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THE PHOTONIC DEVICE FOR INTEGRATED EVALUATION OF COLLATERAL CIRCULATION OF LOWER EXTREMITIES IN PATIENTS WITH LOCAL HYPERTENSIVE-ISCHEMIC PAIN SYNDROME

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ABSTRACT

The given paper analyzes principles of interaction and analysis of the reflected optical radiation from biotissue in the process of assessment of regional hemodynamics state in patients with local hypertensive- ischemic pain syndrome of amputation stumps of lower extremities, applying the method of photoplethysmography.

The purpose is the evaluation of Laser photoplethysmography (LPPG) diagnostic value in examination of patients with chronic ischemia of lower extremities. Photonic device is developed to determine the level of the peripheral blood circulation, which determines the basic parameters of peripheral blood circulation and saturation level. Device consists of two sensors: infrared sensor, which contains the infrared laser radiation source and photodetector, and red sensor, which contains the red radiation source and photodetector. LPPG method allows to determined pulsatility of blood flow in different areas of the foot and lower leg, the degree of compensation and conservation perspectives limb.

Surgical treatment of local hypertensive –ischemic pain syndrome of amputation stumps of lower extremities by means of semiclosed fasciotomy in combination with revasculating osteotrepanation enabled to improve considerably regional hemodynamics in the tissues of the stump and decrease pain and hypostatic disorders.

Keywords: optical sensors, photoplethysmography, level of blood filling, biotissue, biomedical signal, local hypertensive-ischemic pain syndrome, stumps.

1. INTRODUCTION

Nowadays more and more methods, based on application of laser and optoelectronic devices are introduced in medical diagnostics. These methods include photoplethysmographic method (PPM), that enables to measure blood flow and vascularity both in basal veins and arteries and in peripheral vessels and capillaries.

The problem of violations of the peripheral blood circulation is becoming more important. In conditions of modern scientific and technological progress which is increasingly causing a negative influence on the environment, including human health, the age of many diseases associated with disorders of the peripheral blood circulation began to fall critically [1,2]. For successful treatment of a disease, it is important to conduct timely diagnosis, because identification of some problems at an early stage greatly increases the probability of the patient's full recovery. Therefore, the development of new diagnostic devices is making great contribution to the development of modern medicine [1,3,4.]

One of the promising directions of the usage of opto-electronic methods of peripherial blood circulation analysis is the application of laser radiation for the diagnostics of hemodynamic disorders in patients with local hypertensive –ischemic pain syndrome of lower extremities amputation stumps. Amputation of the extremity, besides the loss of anatomic segment, is complicated by various diseases and defects of stumps, pain syndrome being one of them , it is one of their manifestations or more frequently, independent nosology [2,6,10]. Its frequency is 60%-80%. Such high percentage of after- amputation pain syndrome development, that traditionally combines phantom, local and mixed pain shows that the given problem is not sufficiently studied and dictates the necessity of development new aproaches, aimed

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at its prevention and treatment. To assess the character and degree of blood stream damage in patients with amputation stumps such methods as arteriography, phlebography, oscillography, sphygmography, rheography, thermography, plethysmography and others are often used. However, in spite of a long list of methods and rather long period of their application, diagnostics of vascular changes and violation of regional blood circulation , especially in patients with chronic hypertensive ischemic syndrome, is not completely studied. That is why , introduction in clinical practice new methods of evaluation of regional blood circulation state (particularly, laser and optoelectronic methods) would enable not only to determine the expressiveness and severity of vascular disorders but efficiently apply pharmacotherapy. Taking into account the above-mentioned, the aim of the research is the usage of principles of interaction and analysis of the reflected optical radiation from biotissue and assessment of the state of regional hemodynamics in patients with local hypertensive-ischemic pain syndrome of amputation stumps of lower extremities, applying the method of photoplethysmugraphy.

