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INVESTIGATION OF THE HEMODYNAMICS IN THE MICROVASCULATURE OF THE BLOOD CIRCULATION SYSTEM

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Abstract. There was designed a portable device for non-invasive examinations of the microvasculature segment of the blood circulation system. The basic operation principle of the device is related to the measurement of the blood supply in the finger tissue by two-wave emission. The value of the blood supply is measured with account of the dependency to the relevant time interval and the excess compression inside the pressure ring that is positioned onto the finger.The form of the above dependency characterizes the condition of the periphery blood circulation system and could be applied for diagnostic purposes.

Keywords: intellectual sensors, microvasculature section, compliance, hydraulic resistanc, hemoglobin

ДОСЛІДЖЕННЯ ГЕМОДИНАМІКИ МІКРОЦИРКУЛЯТОРНОЇ ЛАНКИ СИСТЕМИ КРОВООБІГУ

І. Д. Войтович, В. І. Дегтярук, Ю. О. Брайко, Р. Г. Імамутдінова, Ю. Д. Мінов, П. Г. Сутковий

Анотація. Розроблено портативний прилад для неінвазійного дослідження гемодинаміки мікроциркуляторної ланки системи кровообігу. В основу роботи приладу покладений принцип виміру кровонаповнення тканини пальця шляхом використання двохвильового опромінення. Величина кровонаповнення вимірюється залежно від часу й надлишкового тиску в манжеті, що одягається на палець. Форма цієї залежності характеризує стан периферійної системи кровообігу й може використовуватися в діагностичних цілях.

Ключові слова: інтелектуальні сенсори, мікроциркуляторна ланка, компліанс, гідравлічний опір, гемоглобін

ИССЛЕДОВАНИЕ ГЕМОДИНАМИКИ МИКРОЦИРКУЛЯТОРНОГО ЗВЕНА СИСТЕМЫ КРОВООБРАЩЕИЯ

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Аннотация. Разработан портативный прибор для неинвазивного исследования гемодинамики микроциркуляторного звена системы кровообращения. В основу работы прибора положен принцип измерения кровенаполнения ткани пальца путем использования двухволнового облучения. Величина кровенаполнения измеряется в зависимости от времени и избыточного давления в манжете, одеваемой на палец. Форма этой зависимости характеризует состояние периферийной системы кровообращения и может использоваться в диагностических целях.

Ключевые слова: интеллектуальные сенсоры, микроциркуляторное звено, комплианс, гидравлическое сопротивление, гемоглобин

1. Introduction

The entire experience of the human civilization witnesses that the better and more correct people understand the world, the more expanded, exact and profound is their knowledge of it, the better and with more success they live. The extent of our knowledge about the world, its precision and depth depend on the means and tools, through which we observe this world, trace the changes and phenomena within.

At the dawn of humanity our ancestors used only their senses. Yet, in the course of technological, technical, scientific development, more and more of diverse devices and gadgets came into use that complement or even replace our sensory organs. Such devices became to be called sensors.

It can be declared with confidence, that along with some other important factors, the level of development of a civilization is characterized by the development level of the sensors. Their role is of highest value to make our perception of reality more exact and in-depth, to increase the quality and efficacy of our actions. This is particularly true when it comes to biology, medicine, ecology, high-tech sectors, where judging ‘by eye’ is absolutely not enough.

Until quite recent times, people have been using primarily simple sensors conveying only the primary, ‘raw’ information about the observed objects and processes. The decoding and processing of the information, its comparison to other data was performed by people.

The impressive upturn, within the past decades, of cybernetics, microelectronics and the optoelectronic element base of information technologies made it possible to develop a new generation of intellectual sensors [1]. These ones are specified by compact dimensions, capacity to function in conjunction with living objects, by profound and complex processing inside the device of the primary, ‘raw’ information and by the output to the intended user of data that are already processed, verified, has a handy format and has its interface in the PC.

One of such intellectual sensors we designed. It is used for diagnose of microvasculature section of the blood circulation system.

