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A Personalized mHealth Monitoring System for Children and Adolescents with T1 Diabetes by Utilizing IoT Sensors and Assessing Physical Activities

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Abstract

The problem of diabetes mellitus is becoming alarming due to the increase in morbidity among children. Patients are undergoing vital insulin replacement therapy, the dose depends on the level of glucose in the blood. The glucose level prediction program, taking into account the impact of physical activity on the body, the use of mobile health capabilities will allow us to develop personalized tactics for a child patient and minimize the risks of a critical health condition. The target group of this study are children and adolescents with type 1 diabetes. This study provides an IoT based mHealth monitoring system, including sensors, medical bracelets, mobile devices with applications. The mobile healthcare application for personalized monitoring can implement the functions of more effectively targeting young users to support their own health and improve the quality of life. In addition to monitoring blood glucose levels, the effect of physical activity on the condition of patients is also taken into account. The use of the proposed method for calculating the probable change in the patient's blood glucose level after the end of physical activity will allow the doctor to make individual recommendations for the diet before the start of physical activity and its intensity.

Keywords: mHealth, monitoring system, IoT sensors, children and adolescents with T1 diabetes, glucose level.

1 Introduction

The problem of diabetes mellitus is becoming alarming due to the increase in morbidity among children. Patients are undergoing vital insulin replacement therapy, the dose depends on the level of glucose in the blood. The condition of patients depends, along with the injected insulin, on a number of factors affecting sugar levels: nutrition, physical activity, hormonal background, individual metabolic characteristics, psychosomatic factors. The strategy of the complex of therapeutic and preventive measures is aimed at achieving stable target glucose levels. The glucose level prediction program, taking into account the impact of physical activity on the body, the use of mobile health capabilities will allow us to develop personalized tactics for a child patient and minimize the risks of a critical health condition. The target group of this study are children and adolescents with type 1 diabetes.

In recent years, there has been an explosive growth in the number of mobile applications [27], including mobile healthcare applications [5]. However, it is often difficult for patients to find suitable applications that meet their needs and preferences [20]. According to the authors' review, developers of Mobile Health applications need to fully take into account the needs of users and work closely with medical staff when developing features for patients. The key function in mobile applications designed for patients with type 1 diabetes, according to experts, should be patient self-control. Since type 1 diabetes is an insulin-dependent disease, it is necessary to pay close attention to glycemic control. Since the responsibility for the child's health is borne by the parents, in the mobile application presented in this paper, in addition to the function of self-monitoring of the patient, there is also a function of remote monitoring by the parents.

Clinical research methods included assessment of the patient's health status based on clinical and laboratory characteristics of the disease (compensation level, insulin dose, glucose levels), physical activity, risk assessment of complications of the disease. Clinical examination of patients and data collection were carried out in the Medical Center "Institute of Endocrinology" with the participation of endocrinologists. An IoT system has been developed for monitoring patients, including sensors, medical bracelets, mobile devices with applications.

There are not very many mobile applications aimed at changing behavior to improve self-control and stimulate physical activity in patients with diabetes mellitus [14]. Thus, the mobile healthcare application for personalized monitoring can realize the functions of more effectively targeting young users to support their own health and improve the quality of life [9]. The application developed by the authors together with pediatric endocrinologists pursues exactly these goals. At the same time, in addition to monitoring blood glucose levels, the effect of physical activity on the condition of patients is also taken into account. This study provides several contributions:

- The analysis of mHealth interventions for children and adolescents with T1 diabetes was carried out;
- IoT based mHealth monitoring system architecture is proposed;
- The relationship between physical activity and the level of glucose in the patient's blood was investigated;
- Recommendations on physical activity have been developed taking into account the characteristics of an individual patient;
- Developed mobile app for children and adolescents with T1 diabetes self-management.

The remaining organization of this paper is as follows. In Section 2, we present the related work in glucose monitoring by utilizing IoT sensors. Section 3 contains the system design with architecture and its implementation. In Section 4, the results of the study and a discussion are presented. In Section 5, we discuss several limitations and remaining challenges, and finally, concluding remarks are offered.