2. ANALYSIS OF MEDICAL ASPECTS

One of the forms of local after-amputation pain syndrome is chronic hypertensive-ischemic syndrome (compartment syndrome), that is characterized by ischemic processes, developing in extremity tissues on the background of vascular diseases [1]. Central element of ischemic damages pathogenesis in amputation stump is increased intertissue pressure, that appears in conditions of closed osteofascial compartments [3,5,7]. Increase of fascial compartment pressure 1.5-2 times causes the violation of arterial-venous gradient that leads to blocking of capillary blood circulation in muscles and results in development of focal abnormalities [2]. Among the reasons of chronic hypertensive ischemic syndrome development in amputated stumps of lower extremities irrational prosthetics (tight receiving cavity, that creates increased pressure on the tissues of the stumps, narrow upper contour of the receiving cavity, improper fixation of artificial limb, uneven load) and local ischemic disorders with violation of arterial afflux and lymphovenous outflow are distinguished. Local pressure on the area of neurovascular bundle also plays certain role. It causes the violation of the outflow. The latter is increased due to tight receiving sleeve. If fitting contour of the receiving sleeve is narrow , it blocks venous outflow, because in prosthesis of malleolus both with sleeve and without femur sleeve the pressure on the stump on the level of its fitting contour exceeds physiologically admissible values 2-2.5 times. Constant traumatism of the tissues causes sclerotization of fascia superficialis that may become independent obstacle for lymphovenous outflow. Another important reason of chronic hypertensive-ischemic syndrome in the stumps of lower extremities are ischemic disorders with violation of arterial afflux and lymphovenous outflow [2,8]. Combination of these two reasons or one of them causes greater part of cases of this form of phantom-limb pains. Long duration of chronic hypertensive ischemic syndrome results in the development of the expressed trophic and necrotic changes in amputation stump and in greater part of cases requires reamputation of the stump or amputation of the extremity on still higher level [1,6].

3. PHYSICAL MATHEMATICAL MODEL OF OPTIC RADIATION INTERACTION WITH BIOTISSUE

Quite important is the development of photoplethysmographic diagnostics devices, based on the detection of reflected optical radiation or passed through the biological tissue. But the radiation intensity, that is recorded by photodetector depends on the absorption capacity of the matter, primarily, it depends on: electronic structure of molecules and atoms, the radiation wavelength, absorbing sample thickness, temperature and absorbing centers concentration[6,13,15].

In the blue region of the visible spectrum is the absorption maximum, the green and yellow (500-600 nm) regions have less absorption level and it is absorbed by the red blood cells. Shorter wavelengths are absorbed by melanin. In the ultraviolet and far-infrared regions, the light is absorbed by water. Light absorption of red and near-infrared ranges undergo least losses[17,18,19]. Therefore, for the development of optoelectronic sensors for diagnosis of peripheral blood circulation these optical ranges are used (Fig. 1).

Blood has the highest absorption capacity of the surrounding tissues, so with reducing of blood volume, the intensity of light, recorded by the detector is increased. The wavelength and the distance between the light source and photodetector determine the depth of light penetration. Green light is suitable for surface blood flow measurements in the skin. The light in the green-yellow region (5000-600 nm) has the greatest depth of modulation. Near infrared region is suitable for blood flow measurements in the deeper tissues. A red band is used to determine blood oxygen saturation[13,14].