2. Hemodynamics of the Microvasculature as a Health Indicators

Estimation of human health condition

The major indicator of the welfare level in human life is the health condition. For the qualitative estimates of the latter the physical, psychological and social satisfaction levels are measured from subjective angles. The quantitative estimates of the health levels could be obtained only through clinical data, instrumental and laboratory measurements by applying extensive up-to-date diagnostic techniques.

The contemporary medical diagnostics allow for retrieving multiple indicators applicable to determine health conditions. Measuring some of the indicators demands considerable contributions of time, costly equipment and complex techniques. Therefore, there continues the search of methods that could, on the one hand, shorten the list of the required parameters and make their measurement easy, and, on the other hand, could provide data of high credibility and salience.

The most significant impact on the relevance of most indicators applied for qualitative estimates of the individual health is attributed to the pathology of the cardio-vascular system, systolic and diastolic blood pressure, recovery time of the heartbeat, tension index characteristic of the vegetative tone, iterative indicator of the levels of the body oxygen supply.

The comparative analyses of the physiological indicators applied at the health screening evaluations for healthy individuals and for individuals with diverse conditions, as well as treatment are all the evidence that the most popular indicators to estimate health are the same indicators that are predominantly used to monitor cardio-vascular conditions.

Hence, the parameters of functioning of the cardio-vascular system are imperative to define any health condition. Particular interest is focused on non-invasive techniques that allow to measure in the real-time scale the kind of data that has not been available as of recently and that renders to the practitioners new options both in determining the health conditions and improving them.

Microvasculature of the cardio-vascular system

The key segment in the cardio-vascular system is the microvasculature [2]. All the other elements of the system work to provide for its major functions — supplying oxygen and nutrients for the body and discarding it of the waste material. Microvasculature is the totality of blood vessels with diameter of up to 2 mm. These are terminal arterioles and metarterioles, arteriolar sphincters, capillaries, postcapillary venules, minor veins. Each type of vessels perform their function in the microcirculatory process.

Within the structure of nowadays diseases and mortality reasons noninfectious chronic diseases prevail where cardio-vascular pathologies take the lead. The third rating in frequency is attributed to diabetes, the most serious complication of which being affected vessels and circulation problems.

In the above context, to the foreground came the methods to estimate the functioning of the circulatory system, revealing its stability resources, specifically under stressful conditions. The particular accent is put on the microvasculature that is the first to respond to a potential problem allowing to estimate the danger and to apply timely the preventive measures, to monitor the effect from the treatment and to estimate the individual defense potential.

3. Development of the Intellectual Sensor

Theoretic approach

The approach herein is based on the phenomenon of the light absorption by hemoglobin molecules. The band of absorption is shown in Fig.1.

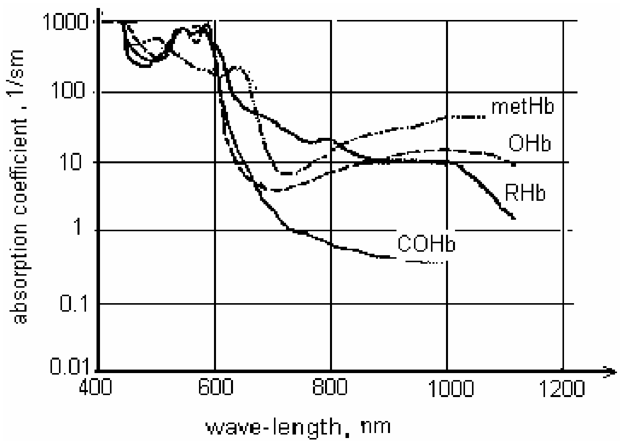

Fig. 1.The light absorption band by hemoglobin molecules

The formula correspondences applied as the framework to develop the intellectual sensor are provided hereunder according to [1].

It is given that

$$I = TI_0 \exp(-Kd)\ , \qquad (1)$$

where I_0, I — are light spectral intensities at entering the solution and at the departure point;

K — is the ratio of the light fall-off inside the solution;

T — the light transmission ratio of the cuvette with translucent solution,

d — the depth of the solution layer.

If the solution comprises one colorant, then the colorant concentration is

$$K = k_{mol} c\ , \qquad (2)$$

where k_{mol} — is the molar absorptivity ratio of the colorant;

c — is its molar concentration.