2 Related work

2.1 Glucose Monitoring by utilizing IoT sensors

Although diabetes is incurable, monitoring blood glucose levels in combination with appropriate medications can improve the effectiveness of treatment, alleviate symptoms and reduce complications [1, 25]. It is important to monitor glucose levels in diabetic patients, as this can provide better control over their condition [3], and take appropriate measures for hyperglycemia and hypoglycemia. Monitoring will also reveal the effects of medications, exercise, diet and use the data obtained to optimize the treatment strategy of patients [21].

The use of IoT devices for glucose monitoring opens up wider opportunities for providing quick warnings and decision-making [8]. There are many solutions for monitoring blood glucose using IoT sensors [24]. The IoT platform offers a workable solution for diabetic retinopathy, which allows saving the patient from vision loss based on sensor readings [18]. In the article [15] a blood glucose monitoring system based on the body's wireless LAN is proposed to detect diabetes. The system is built using a glucometer sensor, an Arduino Uno and a Zigbee module. [7] explores the design and implementation of a system that improves commercial CGMS by adding Internet of Things (IoT) capabilities to them that allow remote monitoring of patients. In order to motivate users to add new data to the system, a reward system based on the digital cryptocurrency GlucoCoin was developed. Such a system uses a blockchain that can execute smart contracts to automate purchases of CGM sensors or to reward users who contribute to the system by providing their own data. Thus, the range of devices and technologies for continuous health monitoring is constantly expanding. This paper presents the architecture and describes the functionality of a system based on the Internet of Things, which allows continuous monitoring of blood glucose in conjunction with the collection of bracelet data.

2.2 mHealth for children and adolescents with T1 diabetes

The main advantages of mobile healthcare include continuous real-time monitoring with high availability, cheapness, convenience and security of technologies. Widely used mobile health interventions (mHealth) include: mobile applications that are used for training and self-management of their health status; web tools used for patient education/self-monitoring recommendations; text messaging between patients and doctors; a personal digital assistant that collects patient data and can monitor the physiological state of patients; a pedometer that counts the number of steps taken per day [19].

Studies have shown that mobile healthcare can improve the treatment of chronic diseases, but the effectiveness of mobile healthcare in controlling glycemia remains uncertain. According to [12], personalization of applications and increased usability are needed to improve the effectiveness of mobile healthcare interventions. The authors [17] conducted a systematic review and meta-analysis using the available literature. They chose glycosylated hemoglobin (HbA1c) as the studied measure of glycemic control. A review of the work led to the conclusion that mobile medical interventions are effective in patients with type 1 diabetes, while significant improvements were observed in adults. Studies have shown that special approaches should be applied to improve the effectiveness of mHealth for children and adolescents with diabetes mellitus. In the work [4], the authors developed the mHealth application for children and adolescents with type 1 diabetes using gamification elements and individual customization, which stimulated an increase in the frequency of monitoring blood glucose levels. This indicates the importance of creating an attractive intervention to build trust and encourage long-term engagement [11]. The authors [4] concluded that it would be useful if the stimuli were tied not only to the frequency of blood glucose monitoring, but also to the physical activity of the patient. mHealth involves not only the participation of patients themselves, but also parents, as well as caregivers.

It is noted in [10] that the transition from parental management of the course of treatment to management when a child takes on an increased level of self-help can be stressful. The MyT1DHero mobile app made it possible to facilitate positive communication between parents and children, increase adherence to diabetes treatment and quality of life. This study shows promising interventions carried out using mobile phones, especially for adolescents as a more acceptable way to communicate with parents, especially in social contexts, for example, when they are with their peers [6].

mHealth systems significantly reduce medical costs while improving the quality of care. But there are difficulties in the development and implementation of such systems, which are associated with a variety of heterogeneous medical sensors that need to be dynamically removed or added in accordance with the needs of healthcare [22], the heterogeneity of the mHealth environment, which receives important parameters from several sensors for online analysis in real time [23]. Improving the quality of service (QoS) is also an important issue at mHealth. It is necessary to identify the main users, develop a profile and characterize the requirements for supporting mHealth systems in response to the need for services [13].

