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Intelligent Auto-Tuning Controller Design Based on Dolphin Echo Location for Blood Glucose Monitoring System

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ABSTRACT

This paper presents an enhancement technique for tracking and regulating the blood glucose level for diabetic patients using an intelligent auto-tuning Proportional-Integral-Derivative PID controller. The proposed controller aims to generate the best insulin control action responsible for regulating the blood glucose level precisely, accurately, and quickly. The tuning control algorithm used the Dolphin Echolocation Optimization (DEO) algorithm for obtaining the near-optimal PID controller parameters with a proposed time domain specification performance index. The MATLAB simulation results for three different patients showed that the effectiveness and the robustness of the proposed control algorithm in terms of fast generating insulin control action and tracking the dynamics behavior of the blood glucose level of the diabetic patients through minimizing overshoot, rise time and settling time in the transient state as well as the steady-state blood glucose level error is reduced approximately to zero and keep it in the desired glucose level, especially when we added a meal as disturbance effect.

Keywords: Auto-Tuning, PID Controller, Dolphin Optimization Algorithm, Blood Glucose.

تصميم مسيطر ذكي ذاتي التنغيم اساسه خوارزمية تحديد الموقع بواسطة الصدى للدولفين لنظام مراقبة الكلوكوز في الدم

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الخلاصة

هذا البحث تضمن اقتراح تحسين جديد يعمل على تنظيم مستوى الجلوكوز في الدم لدى مرضى السكري ذلك باستخدام مسيطر ذكي (تناسبي – تكاملي – تفاضلي PID) تلقائي التنظيم حيث ان الهدف من هذا المسيطر هو ايجاد قيم اقرب للامثلية لثوابت

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المسيطركونها مسؤولة عن عملية تنظيم مستوى الجلوكوز في الدم بدقة وسرعة عالية، وتعتمد خوارزمية الضبط تحديد الموقع بالصدى للدولفين حيث تم استخدامها لتقليل "مؤشر الأداء الفعال " والذي تم اقترحه هنا بطريقة تتضمن تواجد اغلب المتغيرات التي تتحكم برفع الاداء النظام ضمن نطاق الزمن . ان نتائج محاكاة الماتلاب لثلاث حالات مرضية مختلفة اظهرت فعالية ومتانة المسيطر المقترح لمعطيات التحكم وأظهرت نتائج محاكاة برنامج الماتلاب لثلاثة مرضى مختلفين فعالية ومتانة المسيطر المقترح من حيث سرعة تولد اشارة التحكم الفعالة ومتابعة الخصائص الداينميكية لنظام الكلوكوز من خلال تقليل تجاوز الاخراج عن قيمة الادخال المطلوبة وتقليل الزمن اللازم للوصول النظام الى القيمة الادخال المطلوبة وتقليل الوقت اللازم لوصول النظام الى الاستقرارفضلا عن تقليل الخطاء الى الصفر تقريبا مع ضمان استقرار النظام وخصوصا عند اخذ الاضطراب بنظر الاعتبار .
الكلمات الرئيسية: الضبط التلقائي ، وحدة تحكم PID ، خوارزمية تحسين تحديد الموقع بالصدى من دولفين ، نسبة الجلوكوز في الدم.

1. INTRODUCTION

Diabetes is a metabolic disease in which either the patients' pancreas does not produce the insulin or properly does not use the insulin in glucose absorption so. Diabetic patients have a high glucose level. Typically, the normal glucose range is 70 mg/dl to 110 mg/dl **(Makroglou, et al., 2006)**. There are two types of diabetes type I for no insulin production case and type II for no insulin observation case. The (WHO) Organization declared it as a global epidemic and estimates the annual cost associated with diabetes management to the US $376 billion. It's also predicted that the number of diabetics to increase from 171 million in 2000 to 366 million by 2030 thus, the cost will increase to 490 billion US $ in 2030 **(Zhang, et al., 2010).**