By measuring spectral intensities I_0 and I within the absorption band of the colorant, cuvette transmission T and given the values of kmol and d with formulas (1), (2) the colorants concentration can be calculated.

$$K = K_p c_p + k_1 c_1 + k_2 c_2 + \cdots + k_n c_n\ , \qquad (3)$$

where K_p, k_1, $k_2 \cdots k_n$ — are molar absorption ratios of the solvent substances and 1st, 2nd, ...n st colorants;

c_p, c_1, c_2, ···, c_n — are their molar concentrations.

When the light passes through the living tissue, it becomes extinct not only through absorption, but also as the result of scattering. Hence, in place of (2) there should be

$$K = K_p + k_{mol} c \,, \qquad (4)$$

where K_p — is the extinction ratio conditioned by the light scattering.

The authors selected the two-wave measurement scheme "by reflection", where the scattered light is used reversely as the informative parameter.

In correspondence with the law of the light extinction by absorption and scattering, the light spectral intensities at the departure point from the body are described with equations

$$I_O = T_O I_{R,O} \exp[-(K_{p,O} + K_{B,O} + k_{hb,O} c_{hb})d] \,, \quad (5)$$

$$I_B = T_B I_{B,0} \exp[-(K_{p,B} + K_{B,B} + k_{hb,B} c_{hb})d] \,. \quad (6)$$

Indices "O" and "B" represent the initial λ_O and measuring wave length λ_B.

$I_{R,O}$, $I_{B,O}$ — are the light spectral intensities at entering inside the tissue;

T_O, T_B — are the light absorption ratios by a tissue;

$K_{p,O}$, $K_{p,B}$ — are the scattering ratios given in m-1;

$k_{B,O}$, $k_{B,B}$ — are the light absorption ratios by the tissue elements given in m-1;

$k_{hb,O}$, k_{hbB} — are molar light absorption ratios by hemoglobin given in m2/mole;

c_{hb} — is molar concentration of hemoglobin, mole/ m3;

d — is the mean length of the distance passed inside the tissue by the light that falls on the light sensor, m.

Wave lengths λ_O, λ_B are selected to have almost equal light scattering and background absorption values. (i.e. $K_{p,O} \approx K_{p,B}$, $K_{B,O} \approx K_{B,B}$), and molar absorption ratios by hemoglobin to show significant difference ($k_{hb,B} >> k_{hb,O}$).

One of the processing options for the measurement results is to divide (5) by (6).

$$I_O / I_B = T_O I_{R,O} / T_B I_{B,O} \exp[(k_{hb,0} - k_{hb,B}) c_{hb} d] \,. \quad (7)$$

By solving this equation in relation to c_{hb}, it becomes

$$c_{hb} = \frac{\ln(I_0 / I_B) - \ln(T_0 I_{R,O} / T_B I_{B,O})}{(k_{hb,0} - k_{hb,B})d} \,. \qquad (8)$$

Values T_p, T_B, $I_{p,O}$, $I_{B,O}$ and d — are constant and are determined by the structure of the measuring head and the signal processing channel of the intellectual sensor.

This allows to determine the average hemoglobin concentration levels in a tissue. With the given values of light sensor surface S and distance length d that the light passed inside the tissue, the volume of the tissue can be calculated, fore which hemoglobin concentration is being determined

$$V = Sd \,. \qquad (9)$$

Given the tissue volume and hemoglobin concentration, the blood supply level of the tissue can be determined

$$P = V c_{hb} \,. \qquad (10)$$

4. Device Operation Procedure

The examinations are conducted at phalangettes. The examination area is selected for the reason that minor circulation disturbances in the microvasculature primarily occur at the periphery body parts.

The external appearance of the device is shown in Fig. 2. The examination procedure is described with Fig. 3. A patient occupies a comfortable position on a coach. The hand under examination is placed relaxed onto the laboratory desk. The compression ring is placed around the finger foundation. The compression intensity P_x is selected by the practitioner among the menu options.

Onto the phalangette, the measuring optoelectronic head is placed designed as a low-stress clamp. After the due preparation, the 'start' command is activated from the keyboard and the measuring procedure begins.