2.3 Assessment of physical activities for children and adolescents with T1 diabetes

For people with diabetes, an active lifestyle provides many important health benefits. But at the same time, doctors warn that physical activity can cause a decrease in blood glucose levels. A rapid decrease in blood glucose levels can cause hypoglycemia, which is very dangerous for a child. Therefore, monitoring the level of glucose in the blood when receiving physical activity and assessing the body's response to such a load will help to plan physical activity correctly. For parents of children with diabetes, associations of endocrinologists organize special training, draw up instructions, create web applications where the main recommendations are presented [26, 28, 29]. The work [2] provides an overview of the impact of various types of mobile medicine interventions to assess the condition of patients, including bracelets that allow you to assess the effect of physical activity on blood glucose. The authors cite an example of a study [16] when the use of such a bracelet was highly appreciated by children, and was perceived as a mechanism that reduces the burden of self-management of type 1 diabetes. At the same time, it is emphasized that studies with longer follow-up periods are needed to more accurately assess the effect of physical activity on glucose levels using IoT devices.

Thus, a review of the work showed that there is no information about studies on the system integration of the Internet of Things, mobile healthcare, as well as methods for assessing the impact of physical activity to predict blood glucose levels in children with type 1 diabetes. Therefore, it is necessary to integrate the aforementioned technologies to improve the treatment of diabetes. Assessing the effect of physical activity on blood glucose levels can provide better control over the condition and contribute to improving the quality of life. The proposed mHealth monitoring system, based on the Internet of Things, is expected to help people track data about their vital functions. In this way, a person can avoid the worst conditions in the future.

3 Methodology

3.1 System Architecture

Based on the analysis of the above works, we have proposed a system architecture for collecting, monitoring and analyzing data on the health status of young (children and adolescents) patients with diabetes mellitus. The main idea is to use devices and sensors to collect data on the level of glucose in the blood and indicators of physical activity of the patient. Further preprocessing and data analysis allow us to create a personalized program for managing the patient's physical activity.

The architecture of the proposed monitoring system includes (Figure 1):

- Sensing layer - the layer of data collection using devices and sensors;
- Data processing layer - the layer of data storage, preprocessing and analysis of patients with diabetes mellitus;
- Application layer - web application and mobile application.

The proposed system for collecting and monitoring data on the health status of young patients with diabetes mellitus uses: a device for continuous monitoring of glucose levels and a fitness bracelet for tracking physical activity (Figure 2). The iPro2 system was chosen as a device for continuous

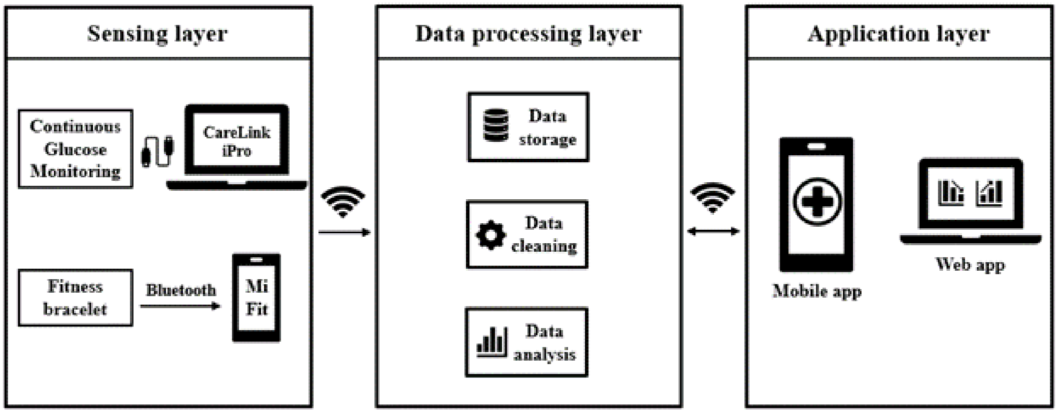

Figure 1: Architecture of the proposed system

monitoring of glucose levels. The iPro2 system consists of the following components: an iPro2 MT-7745WW digital recording device, a docking station, a USB cable, an adapter for a wall outlet, an Enlite MMT-7510 sensor insertion device, an Enlite MMT-7008A sensor.

