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Non-invasive blood glucose measurement

Abstract

The paper presents a system for measuring blood glucose level based on spectroscopy in the near infrared range. Specific features of this system are limited spectral range of measurements, and the use of visible light detector to identify the density of irradiated tissue and to correct measurement results in the infrared range. Presented are principles of measuring system construction, including measures undertaken to increase its precision and results of tests carried out using the constructed measurement system. The results are close to those obtained from a traditional meter.

Keywords: glucose level measurement; IR spectroscopy; non-invasive diagnosis.

1. Introduction

Traditional form of measuring glucose level consists in measuring its concentration in blood in fingertips capillaries. A small amount of blood obtained by puncture is applied to a special, single use test strip placed in an electronic device called a glucometer. It displays the result usually in mg/dl. The method is painful and is associated with a repeated finger puncture which may cause adhesions and epidermal thickening. People with diabetes test in this way sugar levels from a few to a dozen times a day. Non-invasive measurement techniques can provide relief to the ever-growing number of patients with diabetes [1]. In recent years several different ways of measuring sugar level in body have been developed. There are methods based on analysis of glucose in the human eye (the quantity is proportional to the concentration in the blood), microwave spectroscopy and infrared, based on Raman scattering [2, 3, 4].

In this paper, there is described a device that uses the technique of NIR spectroscopy (Near InfraRed), but in a very limited spectral range, Section 3. The solution is based on detection in the band from 750 to 1150 nm (NIR spectral range is between 800-2500 nm [5]), and also in the visible light. There are several examples of devices based on measurement of glucose level in the infrared. They are based on different principles, working in different spectral ranges, nevertheless, the place of measurement has usually been an earlobe or a finger. The most significant innovation in the presented here concept is the use of a broad spectrum of visible light for additional calibration making possible measurements anywhere on hands. This will allow monitoring of glucose level in a way convenient for a user. We examined several design solutions, from the arrangement of detectors to their number, duration of exposure, radiation power, and system control and data acquisition. The main findings and insights that emerged during the study are discussed in Section 4. The idea of NIR Spectroscopy and research methodology are presented in Section 2.

2. Theory

2.1. Spectroscopy

Spectroscopy is an analytical technique that allows unambiguous identification of chemical compounds in a sample and determination of their quantity. The point is that each compound has various types of chemical bonds and each of it is characterized by absorption of energy of electromagnetic radiation for characteristic frequencies [5]. Because of that, in the spectrum of light transmitted through a chemical compound one can observe characteristic absorption peaks for a specific wavelength. The structure of a spectroscope is shown in Figure 1.

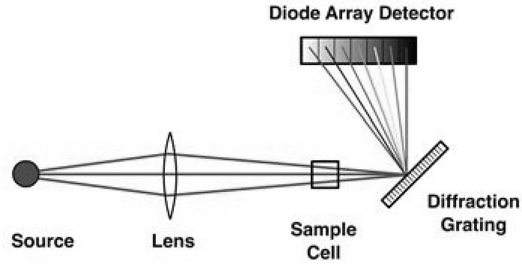

Fig. 1. Structure of a spectrometer [6]

2.2. Diabetes

The primary symptom of diabetes is a temporary occurrence of elevated levels of blood sugar. The reason is the lack of or insufficient production of insulin by pancreas. This leads to a condition in which there is too much glucose in blood. This condition is called hyperglycemia, and over a long time it can cause damage to internal organs, especially kidneys and eyes. To avoid this, it is necessary to deliver insulin by intramuscular injection. Too much insulin can cause drop of glucose amount below a safe level, which leads to hypoglycemia (it can lead in short time to coma, or even death). Therefore, it is extremely important to do ongoing monitoring of blood sugar levels. Its normal level should be in the range of approximately 80 mg / dl to about 120 mg/dl for a healthy person. Hypoglycemia is the condition when the level is below 55-60 mg/dl, and hyperglycemia above 150 mg/dl.

