

Enhanced Wearable Medical Systems for Effective Blood Glucose Control

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Abstract—Wearable medical systems are prevalent in recent years. Researchers have done enormous experiments and thousands of people have got benefits from them. Wearable medical systems involve many fields, and we mainly talk about blood glucose-insulin control in this paper. The general living standards continue to improve, even though the prevalence of diabetes is dramatically rising. Current methods for treating diabetes is mainly confined to manually injecting insulin for the patient, which is inconvenient and highly expensive. Meanwhile, they are not fine-grained for doctors to accurately control insulin levels, so we try to improve the whole system for blood glucose-insulin control. Wearable medical system for blood glucose-insulin control mainly consists of three parts; Continuous Glucose Monitoring System (CGMS), insulin pump and loop control algorithm. CGSM and insulin pump have made great advances in recent years, but we are still trying to find a better method to decrease errors introduced by mechanical measurement. Loop control algorithm is vitally important and complex to study in this system. We introduce a novel algorithm which can better control blood glucose and insulin levels. To optimize this algorithm and solve storage problem, we also add big data analysis to this system. Our simulations are based on real data from 8 patients during 3 days stay in hospital. We have finally concluded that our system performs well. The research of blood control is one part of wearable medical systems which is of great significance.

Keywords—dynamic control; closed-loop; optimized algorithm; predictive model;

I. INTRODUCTION

The wearable medical system has brought enormous benefits to human beings and promoted great development to the society. It is known to us that it can monitor some part of our body and support specific feedbacks. In other words, it aims to use real-time feedbacks to provide intelligent monitoring of patients. Wearable monitoring system assists in managing the treatment of chronic diseases such as heart diseases, asthma, and diabetes and the monitoring of vital signs such as heart rate, blood oxygen level, respiration, and body fat. They normally provide noninvasive sensing, local processing, user feedbacks, and communication capabilities [1]. There are more and more products streaming into the market such as intelligent bracelets, heart beat detector, CGMS and so on. There are also some challenges during the research of wearable medical systems, such as function, wearability, accuracy and security. The size and requirement

of wearable medical systems have defined these difficulties. In this paper, we will pay more attention to one kind of wearable medical system which shows good performance on the blood glucose-insulin control.

For many decades, the control of diabetes has gone through many stages. However, external control cannot reach the perfect effect as the physiological insulin secretion pattern [2]. Human body system is complex, and it is difficult to construct a manual system to realize its function [3]. Especially for these patients who nearly cannot control the insulin by their own pancreas, the manual control can hardly give good performance as the blood glucose changes greatly. Artificial pancreas is a novel research direction in recent years, and it can imitate the pattern of pumping up of insulin by pancreas and inject insulin automatically [4]. Compared with the manual control, it is more reliable, more convenient and more flexible. Artificial pancreas in this paper consists of three parts, CGMS, insulin pump and closed-loop control algorithm. Medtronic is the biggest company which dedicated to research medical devices, and it has the best sale on CGMS and insulin pump. However, they have not given a complete system with closed-loop control algorithm.

Despite these, another question we have to consider is the communication or data exchange between CGMS and insulin pump. The communication between CGMS and closed-loop control can guarantee that the values of blood glucose can be transferred to the algorithm in time. The communication between insulin pump and closed-loop control can guarantee that the signal of insulin can be executed correctly. The closed-loop control algorithm can be embedded into insulin pump if the data processing is not too complex. However, if we want to make this algorithm accurate, we have to get enormous data, and we have to consider the storage of insulin pump. In this paper, we introduce another part which is especially designed to process data and optimize the algorithm. The whole system and the relationship among them can be described in Figure 1.

There are three innovative points in this paper and they can be summarized as follows:

- *Design of a system for blood glucose-insulin con-*

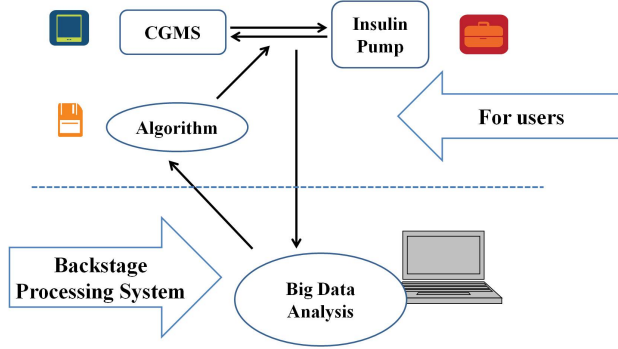


Figure 1. The relationship of this system including big data analysis

trol: We design the whole system for blood glucose-insulin control. This wearable medical system for blood glucose control consists of CGMS, insulin pump and loop control algorithm. These three parts guarantee the automatic control.

- **The proposal of one control algorithm which is based on model predictive control:** To better control blood glucose and insulin, we put forward a kind of algorithm based on Model Predictive Control (MPC). We have done many kinds of experiments to validate the performance of this algorithm. Compared to other blood glucose control algorithms, the algorithm in this paper has excellent robustness and individuation.
- **The proposal of a kind of control mechanism which is based on big data analysis:** On one hand, we hope that the insulin carrier is portable, but it will influence the storage of data. Thus, we put forward one method which can solve the storage problem. Meanwhile, we introduce big data analysis which can dynamically optimize our closed-loop algorithm and make our algorithm adaptive to individuals.