The diagnostic criteria are i) oral glucose tolerance test –more than 200 mg/dl; ii) fast blood glucose level more than 126 mg/dl; iii) random blood sugar–more than 200 mg/dl; iv) hbA1c-more than 6.5%, it is the best parameter to know about diabetic control. There are three glucose control strategies: 1) Open loop, when the patient injects pre-determined insulin based on three or four tests. This method is painful and inaccurate. 2) Semi-closed loop is better than the open loop, the insulin dose is determined by using intermittent blood glucose reading, but it suffers from missing sampling and reading disturbance. 3) Closed-loop is an automated insulin delivery and continuous glucose monitoring system. This is the optimal strategy, and it simply acts as an artificial pancreas so it will play a vital role in diabetes patients' survival **(Yasini, et al., 2009)** and **(Bergman, et al., 1981).**

The authors studied the modeling, controlling, and regulation of glucose in diabetes. In a modeling approach, the authors described the interaction relation between glucose and insulin. **(Ackerman, et al., 1960)** proposed a simplified compartmental model, and **(Bergman, et al., 1970)** developed a simplified mathematical model for glucose-insulin regulatory mechanism named Glucose Insulin minimal Model. **(Hovorka, 2005)** introduced a closed-loop insulin delivery system and made it close to the artificial pancreas called "artificial pancreas". Fuzzy controller for insulin pump proposed in **(Sudhaman, and HariKumar, 2009)** to keep the glucose level at the right level and implemented the proposed controller in the Field Programmable Gate Array (FPGA) the drawback of this method is used only offline tuning control gain algorithm. Also**, (Anilkumar, et al., 2014)** illustrated the closed-loop PID glucose control system based on the Ziegler-Nichols method to tune the control parameters and monitor the glucose level. This work did not use an intelligent algorithm for tuning control parameters.

On the other hand, many papers developed controllers and algorithms responsible for controlling these models. **(Sharma, et al., 2016)** used Ziegler-Nichols and Cohen-Coon method to design a digital closed-loop controller for the differential equation of blood glucose**.** The drawback in this work was the offline tuning and the fixed parameter.

In addition, the backstepping method-based nonlinear controller for Bergman minimal model introduced by (Hassan, et al., 2017) used the Lyapunov method with a nonlinear controller

algorithm to stabilize the glucose level. Still, the drawback of the proposed algorithm was the parameters of the controller are fixed. The Internal model control (IMC) closed-loop glucose control which act as a good disturbances rejection for unstable processes due to the use of a filter with the controller model that is explained in **(Sivaramakrishnan, 2017)** but the issue of the proposed work was not an adaptive controller and did not use the identifier model to tune the (IMC). **(Liu, 2018)** introduced parameter uncertainties into a mathematical model of the blood glucose regulation system to show the response of the glucose level behavior.
However, the stability, controllability, and observability of the linearized Glucose Insulin model are studied in the work of **(Farman, et al., 2018)**. **(Bell, and Lee, 2019)** studied and investigated different glucose-insulin models to compare similarities and differences between them.
The problem definition for this work is to track and stabilize the glucose level response in diabetes patients. Therefore, the motivation of this research is taken from **(Sharma, et al., 2016)** and **(Hassan, et al., 2017)**.
This work's contribution is to design an adaptive and robust PID control action for the Bergman minimal model based on echolocation tuning control gains algorithm with proposed performance index equation to enhance the dynamic behavior of the Glucose control system in diabetes patients.
This paper is organized as follows. Section 2 introduces the mathematical model of the Bergman Glucose Insulin Minimal Model. Section 3 contains the methodology and the structure of the Dolphin-PID controller. Section 4 demonstrates the simulation results. Finally, in Section 5, the conclusions are explained.

2. BERGMAN GLUCOSE-INSULIN MINIMAL MODEL

Based on nonlinear ordinary differential equations, the Bergman Glucose Insulin minimal model described the relation between the Plasma glucose compartment level G(t) in mg/dl and the remote insulin compartment level I(t) in mU/dL. It was assumed that the blood glucose and hormone insulin are contained in two different compartments and interact with each other.
Many paper studies, analyses, and control the Bergman glucose-insulin minimal model with no biological complexities **(Bergman, et al., 1981)**. **Table 1.** shows the parameter of the Bergman equations model Eq. (1), Eq. (2), and Eq. (3) as follows:

$$\dot{G} = -P_1[G(t) - G_b] - X(t)G(t) + D(t) \quad (1)$$

$$\dot{X} = -P_2X(t) + P_3[I(t) - I_b] \quad (2)$$

$$\dot{I} = -n[I(t) - I_b] + Y[G(t) - h]^+ \, t + u(t) \quad (3)$$

The diabetic patient does not have glucose regularity control the $Y[G(t) - h]^+ \, t$ =0, so it will not include the derivation of the transfer function, i.e., a specific parameter will be taken with an assumption of some steady-state condition. Thus,

$$\dot{I} = -n[I(t) - I_b] + u(t) \quad (4)$$

$$\mathrm{sI(s)} = -\mathrm{nI(s)} + \mathrm{u(s)} \quad (5)$$

$$\mathrm{I(s)} = \mathrm{u(s)/s} + \mathrm{n} \quad (6)$$

$$sX(s) = -P_2X(s) + P_3 \, I(s) \quad (7)$$

$$X(s) = P_s u(s)/(s + P_2\ )(s + n) \tag{8}$$

$$s(G) = -P_1 G(s) - G_b\, X(S) \tag{9}$$

$$G(s) = \frac{-G_b\ P_2\, u(s)}{(s + P_1)(s + P_2)(s + n)} \tag{10}$$

$$\frac{G(s)}{u(s)} = \frac{-P_3\, G_b}{(s + P_1)(s + P_2)(s + n)} \tag{11}$$

The Bergman model will be represented with a 3rd order transfer function Eq. (4) as in **(Sharma, et al., 2016)** and **(Anilkumar and Phadke, 2014)**.

$$\frac{G(s)}{u(s)} = \frac{-P_3\, G_b}{s^3 + s^2(n + P_1 + P_2) + s(nP_1 + nP_2 + P_1P_2\ ) + P_1P_2n} \tag{12}$$

Where, u(s) denotes the input (insulin) in (mU/min).

Table 1. The description of parameters with their values (**Anilkumar and. Phadke, 2014).**

Parameters	Normal	Patient1	Patient2	Patient 3
Insulin independent constant (P_1) in (1/min)	0.031	0	0	0
Decrease the rate of tissue's glucose up taking (P_2) in (1/min)	0.012	0.011	0.007	0.014
Enhanced glucose up taking capability (insulin base) P_3 in (µU/ml)/ min^2	4.92^{-6}	5.3^{-6}	2.16^{-6}	9.94^{-6}
Insulin secretion of ß cells(Y) in µUm/ml/ min^2/(mg/dl)	0.0039	0.0042	0.0038	0.0046
The decay rate of plasma insulin (n) in (1/min)	0.265	0.26	0.246	0.281
Threshold value(h) in (mg/dl)	79.035	80.2	77.578	82.937
The base level for the glucose before injection (Gb)in (mg/dL)	70	70	70	70
The base level for the insulin before injection(Ib) in (µU/ml)	7	7	7	7
Glucose initial level (G_0) in (mg/dl)	291.2	220	200	180
Insulin initial level (I_0) in (µU/ml)	364.8	50	55	60

3. METHODOLOGY AND STRUCTURE OF DOLPHIN PID CONTROLLER

The proposed dolphin PID diagram is shown in **Fig. 1** that demonstrates the dolphin PID controller's methodology and structure. The PID controller transfer function is defined as in Eq. (13) **(Al-Araji, 2005)**.