Figure 2: a) iPro2 MMT-7745WW; b) Docking station; c) USB cable; d) Adapter; e) Enlite MMT-7008A; f) Enlite MMT-7510; g) Xiaomi Mi Band 5

3.2 System Implementation

It is not possible to successfully control diabetes mellitus using the arsenal of modern medicine, but without the active participation of the patient. The results of treatment always depend on the behavior of the patient. After all, it is he who must follow the doctor's recommendations from day to day, and this requires not only agreement with the doctor, but also certain knowledge, skills and, taking into account the changing circumstances of life (different food conditions, travel, concomitant diseases), making independent decisions of a medical nature, i.e. be able to independently change the tactics of treatment depending on the specific situation. To do this, the patient must be well aware of all aspects of his own disease. Therefore, all the patients participating in the experiment, as well as one of the parents, were trained in the rules of rational nutrition and techniques for counting bread units, the basics of insulin therapy, training in the technique of setting insulin with syringe pens, as well as pump insulin therapy, rules of behavior in emergency situations (relief of hypoglycemic state and ketoacidosis), prevention of chronic complications, tactics during physical exertion.

The study involved 26 patients diagnosed with type 1 diabetes of the age group from 7 to 15 years. Each patient received an individual consultation from an endocrinologist. As part of the experiments, a sensor was installed for 5-6 days for each participant. In the course of clinical trials, 2 participants expressed a desire to interrupt the experiment and freely left the composition of the studied patients.

3.2.1 Sensing layer

Measurements in the iPro2 system are made every 5 minutes, i.e. 288 times a day. A platinum sensor is installed in the subcutaneous tissue of the patient in a silicone shell impregnated with the enzyme glucose oxidase, necessary for the enzymatic cleavage of glucose in the interstitial fluid of subcutaneous fat. The measurement takes place due to a two-stage chemical reaction, as a result of which the glucose molecule gives off 2 electrons, which create an electric current, and the device for NMH measures the current strength, but the result reflects in mmol / L. The higher the glucose content in the interstitial fluid, the more electrons appear, and, accordingly, the higher the electrical potential. The same method is used in most modern blood glucose meters. The convenience of using iPro2 lies in the compactness and water resistance of the device, fast data loading via USB connection.

The Xiaomi Mi Band 5 fitness bracelet can measure the patient's pulse, activity (number of steps, calories), stress level. The sensor that measures the number of steps is a 6-axis accelerometer. Mi Band 5 is detected in space using a 3-axis gyroscope. This sensor is an accelerometer assistant and measures the load during various physical activities. The heart rate is measured in three modes: constant monitoring with a preset frequency, a single measurement in the bracelet and during sleep. The data is stored in the Mi Fi mobile application with the ability to export it for analysis.

3.2.2 Data processing layer

The iPro2 digital recording device collects data from the Enlite MMT-7008A glucose sensor. The data received from the glucose sensor is sent to the CareLink iPro web system for storage and reporting. The main functions of the docking station: charging the iPro2 digital recording device and sending data from it to the CareLink iPro web system. The patient report with the data obtained from the iPro2 digital recording device is sent in PDF format for further investigation.

The Mi Fit mobile app has the ability to export data for further research. To do this, in the mobile application, you need to go to "Profile", then to "Settings", then to "About", then to "Exercising user rights", then you need to select "Export data". Then a login and password are entered, after which the data type and dates to be exported are selected. These include: personal data (height, weight, profile photo, date of birth, name), activity (activity time, number of steps, distance, calories burned), pulse, sleep and exercise data. After that, you need to fill in the email address to which the exported data will be sent. An email with a download link is sent to the specified email address. Fitness bracelet data is stored in CSV files. To open these files, you need to know the password that is provided for each user separately during the download of the exported data.