This paper is organized as follows: First of all, we talk about research status and challenges of each part in this system. Then, we introduce the design of the system framework and the loop control algorithm in Section III. We provide some optimization methods to algorithm including constraints and big data analysis in Section IV. Section V presents the simulation results of this system. Section VI discusses some related work and describes future work. Finally, Section VII concludes the paper.

II. CURRENT STATUS AND CHALLENGES

In this part, we will introduce current research status and challenges of this system including CGMS, insulin pump and loop control algorithm.

A. Current Status

1) **CGMS:** CGMS is a kind of wearable medical device [5] which can detect patients' blood glucose level.

A sensor, which is beneath your skin, will collect some information about blood glucose. Based on the complex algorithm, CGMS can calculate the final statistics and show them on the screen. Doctors can judge whether patients blood glucose level are in a security range by the statistics. In recent years, many companies have invented some practical products which can detect the blood glucose level in high accuracy.

2) **Insulin Pump:** Insulin pump can relieve patients pain and ache, and it can inject insulin to the body automatically via a micro-motor [6] which is different from manual injection. To imitate the mechanism of body control, insulin pump has two kinds of injections including basic quantity and incremental quantity. When the patients have meals, insulin pump will inject according to incremental quantity and the other one work at other time. In the field of insulin pump, most of them are disposable because insulin is difficult to store.

3) **Loop control algorithm:** The development of CGMS and insulin pump has been stable while the loop control algorithm is difficult to be put into practice. On one hand, the experiment to be tested in the body is long-time because of considerations of security. On the other hand, due to the complexity of blood glucose system, there are various kinds of conditions which can have influence on the injection of insulin. It is extremely difficult for researchers to propose an ideal algorithm to imitate the process of insulin adjustment completely.

Some researchers and doctors have conducted some clinical tests on patients. They use different kinds of algorithms to test their performance. For example, one kind of algorithm is to control blood glucose at night, aiming to guarantee the level of blood glucose at night. The result shows that their algorithm can make hypoglycemia lower than 20% [11].

In this paper, we put forward a kind of algorithm named Dynamic Closed-loop Control (DCLC) of Insulin which is based on the predictive model. Unlike open-loop control mode, feedback results are added to this algorithm to guarantee accurate operation [7]. We also take some constraint conditions into consideration. Therefore, it can be called an Enhanced Dynamic Closed-loop Control algorithm (ED-CLC). By analyzing our simulation results, it shows realistic and stable control over the changes of blood glucose.

B. Challenges and Expectations

There are some challenges and expectations about each part of this system. The first problem about current invasive CGMS is that most of these devices need the assistance of blood glucose meter which will definitely introduce much trouble. Secondly, there are differences among different devices when blood glucose at low levels [8]. It is serious because hypoglycemia might cause other diseases. Finally, no matter how we improve the accuracy, time-delay always exists, because of the existence of biological response in the

body [9]. We can hardly overcome it at least in these several years. Like CGMS, insulin pump is also faced with time-delay. Because of biological response, insulin from insulin pump needs time to reach internal. Therefore, it is of great importance to solve this kind of problem [10].

Closed-loop algorithm has to overcome the following problems: Firstly, the relationship between blood glucose and insulin is not stable. Secondly, the relationship between blood glucose and insulin is not liner. Thirdly, blood glucose systems are different in different kinds of people and we have to find a model to be adaptive to this difference. Fourthly, some external conditions like diet, exercise and so on can have a big impact on blood glucose control.

Nowadays, wireless communication between CGMS and insulin pump becomes hot because its convenience. Meanwhile, some security problems emerge. Anyone can detect information from wireless channel, and hackers can modify data if he use special technologies. We have to study a kind of wireless communication with highly reliability. Closed-loop control algorithm is significant because it combines CGMS with insulin pump. It can affect the levels of blood glucose and insulin. Moreover, there are no perfect algorithms which can control blood glucose completely. In our paper, we put forward one kind of algorithm which can be used together with CGMS and insulin pump.

III. REQUIREMENTS AND DESIGN

Because CGMS and insulin pump have mature technology, the most difficult part of this system is loop control algorithm. Until now, there are no such a kind of algorithm can control blood glucose automatically in the market all over the world. We have studied some famous and effective algorithms which have been put forward. There are some drawbacks, although they can show good performance in some parts. Our algorithm is based on model predictive control which is a kind of auto control algorithm, and we research the requirements of this system and confirm the main structure of this algorithm. In this algorithm, we have to take various kinds of factors into consideration including values of blood glucose, insulin and so on. We also give a specific equation about how we get certain values.

A. Requirements

The purpose of this system is to control blood glucose and insulin automatically. In a word, we need to imitate the function of pancreas. So we have to think about some factors which will affect the blood glucose, such as diet, exercise, daily habit and so on. On the other hand, we can refer to the values from the past, they contain lots of information, and we can study one algorithm which can mix these values together and calculate the exact values we want to know. In the next several parts, we will introduce our design thought, and the algorithm in this system.

B. Closed-loop control

The main difference between open-loop control and closed-loop control is whether the output values are used. Obviously, inputs and outputs are necessary in our algorithm [12]. Meanwhile, outputs can take effects on inputs. The key points are how can we turn input values into outputs as we want and which conditions should be paid more attention during this process [13].