$$\frac{u(s)}{e(s)} = Kp + \frac{Ki}{s} + Kds \tag{13}$$

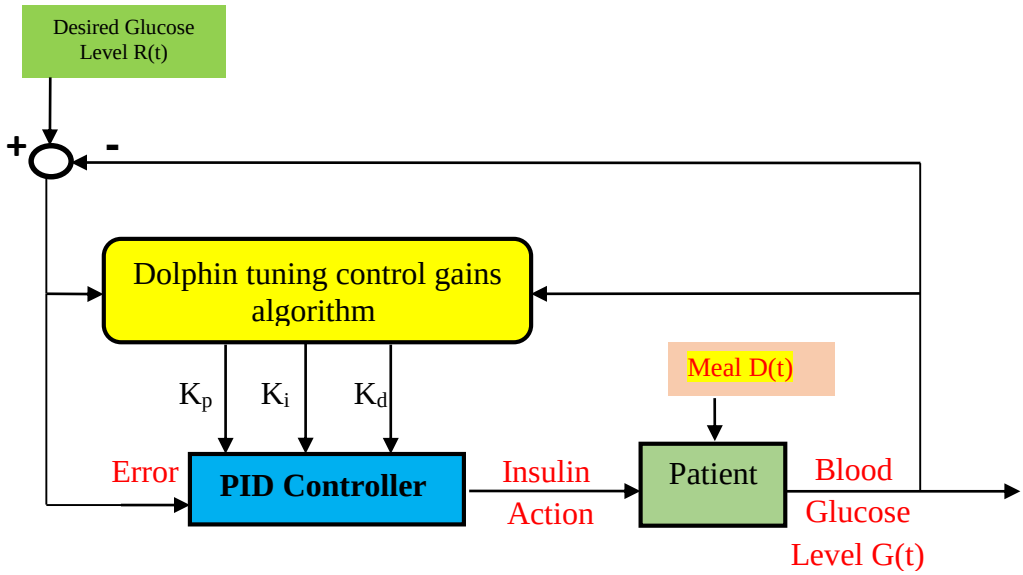

Figure 1. The proposed dolphin PID controller diagram.

The input for the PID controller is the error, which represents the difference between the desired glucose level =80 *mg/dl* and the actual level (output). In contrast, the output of the PID controller represents the estimated require Insulin level responsible for glucose regulation in the patient. The controller constant k_p, k_i, and k_d are produced and adaptive by the dolphin tuning control gains algorithm **(Al-Araji, 2014)**. The tuning is based on the current error signal (glucose level error) and current system output (glucose level). The parameters of **Table 1.** are substituted in Eq. (12) to create different transfer functions for different cases as follows: normal person as in Eq. (14), patient 1 as in Eq. (15), patient 2 as in Eq. (16) and patient 3 as in Eq. (17).

$$G(s) = \frac{-0.0003444}{s^3 + 0.308\,s^2 + 0.0118\,s + 9.858e-05} \tag{14}$$

$$G(s) = \frac{-0.000371}{s^3 + 0.271\,s^2 + 0.0029\,s} \tag{15}$$

$$G(s) = \frac{-1.5120e-04}{s^3 + 0.2530\,s^2 + 0.0017\,s} \tag{16}$$

$$G(s) = \frac{-6.9580e-04}{s^3 + 0.2950\quad s^2 + 0.0039\ s} \tag{17}$$

3.1 The Proposed Performance Index Equation

Performance index and fitness function play a vital role in the design and optimization of any control algorithm. Modern, adaptive, and intelligent control required more sophisticated performance criteria than traditional; the proposed performance index is shown in Eq. (18) is developed from the time domain complex performance index that taken from **(Dagher, 2013),** and this performance index deals with the golden area covered by the overshoot, rise time, settling time and steady-state.

$$f = \max\left(\frac{1}{(1-e^{-\lambda})\times(Mp+e_{ss})^2\times e^{-\lambda}\times(t_s-t_r)^2}\right) \quad (18)$$

Where, f :is proposed performance index : λ: tuning factor $0 < \lambda < 1$; Mp: Maximum overshoot=$Mp_{ref} - Mp^{(i)}$ is equal to zero; e_{ss}: steady state error=$G_{ref} - Gss^{(i)}$; t_s: Settling Time=$ts_{ref} - ts^{(i)}$; t_r: Rise time=$tr_{ref} - tr^{(i)}$ *and i:* i^{th} number of iterations.

3.2 Dolphin Echolocation Optimization (DEO)

In recent decades many metaheuristic optimizations are proposed and developed. Therefore, one of these methods is Dolphin Echolocation Optimization (DEO) by **(Kaveh and Farhoudi, 2013);** then, a new modification named Simple Dolphin Echolocation SDE is proposed by **(Kaveh, and Hosseini, 2014)**. The (DEO) and (SDE) inspire from the biological hunting skills of the dolphins, which may be summarized in two phases. The first phase represents the transmitting phases in which the dolphin produce squeak in water, so the sound is transmitted in all direction. The second phase is named the receiving phase, which started when the sound waves hit an object such as fish or any object; hence, the object reflected sound, and the echo backs to the dolphin. The estimated time and how the echo backs tell the dolphin the location, the size, and the type of the object. **Fig. 2** shows the proposed dolphin echolocation process.