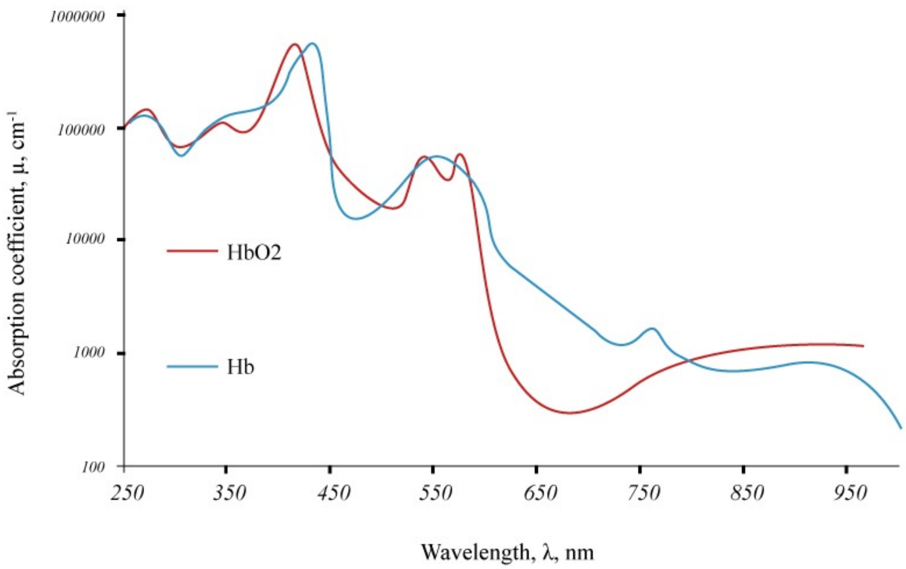


Figure 1. Dependence of the absorption coefficient on the wavelength[6,7]

Depending on the wavelength of laser radiation, entering the biotissue, 60% of it is reflected. Scattering depends on non-homogenous structures of biotissue and is determined by various refraction indices in different layers and by the difference between the layers and their environment. Waves with the length greater than the thickness of the layer are scattered by cellular structures only to minor degree. But as electromagnetic spectrum of lasers used is within the limit of IR to UV range of wavelength, as a rule, we always deal with the scattering. The depth of penetration for wavelength greater than 1.0μm can be calculated on the base of Lambert-Beer law in the first approximation [6,27,28,29,30]:

$$I = I_0 e^{-\mu d}, \tag{1}$$

where I_0 – -intensity of incident radiation

I -intensity of radiation in the tissue on the depth d;

μ -absorption factor

Lambert-Beer relation is valid in the case, when absorption exceeds greatly the scattering.

Equation, describing propagation of laser radiation in biotissue with the account of absorption and scattering, has the form[17,18]:

$$\frac{dL_c(r,z)}{dz} = -gL_c(r,z), \tag{2}$$

where $Lc(r,z)$ –density of radiation power [Wt/m^2] of the beam in the location p(location vector)in the direction z

g- attenuation coefficient (sum of scattering coefficients) [m^{-1}] and absorption [m^{-1}].

Process of optical radiation interaction with biotissue is shown in Fig.2.

Incident light beam (I_0) is partially reflected from biotissue surface, the reflected light can be divided into two components: regular (Ir) and diffusive (Id). Radiation, that penetrated in the biotissues, is partially absorbed and scattered in it. .Scattered radiation (Is), has characteristic distribution in spatial angle 2π, that is determined by optical properties of biotissue. Part of the scattered light (I_{BS}) that is not absorbed during propagation in the tissue passes through its surface in the direction, opposite to the direction of the bundle. Thus, in general case, light reflected from the biotissue, has three components: Ir, Id and I_{BS}[6].

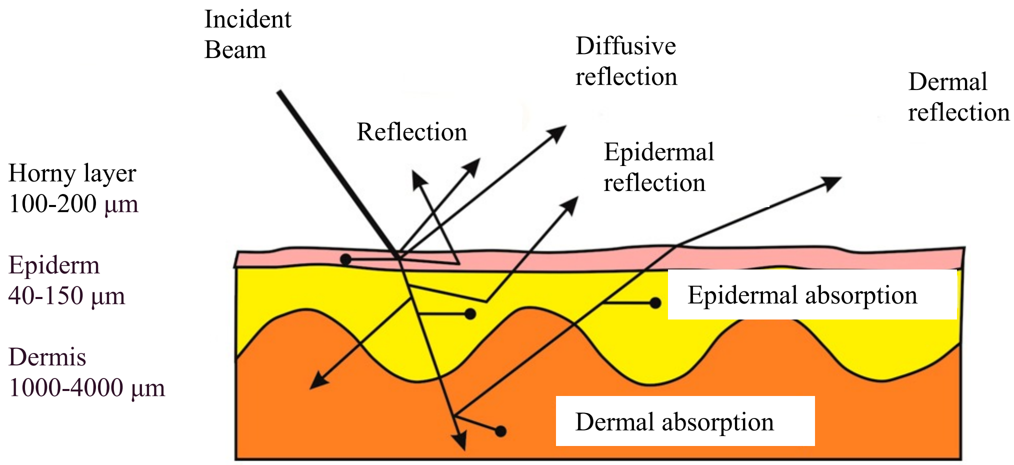


Figure 2. Optical properties of laser radiation on the soft biological tissue (skin)[6]