C. Predictive model

There are several algorithms which have been widely studied during these years, Proportion Integration Differentiation (PID) and MPC show good performance according to the experiment results, and both of them includes closed-loop control [14]. PID is a kind of algorithm which calculates the optimal amount of insulin by analyzing the patient's past and current situation analysis of blood sugar, blood glucose fluctuation rate. But there are a lot of people think that this method does not cope well with complex blood glucose control system (including food digestion and absorption of insulin, insulin and physical half-life movement and other factors) [15], while MPC is able to predict the future based on the physiological characteristics of blood sugar levels in patients and look for the best control strategy for next some time [16]. In this paper, we introduce DCLC which is based on predictive model.

D. Parameters

DCLC can make predictions for the future results based on past data, it fuses all kinds of proper information in the past. It doesn't pay much attention on specific formula but focuses on the process of finding a core variable which can optimize the final results.

In DCLC, we can set up some parameters for blood glucose values and insulin values. First and foremost, $G(d, t)$ represents patients blood glucose in d day and t moment, which comes from CGMS. As a result, $G(d, t - 1)$ is the blood glucose value before this moment, and $G(d - 1, t)$ is the blood glucose value before this day. We do not only need real time statistics, but also review types. Therefore we should take these past data into consideration. In order to measure the current level of patients blood glucose, we need the security values of blood glucose which are a set of referable blood glucose values at every moment. For example, at 7:00 p.m., a patient is supposed to have breakfast, so his secure blood glucose value can be set 10 *mmol/L*. We use $G_s(t)$ to represent this kind of values. To show the difference between $G(d, t)$ and $G_s(d, t)$. We use $Gx(d, t)$ which equals $G_s(t) - G(d, t)$. In addition, for insulin values, we use $I(d, t)$ to represent the insulin value in d day and t moment. To reflect the changes of the insulin values, we introduce another parameter which is $R(d, t)$, it equals $I(d, t) - I(d - 1, t)$. $R(d, t)$ is also an important parameter, because it can decide the trend of the changes of the insulin

values and it is the variable we just mentioned above which is very important. Last but not least, we introduce a new concept which is called control difference. It consists of some data from negative to positive and is calculated by the cost function which has many parameters including blood glucose values and insulin values. We use F to represent the dependent variable in the function and R to represent the control difference. In the later parts, we will introduce this function. Because R has many values, F is variable. We select the minimum F and get the corresponding R , which is the $R(d, t)$ we want to get. And then, we can get $I(d, t)$. $I(d, t)$ can have impact on $G(d, t)$, thus the algorithm forms cycle and iteration.

E. Algorithm structure

The structure of the algorithm can be divided into three parts. The first part is the collection of blood glucose values, we can get $G(d, t)$, $Gs(d, t)$ and their past values. The second part is mainly about calculating the control difference. The third part is to get the insulin values. Figure 2 shows the structure of this algorithm.

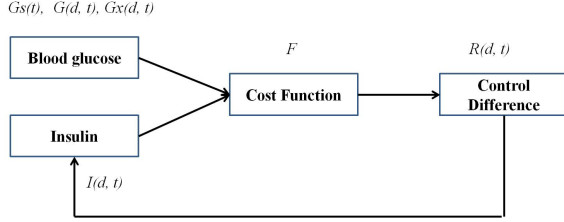


Figure 2. The structure of the algorithm

F. Algorithmic process

(1) We get blood glucose values from CGMS, the current value is recorded as $G(d, t)$, and then we can calculate $Gx(d, t)$.

$$Gx(d, t) = Gs(t) - G(d, t) \quad (1)$$

(2) To get precise data, we should take various kinds of factors into consideration. We have mentioned some parameters above, such as $G(d, t)$, $Gx(d, t)$, $I(d, t)$, $R(d, t)$. Each of them is related to the current value of insulin, $I(d, t)$. The value of insulin is variable, therefore we introduce R and $R(d, t)$ to represent change and then we can get $I(d, t)$. $R(d, t)$ equals to $I(d, t) - I(d - 1, t)$, and we can calculate $Gx(d, t) - Gx(d - 1, t)$, $G(d, t) - G(d - 1, t)$, $G(d, t) - G(d, t - 1)$ and $I(d, t) - I(d, t - 1)$. All of them are called D-value. To improve the accuracy, we can sum up the values from several days and moments. With $G(d, t)$, $Gx(d, t)$, $I(d, t)$, $R(d, t)$, we can substitute into function F and we can get $R(d, t)$. There are many ways to form function F by combining these parameters, we have tried

many possible functions and get one which has the best effect. Function F can be:

$$\begin{aligned}
 F = & \sum_{i=0}^m [Gx(d + i, t) - Gx(d + i - 1, t)] \\
 & + \sum_{i=0}^n [G(d + i, t) - G(d + i - 1, t)] \\
 & + \sum_{i=0}^k [G(d, t + i) - G(d, t + i - 1)] \\
 & + \sum_{i=0}^l [I(d + i, t) - I(d + i - 1, t)] \\
 & + \sum_{i=0}^p [I(d, t + i) - I(d, t + i - 1)] + R
 \end{aligned} \quad (2)$$

One point we should emphasize here is that there are some extra variables like m , n , etc. They are introduced because of the differences of each kind of patient, we can adjust these variables in order that function F can be adaptive to a specific patient.