The special microconverter performs automatic balancing of the intellectual sensor to ensure optimum processing of the data signal and minimize the noise and interference. After the balancing is complete, the microcompressor is activated and the compression in the ring is increased up to the intended value that is higher than systolic value P_c .

This pressure goes to all blood vessels under the ring. Once pressure becomes higher than that in veins the blood outflow stops and blood filling of a finger is rising from t_0. Interval of the compression is assigned by a physician as well as defined by a research objective.

Measurement results are indicated in real-time mode on a LCD screen as a graph. Speed of signal's increase is proportionate to $ctg\alpha$ or to the amount of blood inflow to a finger thus it can characterize volumetric blood flow in a finger.

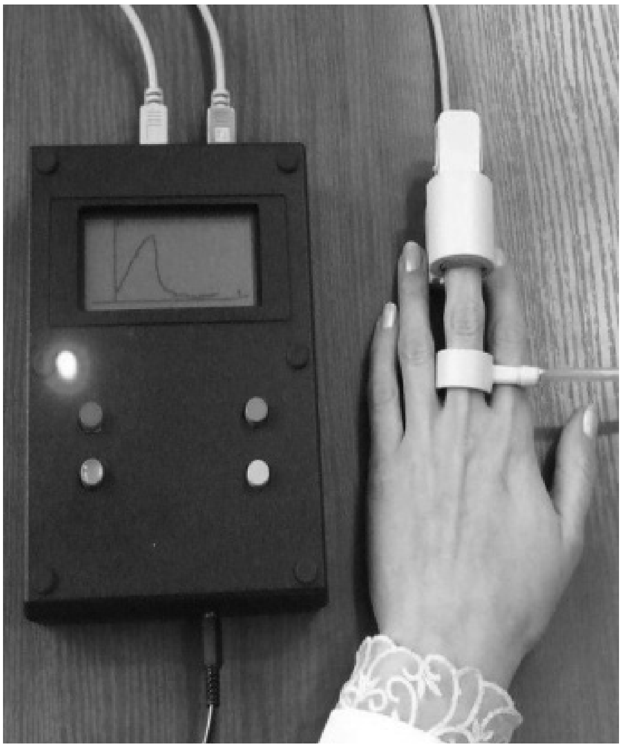

Fig. 2. The outward appearance of the hemodynamic parameter measuring device

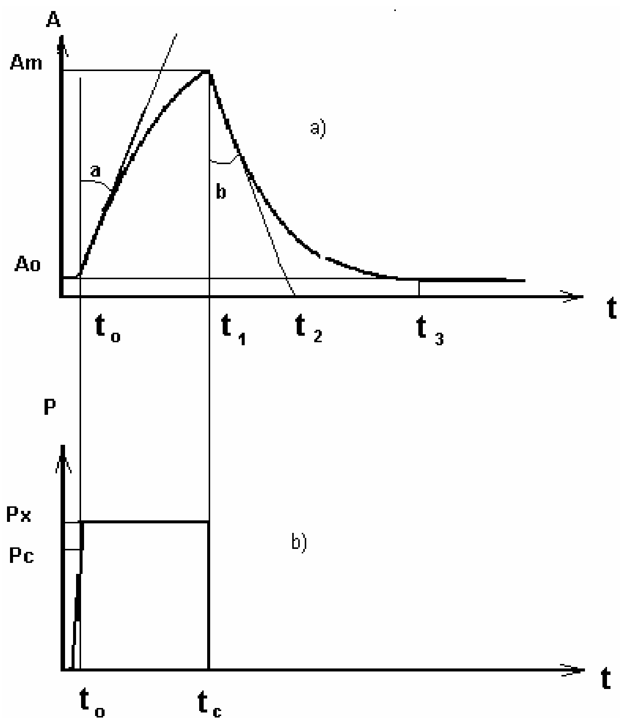

Fig. 3. Graph of blood filling dynamics (a) and pressure in the ring (b)

As pressure in a ring is fixed then maximum value of the signal A_M is higher with better elasticity of finger's blood vessels. Numeric characteristic of elasticity of blood vessels is called a compliance. It is measured in l/Pa.