Incident light beam (I_0) is partially reflected from biotissue surface, the reflected light can be divided into two components: regular (Ir) and diffusive (Id). Radiation, that penetrated in the biotissues, is partially absorbed and scattered in it. .Scattered radiation (Is), has characteristic distribution in spatial angle 2π, that is determined by optical properties of biotissue. Part of the scattered light (I_{BS}) that is not absorbed during propagation in the tissue passes through its surface in the direction, opposite to the direction of the bundle. Thus, in general case, light reflected from the biotissue, has three components: Ir, Id and I_{BS}[6].

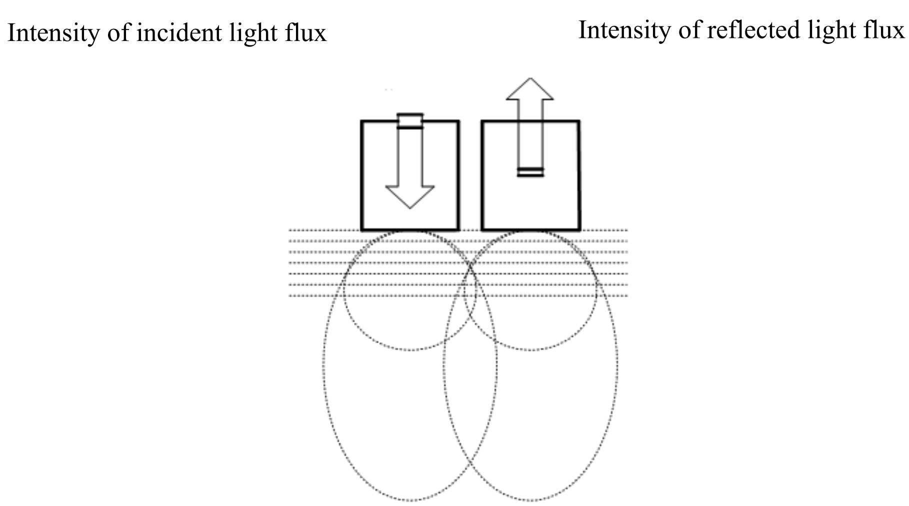


Figure 3. Study of optimal angle

In the research, it has been proved experimentally that optimal angle between light emitting source of light flux and photoreceiver equals 35° (Fig. 3). This enables to improve sensitivity and reliability of optical sensor with the account of optical thickness of the environment change and with the account of intensity change in the process of absorption and reflection in the skin layers[31,32].

4. PRACTICAL REALIZATION

The source of infrared radiation (wavelength - 905 nm) is used to study the deep layers of the skin. To determine blood oxygen saturation a red light source is used (wavelength - 660 nm). Green radiation source emits luminous flux (wavelength - 532 nm) that penetrates only in corneous and epidermal skin layers (0.3 mm) that allows exploring the surface layers of the skin definitely.

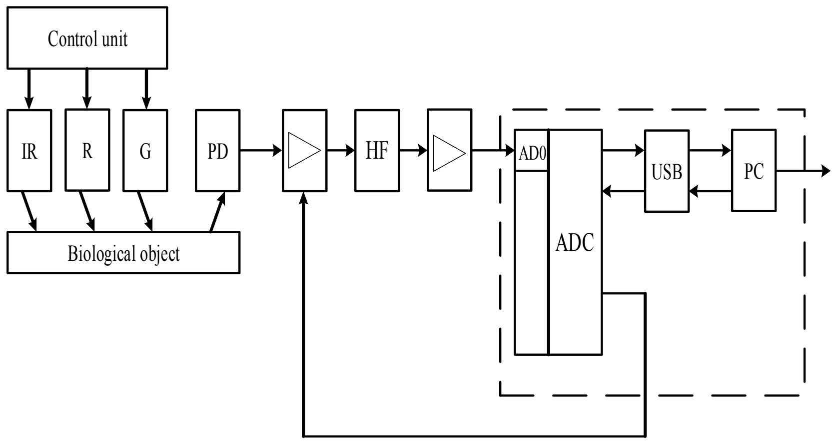


Figure 4. Block diagram of the optical-electronic photoplethysmographic multispectral device for diagnosis of the peripheral blood circulation[31]