Then, $R(d, t)$ is:

$$R(d, t) = \operatorname{argmin}(F) \quad (3)$$

$R(d, t)$ is the control difference we need, it can lead to the changes of the insulin values.

(3) Then we can get $G(d, t)$ in Equation 4:

$$I(d, t) = I(d - 1, t) + R(d, t) \quad (4)$$

And now, we get the current value of insulin, then the injection of insulin can lead to the changes of blood glucose. The cycle process has formed and it can be as Algorithm 1.

Algorithm 1 Framework of blood glucose control algorithm.

Input:

- The value of blood glucose for current date and moment, $G(d, t)$;
- The value of blood glucose for last date and moment, $G(d, t - 1)$, $G(d - 1, t)$;
- The value of insulin for last date and moment, $I(d, t - 1)$, $I(d - 1, t)$;
- Security values of blood glucose, $Gs(t)$;
- Control difference, R ;

Output:

- The value of insulin for current date and moment, $I(d, t)$;

- 1: Calculate the cost function, F ;
- 2: Get $R(d, t)$;
- 3: Get $I(d, t)$ with $R(d, t)$ and $I(d - 1, t)$;
- 4: **return** $G(d, t + 1)$;

Because of some drawbacks of MPC algorithm, we add some constraint conditions to this model which can calculate

the relationship between the blood glucose and insulin in a coarse-grained way, and it can ensure the accuracy and practicability. We will pay more attention on these constraint conditions and propose some methods to optimize our system.

IV. OPTIMIZATION

Although this algorithm can show good performance on the relationship between the blood glucose values and insulin values, we have come across some problems. For instance, when a patient's blood glucose value suddenly drops, it may cause hypoglycemia. At the same time, the insulin pump will inject insulin continuously, due to our previous blood glucose values and insulin values, which is extremely dangerous to patients. Meanwhile, we hope that this algorithm can perform well on various kinds of patients, but it is extremely difficult. Therefore, we have to make some changes and optimizations to get EDCLC. In this part, we mainly talk about the optimizations about this algorithm and system. Obviously, we can modify or add some parts to achieve satisfying results. On one hand, we can add some constraint conditions which can eliminate unstable results. On the other hand, we can select some parameters in this algorithm and make them variable. These values depend on the big data analysis of the treatment of patients, thus different patients have different parameters.

A. Constraint Conditions

The first thing which we take into consideration is the curve slope. As known to all, food is the main factor that affect the patients' blood glucose. When a patients' blood glucose values increase or decrease in a short time, it is difficult for our original algorithm to change the insulin values quickly. As a result, it is necessary for us to add some constraint conditions to it. We introduce the constraint of curve slope. For example, the difference of blood glucose values and insulin values between two adjacent moments represents the changing speed, and we can call it curve slope. If the curve slope of the blood glucose is beyond the secure value, it may cause some problems. So we should set a constraint to make the curve slope maintain the secure ranges.

When we sleep, the blood glucose values are stable because we do not have any food. However, some little changes will also lead to the changes of the insulin values. To simplify the running system and save the energy, we set a stationary insulin value when the patient falls asleep. For example, if the patient goes to bed before 10 p.m. every night, and wakes up at about 6 a.m.. We can set the $G(d, t)$ equals a constant like 0.3 during this period, which means the insulin value during this period is regular. However, if there are some huge changes at night, the patient may have some snack after 10 p.m., we will set a constraint

function which will adds some insulin temporarily to ensure maximum security.

The core of our algorithm is the cost function which can decide the control difference, and we should pay more attention to it. The cost function includes many kinds of factors, but not each factor has equal effect on the final values. As we know, the values of the last day and moment are the most important while the effect of previous two or three days or moments are limited which is still useful as well. We should take different weight to different values, and the cost function can be optimized with some weights. For example, for the last moment value $G(d, t) - G(d, t - 1)$ we can set the weight 1.5. For $G(d, t - 1) - G(d, t - 2)$, we can set 0.5. This method can fully take advantages of the latest values.

Considering all these optimization method, we can supplement the algorithm which is mentioned in the last section. These constraint factors can be put after we calculate F and get $I(d, t)$ as described in Algorithm 2.

Algorithm 2 Process of optimization for blood glucose control algorithm

Output:

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    The value of insulin for current date and moment from
    cost function and control difference,  $I(d, t)$ ;
1: for each  $t \in [0, m]$  do
2:   for each  $d \in [0, n]$  do
3:      $F = 1.5 * (G(d, t) - G(d, t - 1)) + 0.5 * (G(d, t - 1) - G(d, t - 2)) \dots$ 
4:   end for
5: end for
6:  $R(d, t) = \text{argmin}(F)$ 
7: if  $G(d, t) - G(d, t - 1) > \text{securevalue}$  then
8:    $I(d, t) = \text{blood glucose};$ 
9: else
10:   $I(d, t) = I(d - 1, t) + R(d, t);$ 
11: end if
12: if  $t > \text{bedtime}$  then
13:   $I(d, t) = \text{night value};$ 
14: else
15:   $I(d, t) = I(d - 1, t) + R(d, t);$ 
16: end if
17: return  $I(d, t);$ 

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B. Big Data Analysis

We have optimized the algorithm we put forward, but there is another question. As we know, this algorithm can be embedded into insulin pump. However, insulin pump is so mini that it cannot store too much data generated by this algorithm. For each time point, the data we need are not only current values of blood glucose or insulin, the previous values are also necessary. It will cause the problem that the

storage device can not process these large datasets. In this part, we will introduce a kind of method which can solve the storage problem. Meanwhile, it can optimize our algorithm dynamically. We add another part called big data analysis and it can exchange data with insulin pump.