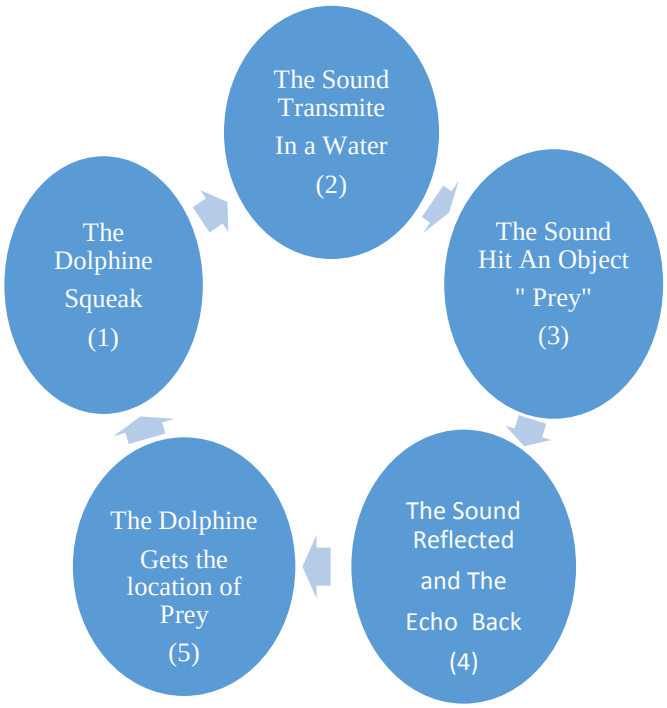

Figure 2. The proposed steps of Dolphin echolocation process.

The DEO is used to tune the PID controller parameters K_p, K_i, and K_d within a continuous search space **(Dagher, 2018)**. The detailed steps for using the DEO algorithm in optimizing PID control's parameters are shown below:

The first step:
In this step, the following matrix and parameter should be initialized:
- Location Matrix $\mathbf{R_{loc}}$, which contain PID parameter:
$[K_p, K_i, K_d]_{n\ x3}$ where: n: number of the random location=20
- Alternative Matrix **Alter,** which contains the alternative location. The matrix dimension is $_{[m\times3],}$ where m is the maximum alternative number =40 in the search space these alternatives will be sorted in ascending order form.
- Maximum iterations number Maxit =10 in which the algorithm should reach the near optimal locations, i.e., near optimal K_p, K_i, K_d values
- Maximum loop number M_{loop}=10
- The predefined probability (convergence factor) PreProb (1) = 0.1 this predefined probability is assigning for a randomly selected location in the first iteration i=1.

The Second Step:
In this step, the predefined probability for the i^{th} loop is calculated by using the following
PreProb (loopi)= PreProb1 + 0.1(loopi-1) where i>1.

The Third Step:
Calculate the fitness and accumulative fitness A_{ccfit} for the i^{th} iteration as follows
J= where j performance index
Fit(i)=1/(J+μ) Where μ>0
Calculate the accumulative fitness A_{ccfit} as follows
- Divide the sorted alternative matrix into two regions, including an affected region (Re) and within the affected radius Re and the not affected region within not affected (Re).

Note Re>=1/4 number of locations
- Find the position of each location in the alternative and then calculate its accumulative fitness within the interval (- Re < re<+ Re).

$A_{ccfit}(i)= A_{ccfit}(i)+(1-(abs(re)/Re)\times Fit(i)$
Note initial A_{ccfit} =0.0001 for each location.

The Fourth Step:
- Find best location which have the best A_{ccfit} and set its $A_{ccfit=0}$
- Find the probability by using

Prob(i)= $A_{ccfit}(i) / \sum_1^m Accfit(i)$

The Fifth Step:
Update the location according to the probability of their alternative.

The Six Step:
Repeat till the termination criteria, i.e., the maximum number of iterations = satisfied
The proposed flowchart of the dolphin tuning control gains algorithm is shown in **Fig. 3**.