Transmural pressure in a middle of vessels affected by the compression reaches P_M. External atmospheric pressure remains unchanged and it is considered to be zero. Blood volume in a microcircular stream increases by

$$\Delta V = C_{\Sigma} P_M \,, \tag{11}$$

where C_{Σ} is total compliance of vessels on a body area under examination blood filling of which increases by

$$\Delta k = \Delta V / V \cdot 100\% \;, \tag{12}$$

where V is volume of body area under examination.

Accounting for (11), (12) specific compliance of microcircular stream vessels can be calculated:

$$C = \frac{C_{\Sigma}}{V} = \frac{\Delta k(\%)}{P_M \cdot 100\%} \cdot P_M = V \cdot c_{hb} \,. \tag{13}$$

In skin and tissue of fingers capillary net is not very dense although a number of capillaries per 1 sq. mm. of skin surface in a nail bed ranges from 20 to 55, on a back palm surface there are 65 of those. There are 3-4 capillaries coming to each skin papillae, and which make loops of 200-400 mkm. Arterial part of the loop is 7-13 mkm in diameter and venous is 9-20 mkm.

Square of the sensitive part of the photoelectric receptor is several sq. mm. Photoelectric receptors OPT-101,OPT-301 produced by BURR-BROWN Corporation which we have used are 5.2 sq. mm. Thus information is received from more than 300 capillaries and post-capillary venuls as well as other micro-vessels seen by the device. Although physicians are interested not only in unprocessed signals but in processed and visualized information as well (saved and stored if possible), and vital decisions can be made based on digital data representing the result of calculations. Suggested intellectual sensor can present to a physician not just surveillance or measuring information but diagnostic information.

Once the compression interval t_1 ends blood filling reaches A_M level and decompression valve is triggered and pressure in a ring falls to zero. Blood circulation begins to restore. Blood filling of a finger starts to fall down. Starting speed of a signal falling down depends on hydraulic resistance of vessels to the blood outflow

$$dk / dt = \Delta A / (C \cdot R), \quad (14)$$

$$R = \Delta A / dk / dt \cdot C\ , \quad (15)$$

where $\Delta A = A_M - A_0$ is amplitude of blood filling dynamics, R is specific hydraulic resistance of vessels to blood outflow.

Thus dynamics of blood filling at the downturn part of the characteristic allows identifying specific hydraulic resistance of microvessels to the blood outflow, i.e. venous part. Hydraulic resistance of arterial part of microvessels to the blood inflow after the compression is being identified in the same fashion, i.e. on an upward part of the hemodynamic characteristics.

Time t_3 determines the return of the area under examination of a microcircular part of blood circulation system to a starting point, and interval t_3-t_1 the time when blood circulation is restored and characterize efficiency of the regulatory mechanisms.

Based on the results of measuring channel balancing information can be obtained about degree of oxygen saturation in peripheral blood.

The intellectual sensor is designed as main unit, measuring peripheral optoelectronic head, compression ring and power unit. Electronic layout of the intellectual sensor is based on microconverter ADuC8xx produced by Analog Devices.

Fig.4 shows the design of the device. Main unit is a separate bloc placing microconverter, indication unit, control unit, external data memory, command unit, original miniature compressor, interface unit for PC if needed, thermoprinter.

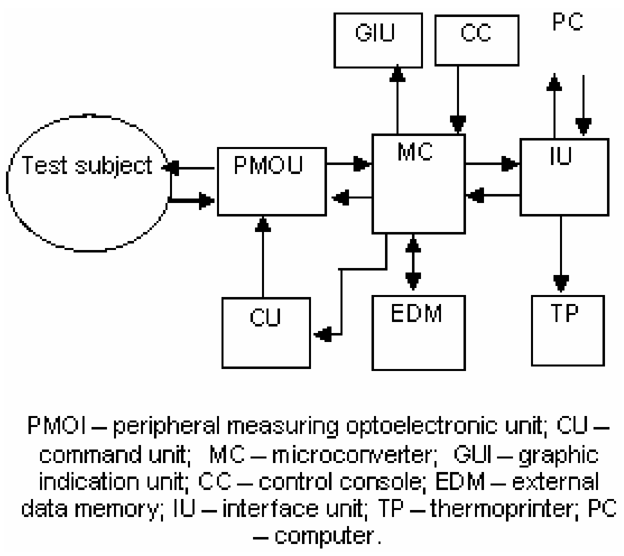

Fig. 4. Layout of device

After examining the condition of microcircular part of blood circulation system in rest physiological state a physician will obtain static parameters. Data obtained after load (either physical or psychological) applied enable the physician to have dynamic parameters and full picture about condition and potentials of the microcircular part of blood circulation system.