In general, big data refers to the datasets that could not be perceived, acquired, managed, and processed by traditional IT and software/hardware tools within a tolerable time [18]. One of the features of big data is big, the amount and values of the data are big. Although it seems all in a mess, it contains various kinds of information we need. There are some recessive relationships among massive data. One system equipped with big data analysis is more like a humanized robot, because it can make decisions according to the past record not by yes or no in embedded programs.

Insulin pump just stores some recent data and most data are stored in big data analysis system. At first, insulin pump has an original algorithm and it can control blood glucose and insulin roughly. When it has enough data to analyze, it will transfer these data to big data analysis system which we can call BPS (Backstage Processing System). However, if we accumulate data during 3 or 4 days and we sample it every 30 minutes, insulin pump probably cannot store so much data. So we adopt one storage method which can change the quantity of data as time changes. For example, in first 5 hours, we store data every 30 minutes. Between 5 hours and 10 hours, we store data every 1 hour. Between 10 hours and 20 hours, we store data every 2 hours. Over 20 hours, we store data every 3 hours. It can be described in Figure 3.

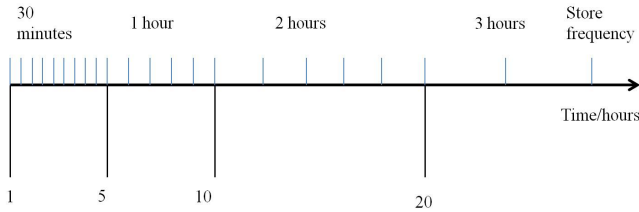


Figure 3. Store method in insulin pump

This method can store more data and keep effectiveness to the maximum extent. CGMS collects values of blood glucose every 30 minutes, and insulin pump gets values of insulin every 30 minutes. Once insulin pump connects BPS successfully, it will transfer all data to BPS and then it will store data with the method in Figure 3.

Also, we use big data to optimize the control of blood glucose and insulin and we hope that the distinguish of different kinds of patients will be clear. At the beginning of this part, we mentioned that we needed to select some parameters to make them variable. The main difference among patients is the human blood glucose system. Different people react differently to different amount of insulin. Therefore, we can change these parameters placed before insulin values

including l and p in Equation 2. Now the problem is that when we should change these variable values and under which conditions we can decide to change. In the third part, we introduce $G_s(t)$ which represents the security value of blood glucose, and we can get $G(d, t)$ from Algorithm 1. We can set a safe point for each security value for each period. Below is Table I which indicates different $G_s(t)$ in different periods.

Table I
 $G_s(t)$ IN DIFFERENT PERIODS

Period	range	$G_s(t)$
7 a.m.- 9 a.m.	5-12 mmol/L	8 mmol/L
9 a.m. - 11 a.m.	5-12 mmol/L	10 mmol/L
11 a.m. - 1 p.m.	8-18 mmol/L	13 mmol/L
1 p.m. - 5 p.m.	5-12 mmol/L	8 mmol/L
5 p.m. - 8 p.m.	8-18 mmol/L	13 mmol/L
8 p.m. - 7 a.m.	3-8 mmol/L	5 mmol/L

Therefore, we can calculate the variance σ^2 between $G_s(t)$ and $G(d, t)$ as shown in Equation 5:

$$\sigma^2 = (G_s(t) - G(d, t))^2 \quad (5)$$

The value of σ^2 indicate the security of the current blood glucose level. If σ^2 is a bit large, $G(d, t)$ is supposed to change. It also shows that the patient is more sensitive to insulin, because the same amount of insulin can make more impact on blood glucose than others. When we want to change $G(d, t)$, we can change l and p . If we decrease l and p , $R(d, t)$ we get in Equation 3 will become smaller and values of insulin will change more slowly. Therefore, to those who are more sensitive to insulin, less amount of insulin will have the same impact on their blood glucose. To different σ^2 , the system will give different judgments. For instance, if $\sigma^2 = 10$, l and p will be decreased to 75%, if $\sigma^2 = 3$, l and p will be decreased to 90%. After we get the latest l and p , BPS will transfer to insulin pump to update Equation 2, there will be a new and more suitable algorithm for this patient. It is important for early treatment because the original algorithm is not suitable to each kind of patients. After several weeks, when BPS gets stable coefficients, the algorithm can have a stable performance to a specific patient.

Insulin pump connects with BPS via Bluetooth. After the patient use the whole system, CGMS detects values of blood glucose and transfer to insulin pump. Insulin pump gets these data and then calculates values of insulin by the embedded algorithm. Because BPS and insulin pump are connected, insulin pump will transfer all data to BPS regularly. If BPS is connected with insulin pump, insulin pump will store data with the algorithm in Figure 3 momentarily. Once they are connected successfully, insulin pump will transfer all historical data to BPS. BPS can calculate suitable coefficients and then transfer to insulin pump to update closed-loop control algorithm. When we use wireless communication, we have to think about security. It is important to communication

and patients treatment. If some coefficients are falsified, it is difficult to imagine. Because of Bluetooth, insulin pump and BPS should authenticate with a private key which can protect data security to a certain extent.