The patient's data will be stored in a shared SQL database after the patient submits their data. In these studies, Azure Machine Learning and Power BI cloud platforms were used for data analysis.

The results of the data analysis are presented in the Result and Discussion section. The purpose of the proposed monitoring system is to prevent hypoglycemia/hyperglycemia as a result of physical activity.

3.2.3 Application layer

As part of the research, we have developed: a web application that is intended for a doctor and serves for analyzing and visualizing patient data; a mobile application that serves as a tool for monitoring the health status of patients with diabetes mellitus. With the help of a mobile application, the patient can observe his previous readings from sensors, enter information about nutrition, blood glucose levels (3-5 measurements per day made by a glucose meter), the nature of physical activity, and see personalized treatment recommendations compiled by a doctor. The patient's parents can also monitor the patient's health status using a mobile application (Figure 3). The mobile application being developed for the patient will be a tool for developing self-management and increasing the joint responsibility of patients to achieve health targets.

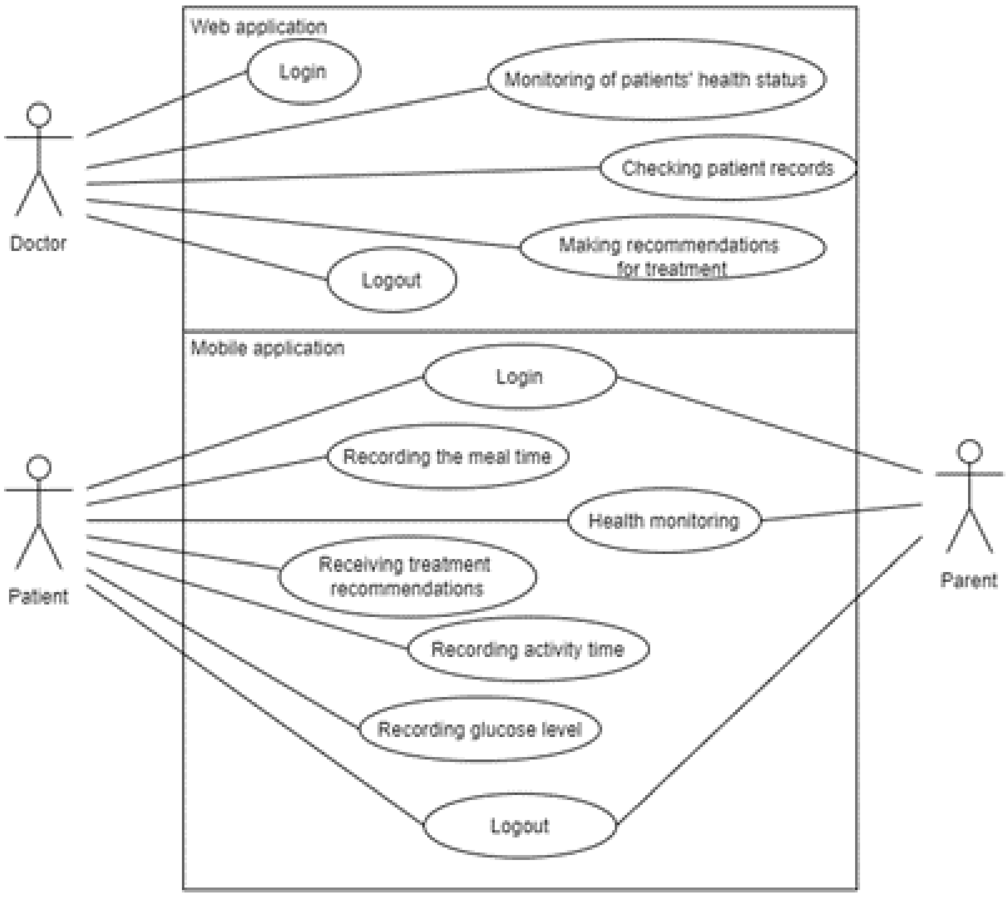

Figure 3: Use Case Diagram of the proposed system

4 Result and Discussion

4.1 The mHealth Monitoring System

Taking into account the components of the proposed monitoring system, the general characteristics are the ability, through the use of hardware and software, to receive input data from users, access and process the received data, as well as store, manage and present information back to the user. To create a system for remote monitoring of the patient's condition, it is necessary to determine the space of diagnostically significant signs that fully characterize the patient's condition. There are different