The device operates as follows. After switching-on, the zeroing process of block evaluator starts, namely by the discharge of a microcontroller (MC) in zero state and setting the permission for the device operation. After that, a control unit sets up a consistent choice of the radiation sources. Then the selected source of radiation emits light flux that is partially absorbed and partially scattered by biological tissues of researched area and is registered by photodetector (PD). The signal from PD goes to amplifier, then it goes to the high-pass filter (HPF) and then to the next amplifier. Amplification factor of the amplifier is set by MC. The MC has integrated analog- to- digital converter (ADC), which converts the signal into digital code, and sends data to a PC via the USB-controller [5,31,32].

We have developed the device to determine the level of the peripheral blood circulation, which determines the basic parameters of peripheral blood circulation and saturation level.

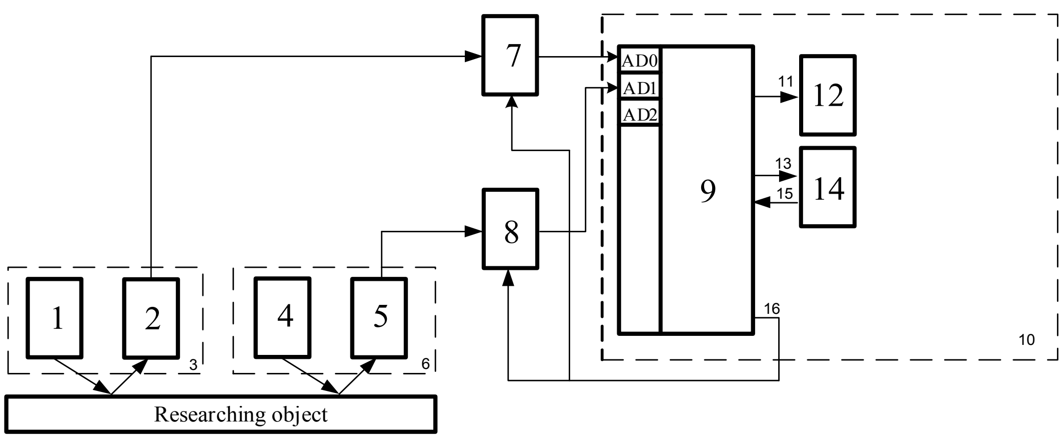


Figure 5. Block diagram of the developed device[32]

We have developed the device to determine the level of the peripheral blood circulation, which determines the basic parameters of peripheral blood circulation and saturation level.

The device consists of two sensors: infrared sensor 3, which contains the infrared radiation source 1 and photodetector 2, and the red sensor 6, which contains the red radiation source 4 and photodetector 5 (Fig. 5). The outputs of the sensors are connected to the inputs of the amplifiers 7 and 8. The outputs of amplifiers are connected to the inputs of the microcontroller. For mobility of device, a graphical liquid crystal display 12 is used, which displays the value of heart rate, blood saturation and blood circulation diagram (Fig. 3). This allows to diagnose the patients without a PC, it is important when examining postoperative patients. In addition, the device has 14 slots for SD-memory card that is connected to a microcontroller, it allows to store data and transfer them to a PC [3,4,6,31].