V. EVALUATION

In this section, we introduce the simulation setup, describe the simulation results, and discuss the causes behind the simulation results. To ensure the reliability and practicability, we have monitored the real-time conditions of 8 patients including their blood glucose and insulin injection. First of all, we have got 24-hour values of blood glucose and insulin for three days of 8 patients in hospital. CGMS can get the values of blood glucose every 30 minutes, and doctors inject insulin by insulin pump at each specific time. Figure 4 shows the realistic scene in the hospital. The left one shows a patient who is using CGMS and the right one is the insulin pump and CGMS.

We use an embedded development board to store data and the algorithm. Our computer can give the values of blood glucose to the board and get the values of insulin from it. The chip is from Freescale which can perform excellent computing and storage power as described in Figure 5. The USBDM port is designed to burn the program and the serial port is for communicating with the computer.

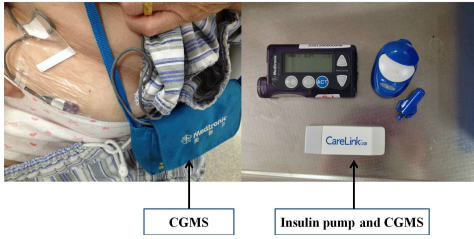


Figure 4. Realistic operation of CGMS and insulin pump in the hospital

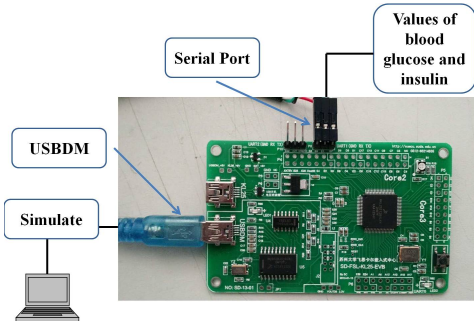


Figure 5. Communication and storage tools

There are 8 subfigures in Figure 6 and 7, they stand for blood glucose curve for 8 patients, and each subfigure has three curves with different colors and shapes for different days. The x-coordinate represents time, every two points

equal 30 minutes because we get the data every 30 minutes. The y-coordinate represents specific numerical value, we can read the value of blood glucose and insulin. Meanwhile, from each figure, we find that there are three peaks which represent the meal time during the whole day. The normal values of blood glucose range from $4mmol/L$ to $15mmol/L$. However, in Figure 6 and 7, some of their values ranges from $4.0mmol/L$ to $15.0mmol/L$ which is beyond the normal standard. With the process of the algorithm, we can simulate the values of insulin according to their blood glucose value. Finally, we can compare the simulation insulin values with the actual insulin values and evaluate the performance of our algorithm [17].

Our experiment includes four parts. The first one is to simulate the insulin values with the original algorithm which we have introduced in Section III. And then, in the second part, we turn to the algorithm which has been optimized. These two parts can indicate the superiority of performance clearly. The third part and fourth part mainly focus on the robustness of this algorithm. To express the figures of simulation clearly, the meanings of some proper expressions are shown in Table II.

Table II
MEANINGS FOR PROPER EXPRESSIONS

Proper Expressions	Meanings
OIC#1	Original insulin curve on the 1st day
OIC#2	Original insulin curve on the 2nd day
SIC#2	Simulation insulin curve on the 2nd day
SIC#4	Simulation insulin curve on the 4th day
SIC#6	Simulation insulin curve on the 6th day
BGC#1	Blood glucose curve on the 1st day
BGC#2	Blood glucose curve on the 2nd day
BGC#4	Blood glucose curve on the 4th day
BGC#6	Blood glucose curve on the 6th day
OIV#1	Original insulin value on the 1st day
SIV#4	Simulation insulin value on the 4th day
SIV#6	Simulation insulin value on the 6th day

On the first stage, we test the insulin values with DCLC algorithm. Now, we take patient 1 for example. We have got the statistics of blood glucose values for completely three days. According to the algorithm, the first-day statistic is necessary, and the values of the second and the third day is based on the iteration of first-day statistic. For each day, we have 48 data, which is sampled by 30 minutes during 24 hours. Now we use the first-day data and simulate insulin results on the second day and the third day. For patient 1, some variables like m , n , etc are different from other patients, and we have tried many times to get good results. The simulation results can be shown in Figure 8(a). Figure 8(a) shows insulin values change along with the changes of blood glucose values. It is based on DCLC algorithm and we can find some waves in the blue curve. We can see that the three peaks of the curve of blood glucose values stand for the meal time, because when a person have meals, his or her blood glucose will increase. Also, the curve of insulin values