approaches to the selection of indicators for monitoring; in the simplest systems, the decision on the success of therapy is made based on one indicator - the level of sugar in the blood. The space of monitoring indicators should objectively and reliably assess the current condition of a patient with diabetes mellitus.

The web application is hosted on a hosting called Allday.kz (Figure 4). Even when choosing a hosting name, there was a special approach, they wanted the name not to remind the user of his illness. After all, with such a diagnosis, a person must self-discipline and constantly remember about possible complications.

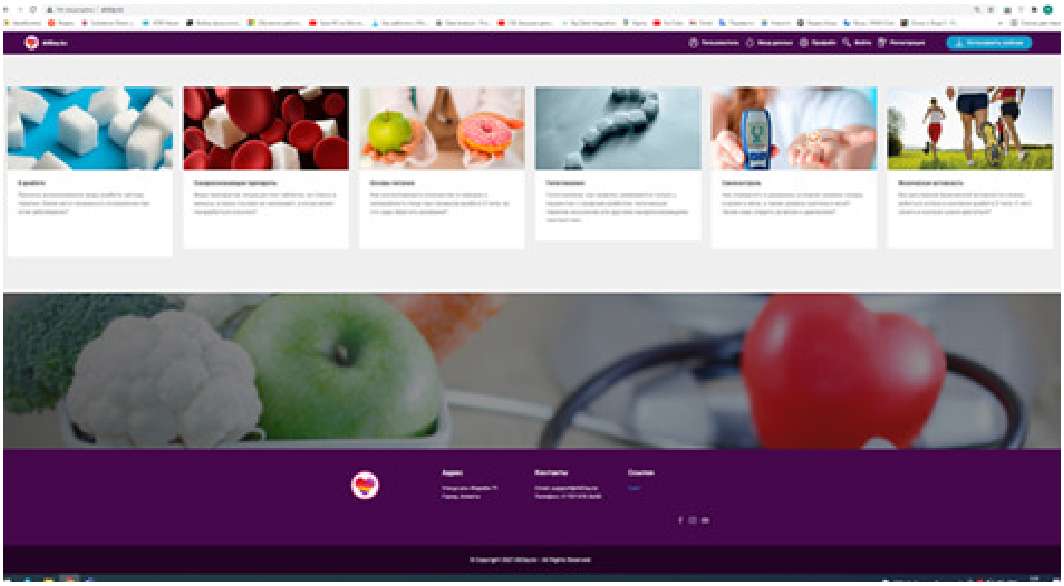

Figure 4: Web Application interface

4.2 Analysis of clinical data and assessment of physical activities

In type 1 diabetes, physical activity increases insulin sensitivity, which makes it possible to reduce the dosage of insulin for the amount of carbohydrates consumed. Moderate physical activity, as a rule, does not require additional planning. But with more intense physical exertion, the risk of hypoglycemia increases, since sugar levels tend to decrease. On the other hand, if physical activity is accompanied by a stressful background or other negative conditions for the body, then glucose levels may increase. The inclusion of intense physical activity in the lifestyle requires monitoring of blood glucose levels to prevent hypoglycemia/hyperglycemia.

The aim of the study is to identify the relationship between physical activity and changes in blood glucose levels for patients with type 1 diabetes after completion of physical activity.

Input data (Table 1):

- the maximum peak of the distance in 5 days according to the pedometer;
- the time period for completing the longest distance;
- glucose sensor readings at the time of start;
- glucose sensor readings within 1 hour after the end of the walk;
- presence/ absence of a stressful background.