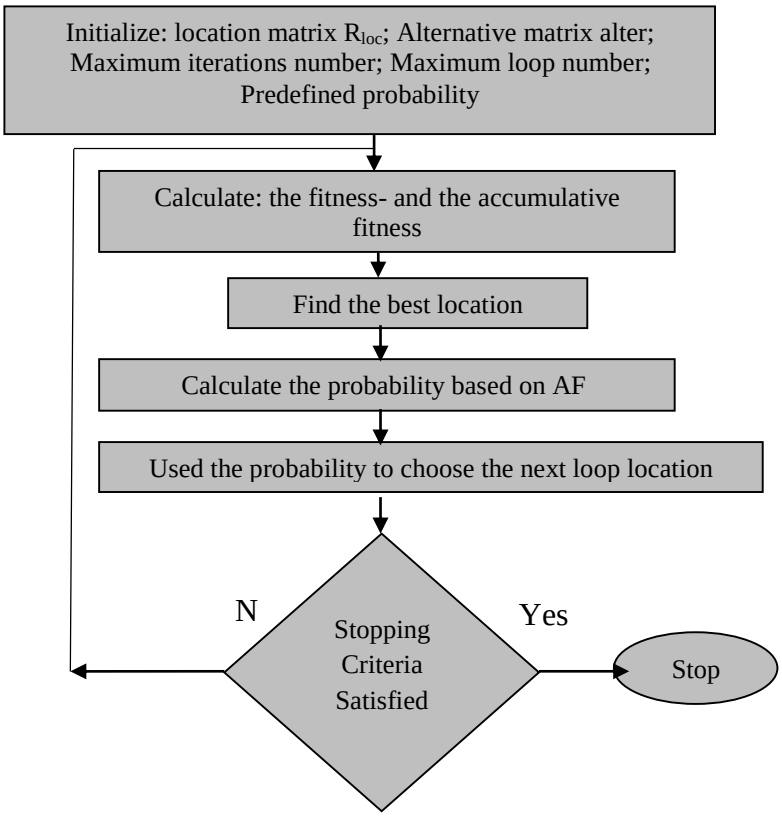

Figure 3. The proposed tuning control DE flowchart

4. MATLAB SIMULATION RESULTS

In this section, we carried out the proposed DEO-PID controller with different types of transfer functions Eq. (14), Eq. (15), Eq. (16), and Eq. (17), which are considered for normal and patient persons, respectively, by using MATLAB package with one-minute sampling time. Therefore, we investigate the effectiveness and the performance of the DEO-PID controller design. **Table 2.** shows the proposed controller parameters search space regions for all patients.

Table 2. The empirical controller parameters search space regions for all patients.

Kp	Ki	Kd
-0.1 to +0.1	$(-0.1 \text{ to } +0.1)\times10^{-6}$	1 to 5

Fig. 4 shows the open-loop for a normal person and three patient persons depend on the initial glucose level (G_0) (291.2, 220, 200, and 180) mg/dl, respectively. The healthy person curve shows a normal glucose level decreasing from high value to the normal glucose level, i.e., physiological level; thus, there is no problem consuming high blood sugar.

The patients' models started with a high glucose level. It decreased very slowly and will never reach its normal level, i.e., the glucose value is very high and so far from the physiological level; thus, the patient is in danger.

Fig. 5 demonstrates the response of the proposed closed-loop DEO-PID controller, which improves the patients' glucose level response through the effectiveness of the insulin-infusion

control action for patient. It is clear the insulin action has ability to stabilize the glucose level where the glucose level of the patient1, which has the red color line, is decreased from 220 mg/dl to 120 mg/dl (the upper normal physiological level and stabilized there within 40 min. The glucose level of the patient2 with the green color line decreased from 200 mg/dl to 120 mg/dl (the upper normal physiological level and stabilized there during 65 min. Finally, the glucose level of the patient3 with the blue color line decreased from 180 mg/dl to 120 mg/dl (the upper normal physiological level and stabilized there during 50 min.