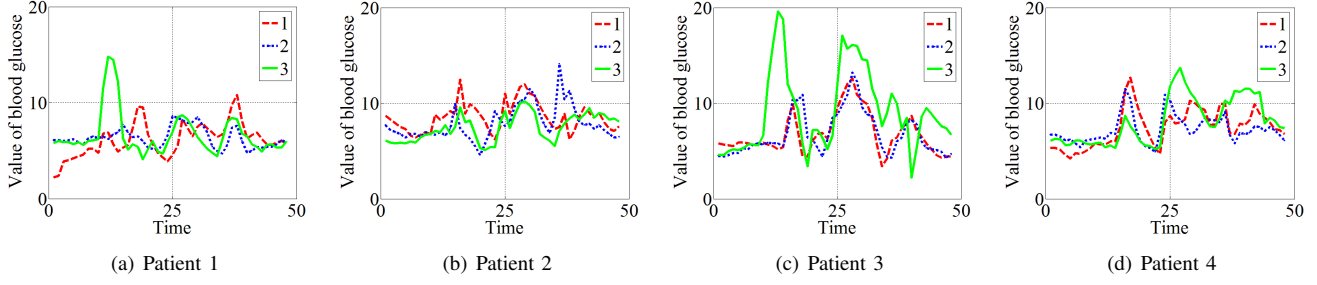


Figure 6. Original blood glucose curve: patient 1-4

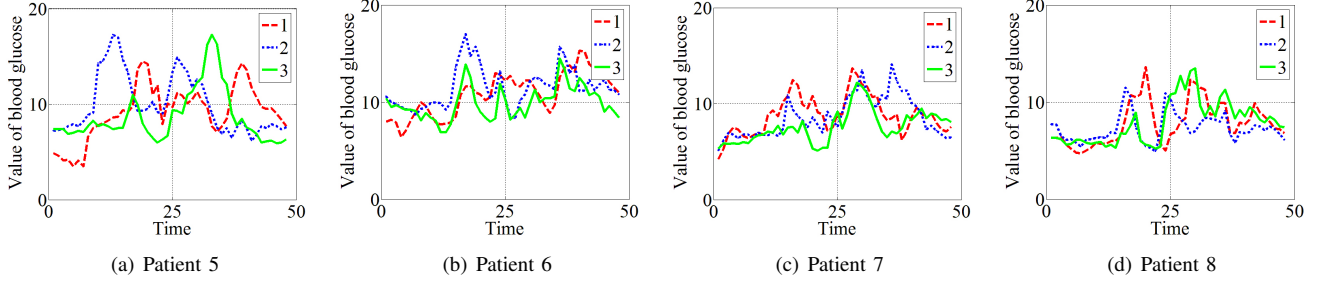


Figure 7. Original blood glucose curve: patient 5-8

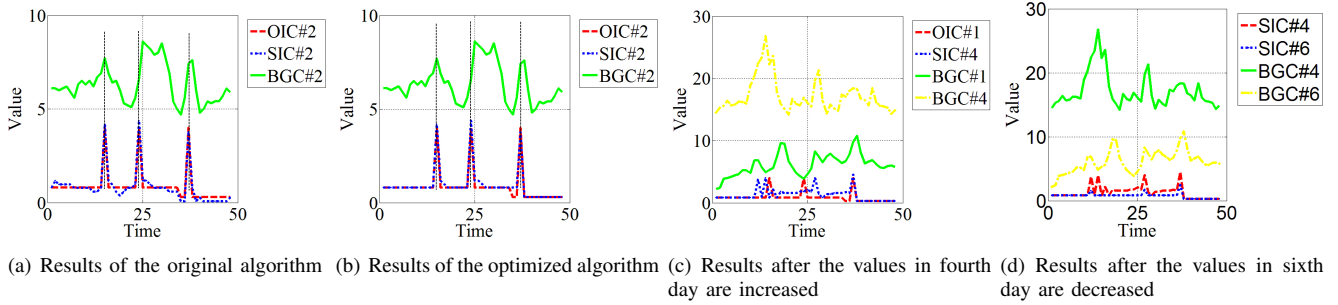


Figure 8. Results

has three peaks which correspond to the curve of blood glucose values. However, there are some problems. Because the simulation result is different from original values at some points and we want to decrease the rate of difference, we add some constraints conditions as mentioned above. We can get Figure 8(b) by simulating EDCLC algorithm. Comparing Figure 8(a) with Figure 8(b), we can validate the stability of EDCLC algorithm. Next, we increase the blood glucose values deliberately. For example, we have three days simulation results, and the blood glucose values on the fourth day are increased twice as that on the third day. As shown in Figure 8(c), insulin values on the fourth day are about twice as much as blood glucose values. In Figure 8(d), when we decrease the blood glucose values on the sixth day, we can find the insulin values also decreased. Figure 8(c) and Figure 8(d) indicate that the insulin curve can change along with the blood glucose curve obviously. In Figure 8(c), as

the values of blood glucose are doubled on the fourth day, the values of insulin are nearly doubled. To get a direct proof, we make a bar chart for the values of insulin on the first day and the fourth day as shown in Figure 9(a). In Figure 8(d), the values of blood glucose on the sixth day are halved compared with that on the fourth day. Figure 9(b) shows the specific value of insulin on the fourth day and the sixth day, and we can understand the relationship between blood glucose and insulin clearly. From these simulations, we can conclude that the enhanced dynamic closed-loop control algorithm has satisfying results.

VI. DISCUSSIONS

To advance the study of blood glucose and insulin control system, researchers in different fields are sparing no effort to do experiments. As we have mentioned above, this system mainly consists of three parts, CGMS, insulin pump and closed-loop control algorithm.