Output data: percentage of change in glucose level (GL) within 1 hour after completion of physical activity.

According to the stress background, the patients were divided into 2 categories:

- Category I - children who have a fitness bracelet 2 days before the peak performance of the distance recorded stress levels of only 0-39 (rest) and 40-59 (minor stress), which we took as no stress.

- Category II - children who have a fitness bracelet 2 days before the peak performance of the distance recorded stress levels of 60-79 (moderate) and 80-100 (high).

Table 1: Data on physical activity and health indicators (for example, patient 001)

Patient 001						
date	**start**	**stop**	**distance**	**steps**	GS_0 **mmol/l**	**Category**
2021-08-10	17:26	17:58	1931	2979	8,4	I

Table 2 shows an example of calculations of changes in glucose levels during physical activity per patient, performed according to the formula:

$$k = (GS_0 - GS_n)/GS_0$$

where GS_0 is the glucose sensor readings at the time of launch; GS_n – readings of the glucose sensor at the moment at time n.

Table 2: Calculation of changes in glucose levels after completion of physical activity (for example, patient 001)

A moment in time (Within 1 hour after physical activity)	GS_n readings		Change in glucose level behavior (%) $k = (GS_0 - GS_n)/GS_0$	
18:02	5,6		0,333333	
18:07	5,3		0,369048	
18:12	5,2		0,380952	
18:17	5,2		0,380952	
18:22	**5,2**		**0,380952**	
18:27	5,3		0,369048	
18:32	5,4		0,357143	
18:37	5,7		0,321429	
18:42	6		0,285714	
18:47	6,3		0,25	
18:52	6,6		0,214286	
18:57	6,9		0,178571	
	min	**5,2**	**max**	**0,380952**
			average value	**0,32**

Calculations based on the data of Patient 001, whose glucose level was equal to 8.4 mmol/l at the beginning of physical activity, showed that the glucose level at the 20th minute after the end of physical activity decreased by 38% and reached a value of 5.2 mmol/l. The average value of changes in glucose levels within one hour after the end of physical activity is 32% (Figure 5). The period of 1 hour after the completion of physical activity was chosen according to the recommendations of endocrinologists, who claim that during this period the body does not have time to fully compensate for the decrease in blood glucose levels.

Thus, it was experimentally confirmed that the period (in this case 1 hour) after the completion of physical activity is dangerous due to the possibility of hypoglycemia. With the help of the proposed method, percentages of changes in glucose levels relative to the initial value were calculated for each patient within 1 hour after the completion of physical activity with an interval of 5 minutes. The use of this method will allow the doctor to make individual appointments according to the diet before the start of physical activity and its intensity.

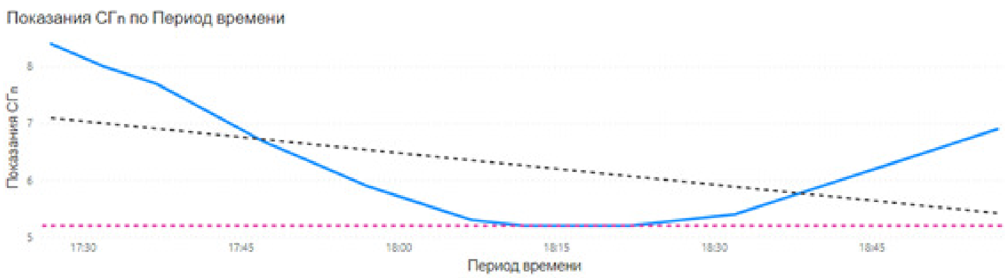

Figure 5: Glucose behavior during physical activity and for 1 hour after physical activity (blue – glucose sensor, black – trend line, pink – the minimum line)

Observing the behavior of glucose levels within an hour after increased physical activity and calculating the k-percent change gives us the opportunity to predict glucose levels. Based on the obtained indicators, endocrinologists compiled personalized recommendations that were included in a mobile application for patient self-monitoring.