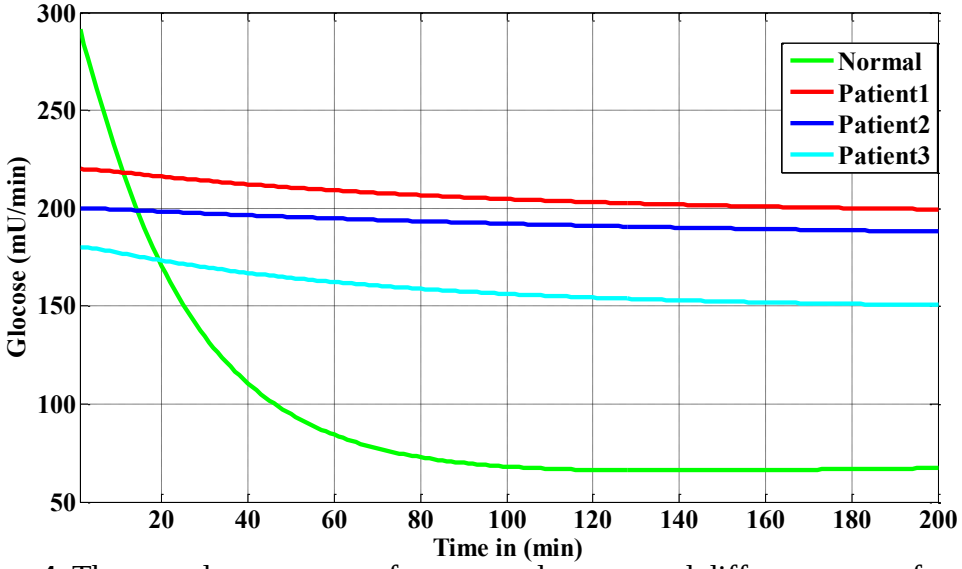

Figure 4. The open-loop response for a normal person and different types of patients.

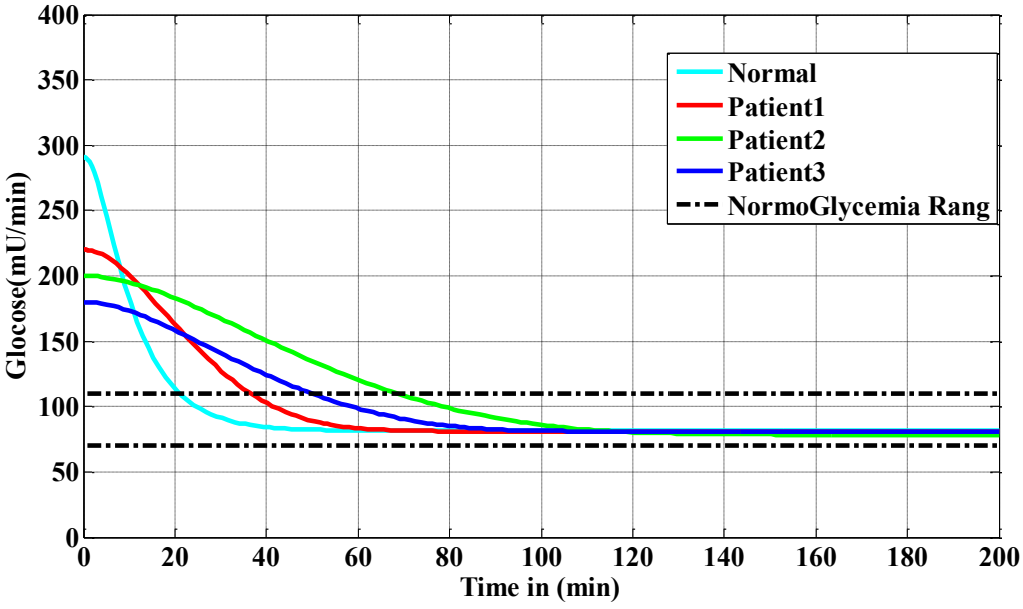

Figure 5. The closed-loop glucose level response for all patient's cases.

Table 3. shows the best values of DEO-PID controller parameters for the patient1, patient2 and patient3 models responsible for decreasing the glucose level and keeping it within the acceptable level in the blood.

Table 3. The best values of DEO-PID controller parameters for three patients types.

Type of patient	K_p	K_i	K_d
Patient1	-0.0409	-1.5739e-06	2.0581
Patient2	-0.0289	-5.4462e-07	4.0646
Patient3	-0.0186	-4.5982e-07	2.5514

To investigate the robustness of the proposed DEO-PID controller, a meal disturbance effect has been added at a time equal to 60 min for all patients cases where the proposed meal disturbance equation as in Eq. (19).

$$D(t) = A \times e^{-Bt} \quad (19)$$

D(t) is a proposed disturbance that represents a meal taken by a patient. The proposed A is a positive integer equal to 8 mg/dl, B is positive value <1 say B =0.2; thus, the glucose level in patient blood increased gradually by 40 mg/dl.