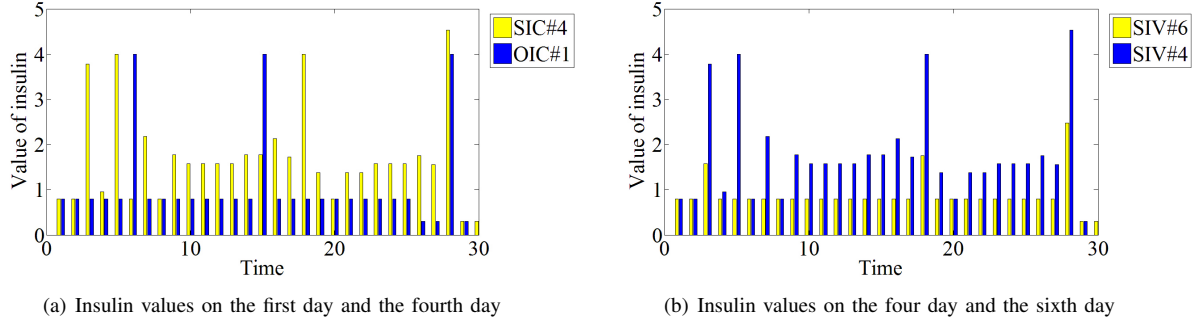


Figure 9. Values of insulin on the 1st day, the 4th day and the 6th day

Reducing correction times and improving measurement accuracy are two focusing points during these years, and it is a long term process and needs countless process adjustments. To improve measurement accuracy, some scientists propose a new method which is based on humor measurement. Scientists from University of Washington and Microsoft have done experiments to detect glucose concentration in human tear, and it shows good results. Some scientists study noninvasive CGMS to make it be adaptive to more patients and lessen pains. Professor Jin Tuo [19] from school of pharmacy in Shanghai Jiao Tong University proposed a kind of micro needle which enables highly efficient transdermal delivery of insulin without depositing the needle tip materials to the skin. It is practically applicable to a variety of protein/peptide medicines requiring frequent dosing by offering painless administration, freedom of refrigeration, and minimal safety concerns.

Decreasing response time after injecting insulin is a key point during the study of insulin pump. Researchers are trying different ways to control effectiveness when patients have meals. Daniel E. Vaughn and other researchers have authenticated that insulin being injected with recombinant human hyaluronidase can improve response speed [20]. Heating the infusion position [21] and infusion in the dermis [22] can also realize this effect. Most of insulin pumps are unidirectional which means that it can just control the injection of insulin. It can low the blood glucose, but sometimes if blood glucose is too low, we need glucagon to promote the decomposition of blood glucose to raise it. Therefore, some researchers are trying to make insulin pump bidirectional. Meanwhile, adding glucagon can improve security in blood glucose-insulin control. It is more acceptable than unidirectional insulin pumps. Mark Evans introduce next generation in insulin pump technology and put forward this bidirectional bionic pancreas [23]. The storage of insulin is another problem, it is difficult for patients to provide low temperature environment. There also researchers are searching for better store methods.

As this system is related to human beings and our daily life, clinical tests are necessary. Most clinical tests are oper-

ated in hospitals which can guarantee the safe of volunteers. When patients use this system, they may be in various kinds of places not only in hospitals. Therefore, some experiments are operated in their homes. Some countries have made some regulations to advance these clinical tests carried on in different places and guarantee people's security. As we know, blood glucose is not only related to diet, exercises, social activities and other important conditions cannot be ignored. The diabetes research in children network study group have conducted an experiment and they find that exercises with medium intensity have a higher probability to cause hypoglycemia [24]. Meanwhile, researches from school of human movement and exercise science, University of Western Australia raise a point that a 10-s sprint performed immediately prior to moderate-intensity exercise prevents glycaemia from falling during early recovery from moderate-intensity exercise in individuals with type 1 diabetes [25].

VII. CONCLUSION

Wearable medical systems are becoming extremely prevalent in recent years, and large amount of human beings are going to use these products gradually because of their convenience and practicability. This paper mainly introduces a kind of wearable medical system for blood glucose-insulin control. It mainly includes CGMS, insulin pump and closed-loop control algorithm.

Although CGMS and insulin are mature in technology, there are many scientists spending much time improving their performance. The core of this system is the enhanced dynamic closed-loop control algorithm. It is based on predictive model control, and we add some constraint conditions to it. From the simulations and experiments we have done, we can conclude that this system is stable, fine-grained and robust, the values of insulin are also reasonable.

We also add another part which is called big data analysis which is intended to solve the problem of storage in insulin pump and to dynamically optimize the closed-loop control algorithm. CGMS, insulin pump and closed-loop control algorithm are three parts for users, while big data analysis

is a backstage processing system. Patients use the same original algorithm when they use it for the first time. As the accumulations of data, the system will obtain a suitable algorithm with individual coefficients. Therefore, algorithms are supposed to be different to different patients.

The road to fine-grained and flexible control of blood glucose-insulin is long. As a kind of wearable medical systems, blood glucose-insulin control has attracted great attentions in recent years. Likewise, there are also some other wearable medical systems or devices which are beneficial but face similar challenges and problems. Besides some problems about their functions, security should also be taken into consideration. As technology develops, especially wearable medical systems are increasingly related to human health, the demand of security will arise.

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