2.3. Glucose

Glucose has absorption peaks at wavelengths: 939 nm, 970 nm, 1197 nm, 1408 nm, 1536 nm, 1688 nm, 1925 nm, 2100 nm, 2261 nm, 2326 nm [7]. Absorption peaks can be used for its identification and for determination of its level (concentration). Another thing, is absorption by a human body. The lowest absorption by a human body is for the spectral range corresponding to the near-infrared and visible light. This is one of the main reasons why precisely this range of wavelengths was chosen. It should be also noted that in this range there are two, lying close to each other, characteristic peaks: 939 nm, 970 nm. This enables more accurate analysis than that for a single point.

3. Measuring system

3.1. Detectors

According to the assumptions, the spectral range of the measurements was limited to two overtones being close to 950 nm. One reason for this decision was the availability and low cost of detectors for this range. Another argument was the smallest light absorption by skin in that frequency window. These observations led to the choice of detectors based on PIN diodes that have a maximum sensitivity at 950 nm. A diode having a maximum emission at 950 nm is used as an infrared light source. Because of that the whole measurement system works in a very narrow band which eliminates interference from other spectral range. The second type of detector diodes are wide-range visible light and near infrared (400 to about 1000 nm). They allow analysis of environmental conditions and as a result more precise measurements. In this way, the device accumulates the signal in the whole band.

3.2. Elements of the system

The measuring system was built using the described above detectors and emitters (wide and narrow band). The entire device was divided into two parts: measuring head and data acquisition system. The measuring head consists of a series of detectors and emitters and also filters and analog to digital converters. Thanks to this solution the noise generated by the system was reduced to minimum and long connections avoided. It is the most important for detection of small signal changes on PIN diodes.

Data acquisition is done through communication with a computer, results are shown on a screen. In this way data analysis and measurement assessment are possible. The diagram of measurements is shown in Figure 2. The block diagram of the algorithm is presented in Figure 3.

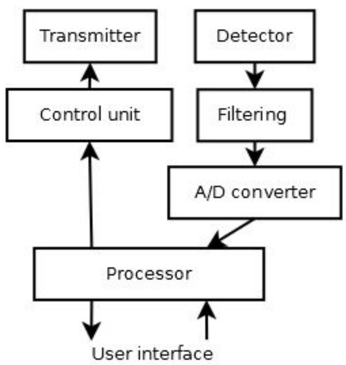

Fig. 2. Structure of measurement device

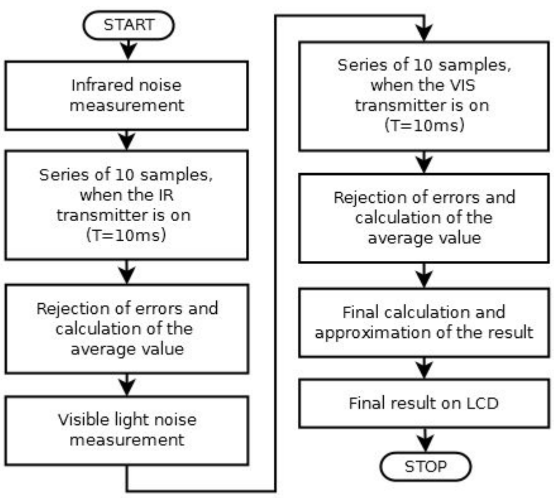

Fig. 3. Flowchart

Signals from the detectors are band limited by specially designed LP filters (to reduce high frequency noise). There are three double pairs detector-emitter in different places on the wrist. Groups consist of visible light and infrared detectors. That allows measuring variable characteristics of the human body and eliminate disturbances. 16-bit A/D converters (with programmable gain amplifier) provide the appropriate level of accuracy. The data are then directed to a control unit, which is a microprocessor from AVR ATmega family. It is responsible for proper control of the entire measuring system and also for conversion of values and data acquisition.