In general, the experimental results confirmed that moderate physical activity for 35-45 minutes a day has a good effect on the glucose level of the next day, the likely decrease in the average glucose level is up to 10%.

The application of the proposed calculation method and mobile application will contribute to improving the quality of life of children with type 1 diabetes, in particular, will prevent hypo- or hyperglycemia.

The recommendation functionality is developed on the basis of the received data and medical reports. According to the recommendations of doctors, notifications are included in the recommendation functionality that before the start of moderate physical activity, glucose levels should be measured and data entered into the tab of the mobile application. With each input, this value will be the initial value for the calculation. After completing the walk, the child receives a corresponding notification-recommendation.

4.3 Mobile app for self-management

The developed mobile application will help patients with diabetes mellitus to adapt socially, especially in adolescence in a normal communication environment, without inconveniencing control. The mobile application is developed for the Android operating system using the integrated development environment – Xamarin. The work related to Xamarin was performed on a Windows computer with Visual Studio and Xamarin installed. Applications can be debugged directly from the desktop or on devices and emulators.

In order for the mobile application to have user authorization, in our case patients, we worked on a simple and convenient Xamarin.Auth library, which has been developing for years and has everything we need:

- displaying the browser with authorization pages;
- managing the redirect flow and authorization process;
- getting the right data;
- providing mechanisms for additional requests to the service, for example, to obtain information about the user.

Also Xamarin. Auth supports the ability to store user credentials in a secure storage. The data of the authorized user of the patient will be stored in a shared SQL database after the patient sends his data. The patient enters FA data and, according to the instructions, receives automated recommendations about possible hypo- or hyper-glycemic conditions. The pedometer in the app will read the number of steps per day for convenience. The patient enters food intake data, which is displayed by the doctor in time, for comparison with the behavior of glucose levels (Figure 6).

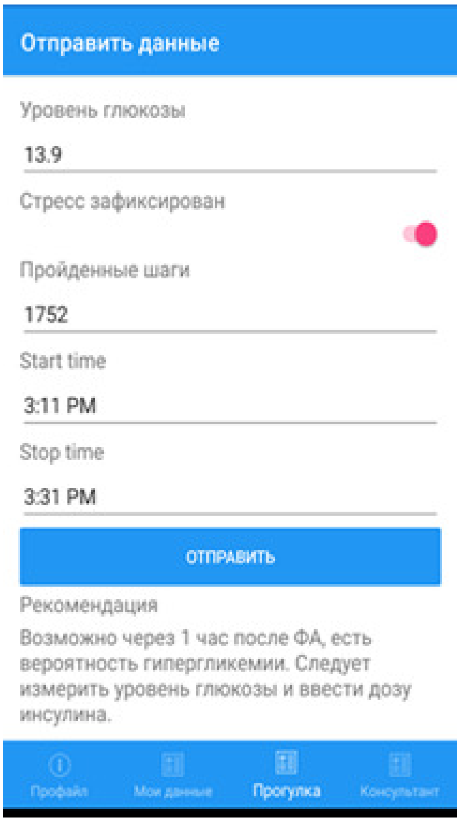

Figure 6: A screen of the received recommendation after a walk

5 Conclusions and Future Works

As a result of the research, the architecture of a mobile health monitoring system based on IoT was proposed, and the relationship between physical activity and the patient's blood glucose level after the completion of physical activity was revealed. The indicators of a decrease in blood glucose levels obtained as a result of computational experiments within 1 hour after the completion of physical activity made it possible to draw up recommendations for physical activity developed taking into account the individual characteristics of the patient. The authors presented a mobile application for children and adolescents with T1 diabetes mellitus, which is a tool for developing self-control and increasing the joint responsibility of patients to achieve health targets.

In the course of further research, we plan to provide a wider connection to a wider range of different devices related to diabetes (glucometer), to develop elements of gamification and functions based on rewards in the mobile application, since the application was originally planned for children with type 1 diabetes, we will consider options for developing functionality based on strategies nutrition or insulin dose adjustments, we will adapt mobile health based on the results of the approbation.

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