Example of recorded photoplethismographic signals is shown in Fig. 6

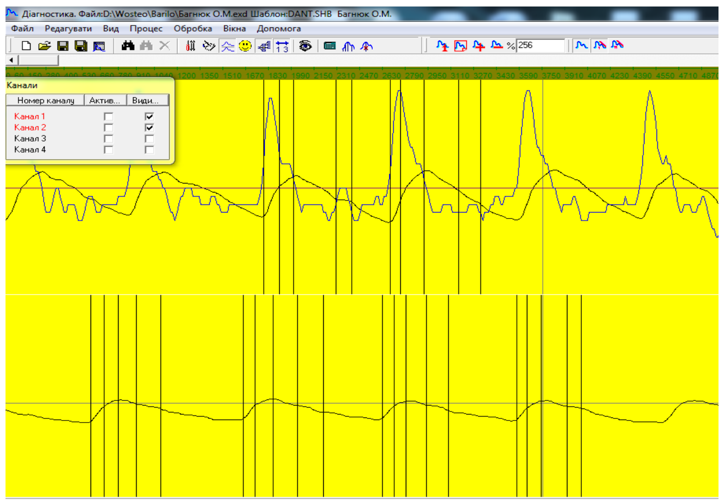
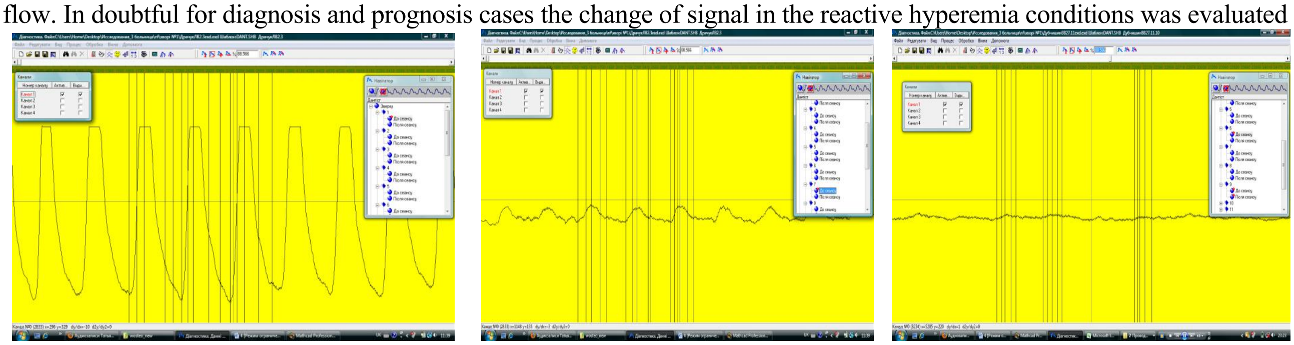


Figure 6.. Photoplethismografic signals in the area of inflammation (channel 1) and the area of normal microcirculation (channel 2)

For assessment of local blood flow, we conducted laser photoplethysmography (LPPH), using the developed photoplethysmographic device (Fig. 7). A high-amplitude shape of regular discontinuous signal corresponded to pulsatile blood flow with large volume and a low-amplitude shape of irregular chaotic signal corresponded to non-pulsatile blood flow. In doubtful for diagnosis and prognosis cases the change of signal in the reactive hyperemia conditions was evaluated



a b c

Figure 7. Determining the flow of blood:
a) high-amplitude pulsatile; b) low-amplitude pulsatile; c) nonpulsatile

5. TECHNIQUE AND THE RESULTS OF RESEARCH

The aim of the given research was to determine sensitivity and reproductivity of the results of regional hemodynamics state assessment in patients with local hypertensive-ischemic pain syndrome of amputation stumps of lower extremities by means of photoplethysmographic method[6,7,,8,9].

We observed 20 patients with local hypertensive-ischemic syndrome of amputation stump of lower extremity, aged from 26 to 77 years. The group of patients consisted of 6 women and 20 men. Amputation defects on the level of femur were observed in one patient, on the level of malleolus-22 patients, on the level of foot -3 patients. The reason of primary amputation are: obliterating diseases of vessels-9 patients, diabetes -8 patients, injury-6 patients, freezing injury-2 patients, pyoinflammatory diseases-1 patient. Period after amputation- from 1 year to 5 years.

