but less 30% (medium degree of intoxication), it is effective to perform photodissociation of blood HbCO directly in lung alveoli by radiation at wavelengths of 540 and 570 nm using optical bronchoscope.

Finally, at HbCO concentrations >30% (severe poisoning), the most effective way is intravenous irradiation of the blood with simultaneous ventilation of the lungs with pure oxygen. As well, venous blood flows through lung alveoli and is enriched in oxygen, which leads to elimination of the toxic effect of carbon monoxide [10].

V. APPARATUS FOR EXTRACORPEREAL PHOTO DESTRUCTION OF BLOOD CARBOXYHEMOGLOBIN

On the basis of research results, obtained both in the numerical simulation of the interaction of laser radiation with blood HbCO and experimental measurements in vivo it is developed the apparatus for phototherapy the poisoning effect of carbon monoxide (see figure 3).

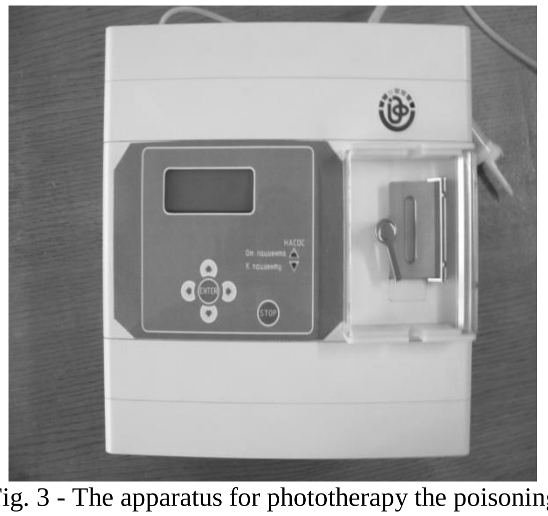

Fig. 3 - The apparatus for phototherapy the poisoning effect of carbon monoxide

This apparatus provides in vitro irradiation of blood by optical radiation in the wavelength range of 530 – 560 nm. Wavelength and the output power of the radiation chosen in accordance with the maximum of absorption bands of blood HbCO. The picture of the cassette for blood irradiation and detoxification of poisonous effect of carbon monoxide is presented in fig. 4.

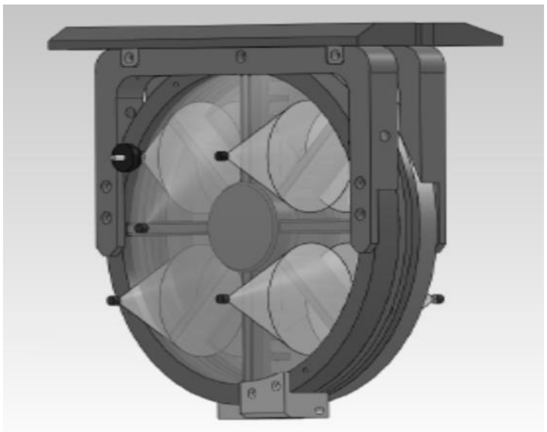

Fig.4 - The cassette for blood irradiation and detoxification of poisoning effect of carbon monoxide

As it shown in fig. 6 the cartridge with circulating blood is irradiated with LEDs from both sides in order to achieve maximum exposure. The blood circulates in the medical tube that arranged in the form of a spiral to provide the maximal volume during the irradiation with LEDs located on the both sides of the cartridge.

Apparatus for extracorporeal blood irradiation is a compact device with three main modules: a spiral cassette with a sample of blood irradiation; peristaltic pump for blood circulation and the optical system, which provides two-side blood irradiation with LED sources. Light sources are selected in accordance with the maximum of absorption bands of blood HbCO in the visible spectral range.

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The device has the following main specifications:

• Operation mode setting time installation after the inclusion of not more than 5 min.

• The speed of the flow of the blood of 5, 10 and 15 ml/min.

• Accuracy of flow rate of blood is no more than + / 20 %.

• Spectral range of the radiation from 530 to 630 nm.

• Time of continuous work of the installation is not less than 8 hours.

• Information on the modes of operation of the installation is displayed on the alpha-numeric display.

• Power supply voltage 230 ± 22 Century, with frequency of 50 Hz.

• Power consumption is not more than 80 VA.

• Overall dimensions not more than 260 × 250 × 143 mm.

• Weight of installation of not more than 7 kg.

Apparatus is equipped with the system of protection against removing the cassette during the work.

In this apparatus a planar LEDs with the selected spectral range and the output power of radiation is used. The algorithm of operation of the apparatus provides selective activation and deactivation of each LEDs that allows one to vary the different parameters of the light effects (such as the pumping wavelength of light, or a combination of wavelengths, optical radiation power, etc.) to achieve the desired therapeutic effect. It is also possible increase or decrease in the «dose» of exposure by changing the speed of pumping blood.

V. CONCLUSIONS

Optical method for eliminating the toxic effect of carbon monoxide is proposed. The method is based on light induced photodissociation of carboxyhemoglobin in blood vessels and capillaries. Criteria of efficiency of light induced photodissociation of blood carboxyhemoglobin by direct irradiation the pulmonary alveoli, through the skin, intravenously and in vitro extracorporeal methods are proposed.

Developed apparatus for extracorporeal blood irradiation can find wide application in modern medicine, and could be useful in emergency situations.

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