3.3. Measurement

The aim of the work was to build a system that could continuously monitor blood sugar levels in a body and could be constantly and comfortably held close to a patient. The most convenient place for such measurements is around forearm or wrist. However, this place generates a lot of problems because there are large anatomical variations between subjects, as well as large variation in measurements due to the actual position of the system - below, at or above the wrist. A much easier solution would be to conduct analysis on the ear lobe or on fingers (as in other similar devices). However, it would be hard to comfortably measure during the whole day in these places. The measuring system consists of detectors in the infrared spectrum and visible light. This allows analysis of the measurements, both in terms of glucose and the properties of the tissue through which the beam passes. A beam of white light was chosen to determine the density of a tissue and as a reference for the proper measurement. This makes possible to reduce errors occurring during the measurement and makes the final approximation much more accurate. One of the prototypes is shown in Figure 4.

Fig. 4. Prototype

4. Results

The human body is complicated and it is very hard to make a good model of it. Research was conducted on volunteers. The results of the experiments can be divided into the following groups:

The measurements showed that the optimum distance between the emitter and detector is 3-6 mm. In a too tight system, the receiver is blinded by the light reflected from skin. Too large distance makes the level of signal close to a measurement error and noise from the environment. The optimal distance enables measurement of light passing through a body. It was also shown that the arrangement of detectors does not affect the measurement, provided that the detectors have direct contact with skin.

The power of radiation beam must be appropriately selected. Too strong can cause blinding of detectors and wrong results, especially at low glucose levels. On the other hand, too low light can be completely absorbed by the body, especially at high levels of sugar. Except for these extreme cases, it was proved by measurements, that the results at different power levels in the "safe" range are dependent on the power in a linear manner (measurement error taken into account).

To eliminate distortions arising from the different arrangements of the measuring head on body, visible light is used. By that detection of tissue through which the radiation beam goes is made. The obtained results show that a properly selected coefficient calculated from the visible light measurement can increase the precision and reduce the errors associated with changing location of measurements.

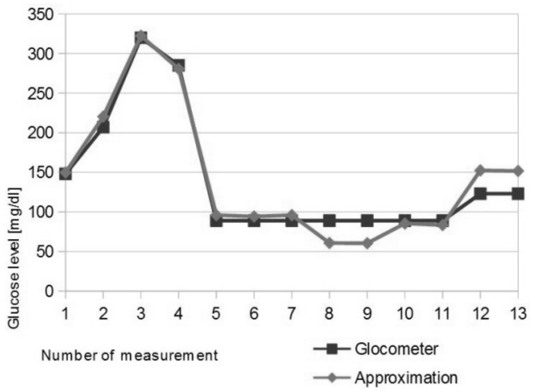

Fig. 5. Results of approximation for the measurement device

The cause of majority of interferences from outside of the system are strong external sources of infrared radiation: sun, light bulbs. A solution to that is a good insulation from the environment, which is difficult at the point of measurement where detectors have contact with skin. The second solution is to subtract the background noise, i.e. subtraction of a detector signal when it is not illuminated by a transmitter. In this method, two measurements should be made.

Figure 5 shows the results of approximation made by the measuring unit and the data obtained from the reference device - a conventional glucometer. A series of measurements having numbers 5-11 was taken to find possible errors in consecutive measurements for different conditions and orientations of the hand. It can be seen that the measurement error is very small. It should be also noted that the error of the standard meter is about 10 mg/dl (several measurements made one after the other do not give the same results).

5. Conclusions

Basing on the results it can be concluded that the proposed version of the technique for non-invasive measurement of blood glucose using spectroscopy in the near infrared range is very promising. The measurement error is close to that of the traditional method while tests can be carried out very often, without the need for a painful puncture. This allows the control of changes in blood sugar levels and a more accurate prediction of a trend. This fast and precise measurement technology can be a starting point for the construction of level analyzers of other chemicals in blood. Further work will lead to the increased accuracy and elimination of occurring errors. The particular emphasis will be placed on finding new spectral dependencies for further improvement of the analysis accuracy and as a result refinement of the current methods of measurement approximation and thermal stabilization. The main task is also the detection of skin color and degradation of system components.

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