Diagnostics of local hypertensive-ischemic syndrome was performed on the ground of patient's complaints, data, obtained as a result of physical, laboratory and instrumental examinations. Among clinical signs, greatest attention was paid to the following signs: pronounced pain, aggravating under physical loadings and usage prosthesis, solid, strained edema of tissue, paresthesia or anesthesia of the stump Diagnosis of compartment syndrome was determined applying R.A.Pedouitz criteria[7].

Masurement of fascial compartment pressure was performed, applying injection method, using Whitesides T.E. technique[10]. Assessment of pain syndrom intensity in amputation stump was performed according to 100-point visual- analog scale (VAS) and results of baroosteziometry. Determination of oxygen tension (SpO_2) in soft tissues was carried out non-invasivelly by means of "Yutac Okci 200" pulseoxymeter.

In accordance with the aim of the research and depending on the obtained treatment all the patients were divided into two representative groups. The first group comprised 12 patients, receiving semi-closed fasciotomy of muscular-facial compartments of amputation stump on the background of traditional conservative treatment(intake of vascular preparations, flammable inhibitors, diuretic preparations, vitamin therapy) . The second group comprised 14 patients, who on the background of the given therapy, together with semiclosed fasciotomy received revasculoting osteotrepanation of metaphyseal zones of amputation. Additionally prosthetics schemes of certain patients were reconsidered. According to output indices of additional methods of study groups did not differ statistically. Intensity of pain syndrome, according to visual analog scale(VAS) in the given group before treatment varied within the limit of 45-75 points and on average was 536+-3.1 points, index of barasteriometry was determined within the limits of 34-82 mm.Hg and on average equaled 52.3+5.4 mm.Hg and the level of oxygen tension in soft tissues was too low and was within the limits of 29-47% (37.9+-3.2%).

Fascial compartment pressure (FCP) in fascial muscular compartments of malleolus was within the limits of 27-59 mm.Hg and in 4 patients it exceeded 50 mm.Hg in malleolus compartments that caused local vascular and trophic disorders. Before and after 3 week course of treatment study of microcirculation by means of laser complex for assessment of microcirculation of peripheral vessels was performed .

6. RESULTS AND DISCUSSION

Three weeks after treatment all the patients felt considerable decrease of pain and improvement of general state. Patients of the first group, where semiclosed fasciotomy was applied , suffered from moderate manifestations of painful and circulatory disorders in amputation stump. Patients complained to periodic aching, dull pain in amputation stump. In the area of stump end bluish discoloration of skin and moderate venous hyperemic were recorded in 33% (4) of patients. In the patients of the second group, where to semiclosed fasciotomy revasculating osteatrepanation was added, primary healing of post-operative wound, lack of pain syndrom both under loading and in motionless state were observed. Skin of amputation stump became of pale-red discoloration, congestive and vascular manifestations sharply decreased.

Resuming of prosthesis usage caused moderate pain manifestations in 25% (3) of patients of the first group and in 7.1% (1) of patients-second group, sense of discomfort-33% (4) of patients and in 21.4% (3) of patients, correspondingly.

By the results of studying hemodynamic indices it is noted that in the patients of the first group the blood filling level increase of amputation stump was moderate by 46.5 % and the level of diastolic outflow increased only by 31%. Dynamics of pain intensity decrease in this group of patients also was inexpressive and was 62.7% (19.2±4% points). Saturation of soft tissues with oxygen and threshold of pain pressor sensitivity increased moderately by 30%(74.4± 2.2%)and 38.6%(52.1±1.5 mmHg) correspondingly (Table 1).

Combined application of semi-closed fasciotomy and revasculating osteotrepanation of amputation stump greatly improved local microcirculation in the patients of the second group and contributed to more rapid elimination of disease manifestations. According to the data of optoelectronic plethysmography, the level of rapid blood filling increased 2.9 times, level of blood filling-2.5 times and the level of diastolic outflow improved by 65%. Dynamics of pain syndrome intensity decrease in this group of patients was more expressive and was 74.5% (13%±2.6 points), saturation of soft tissues with oxygen increased by 66.3% (63.7 ±2.1%). With the increased of the strength and endurance of the stump the index of pain pressor sensitivity increased more than 50% (91.4±1.8 mm.Hg).