All graphic and digital information is printed on a thermoprinter built in the device and stored in the memory. It enables comparing results after a certain time interval, which could be also lengthy one, and monitoring progress of treatment or results of trainings or other effects. The device has external interface by way of which data obtained can be transmitted to a computer for further more detailed processing and database development.

As physiological characteristics used for quantitative evaluation of health condition depend for the most part on changes in cardio-vascular system the data obtained can be used to determine the index of health.

This conclusion can be confirmed by the approbation of the device in V.Komisarenko Institute of Endocrinology and Metabolism and in Institute of Vocational Medicine of the Academy of Medical Sciences of Ukraine. The device was identifying not only professional diseases (Fig. 5) of the patients but also deviations from norm showed by physicians and administrative staff.

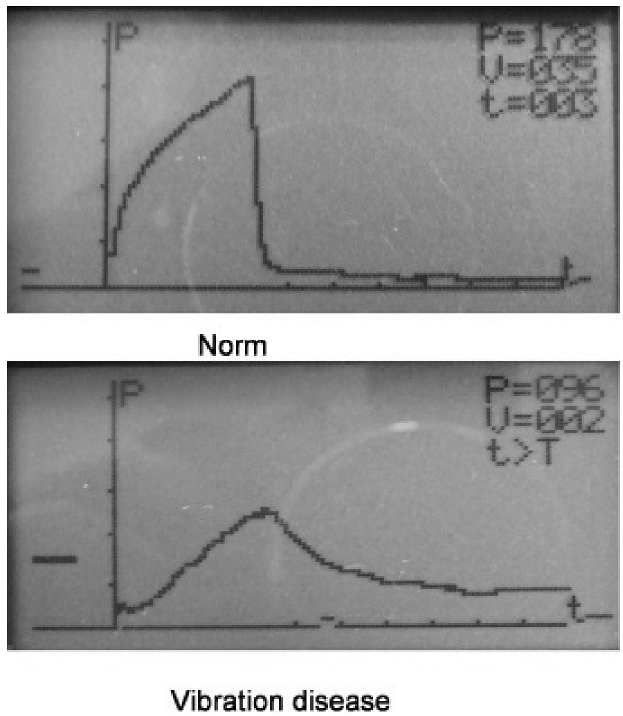

Fig. 5. Professional diseases detection

5. Conclusion

A multiple number of present diseases is connected with cardio-vascular pathologies. For instance, diabetes results in complications that affect blood circulation and condition of the vessels. This paper describes a portable device intended for non-invasive examination of the peripheral blood circulation system. The device's operation is based on the principle of gemodynamics registration of light radiation being absorbed by hemoglobin. With the above purpose, a finger is exposed to point radiation at a wavelength of 570 nm which is the one most absorbed by hemoglobin, the degree and dynamics of such absorption being measured. To achieve the needed precision, the reference radiation is applied at a wavelength of 940 nm that hemoglobin does not absorb. Emitters and photoelectric receptor are installed on a clip attached to a finger's end phalange. Over the same finger, a ring is positioned with the excessive pressure of up to 400 mm of mercury column, which makes the venous vessels compressed. The measured dependencies of the blood supply upon time and pressure in ring are displayed and printed out onto a thermoprinter. Those characterize the condition of the peripheral system of the blood circulation system and can be used by physicians for the early diagnoses, inter alia, of certain professional diseases, which has been confirmed by the tests of the device at V. Komisarenko Institute of Endocrinology and Metabolism and Institute of Vocational Medicine of the Academy of Medical Sciences of Ukraine.

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