Diagrams of microcirculation assessment before and after treatment of the patients of the I and II goups are presented in Fig.8

Table 1. Indices of microcirculation level assessment prior to the therapy and after treatment of patients.

Indices*	I group of patients, n=12		II group of patients, n=14	
	Prior to therapy	After treatment	Prior to therapy	After treatment
LRBF, su	8,8± 2,5	9,8 ±3,1	9,7 ±1,4	28,5 ±6,4*#
TRBF, ms	58,8 ±15,7	61,8 ±23,7	59,9± 9,5	65,7± 11,4*
LSBF, su	8,8 ±2,8	11,5 ±1,4*	10,5 ±2,8	23,9 ±5,8*#
TSBF, ms	71,7 ± 26,7	79,4 ±19,1*	68,4 ±6,7	84,5± 20,8*
LGBF, su	18,7± 3,1	27,4 ±2,7*	20,2± 4,8	52,4 ±4,8*#
LDO, su	7,1±3,1	9,3 ±1,9*	6,9 ±1,4	11,4 ±2,5*#
SpO_2	37, 6±1,9	52,1±1,5*	38,3±1,3	63,7±2,1*#

Note 1:

1. LRBF- level of rapid blood filling, TRBF – time of rapid blood filling, LSBF - level of slow blood filling, TSBF – time of slow blood filling, LGBF- level of general blood filling, РДВ –Level of diastolic outflow .
2. * – p<0,05 – compared with the state prior to therapy.
3. # – p<0,05– compared with the first group.

Diagrams of microcirculation level assessment prior to therapy and after treatment of the patients of I and II groups (Fig.8)

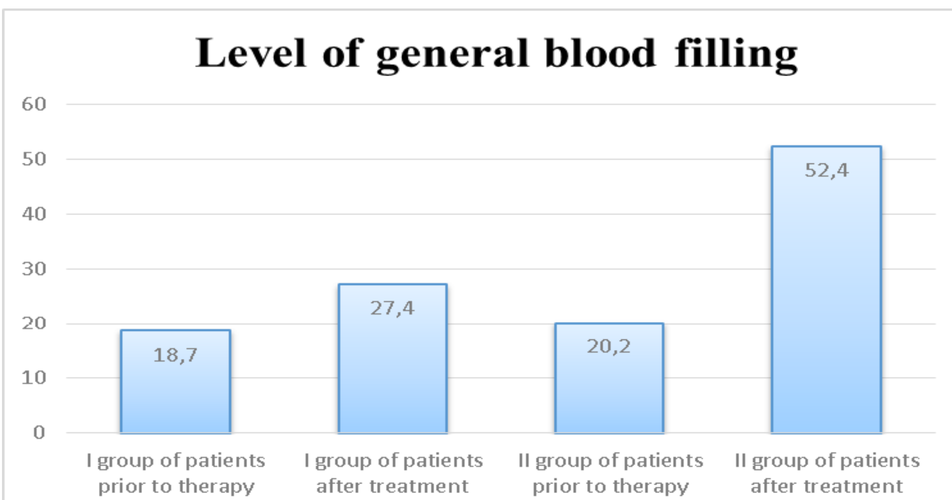


Figure 8. Diagrams of microcirculation level assessment prior to therapy and after treatment of the patients of I and II groups

7. CONCLUSIONS

Paper analyzes the principles of interaction and analysis of the reflected optical radiation from biotissue in the process of assessment of regional hemodynamics state in patients with local hypertensive-ischemic pain syndrome of amputation stumps of lower extremities, applying the method of photoplethysmography.

Local hypertensive-ischemic pain syndrome of amputation stumps of lower extremities is developed on the background of vascular and ischemic disorders in the tissues of stump and is manifested by the pain, edema, increase of subfascial pressure, sharp decrease of regional hemodynamics indices.

Surgical treatment of local hypertensive-ischemic pain syndrome of amputation stumps of lower extremities by the method of semiclosed fasciotomy in combination with revasculazing osteotrepanation enabled to improve considerably regional hemodynamics in the tissues of stump and reduce pain and congestive disorders

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