Fig. 6 shows the response of the proposed time-domain specification cost function of closed-loop DEO-PID controller for all patients during ten iterations.

The desired time domain is 1) The reference glucose level G_{ref} is equal to 80 mg/dl. 2) The Mp_{ref} is near zero. 3)The reference settling time ts_{ref} equal to 40 min. 4)The reference rise time tr_{ref} equal to 10 min.

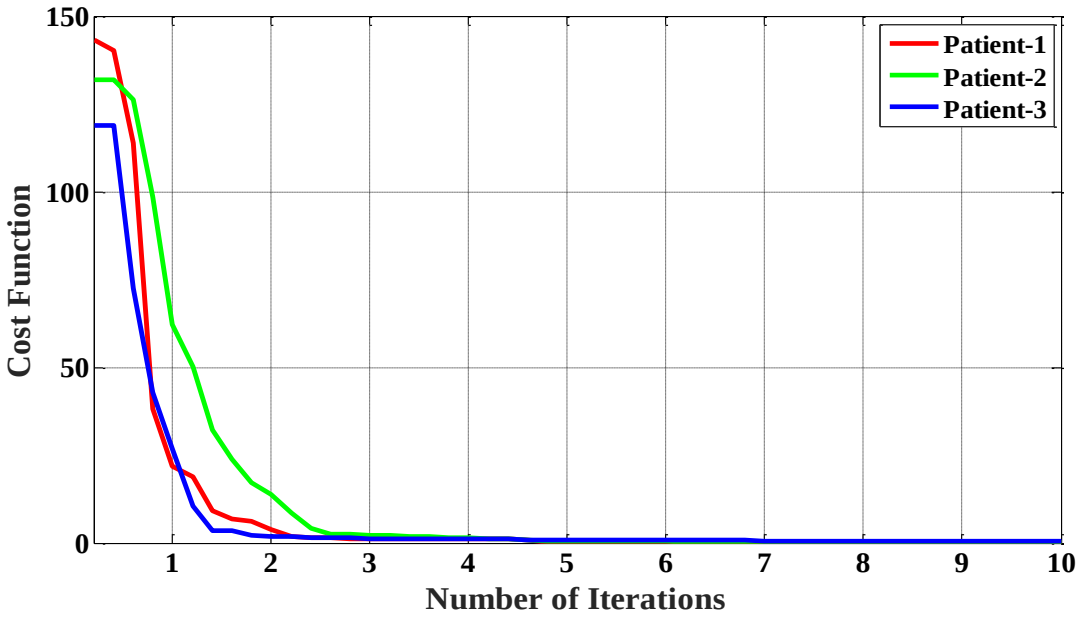

Figure 6. The response of the proposed cost function of closed-loop DEO-PID controller for all patients.

Figs. 7, 8 and 9 illustrate the glucose level responses for the patient1, patient2 and patient3, respectively.

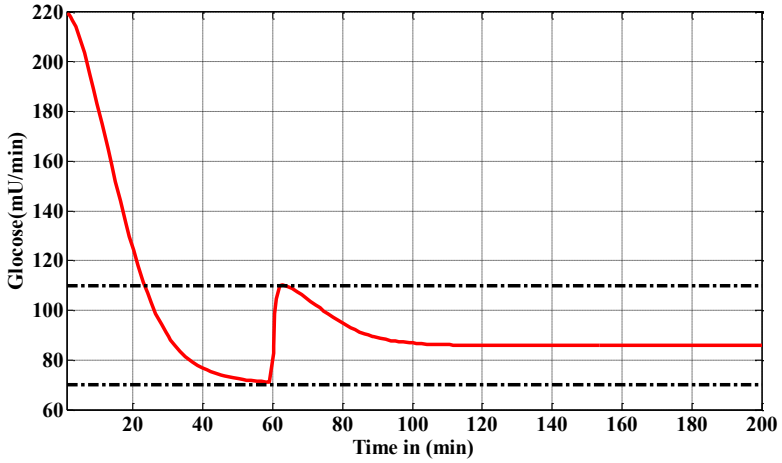

Figure 7. The closed-loop glucose level response for patient1 model with meal disturbance.

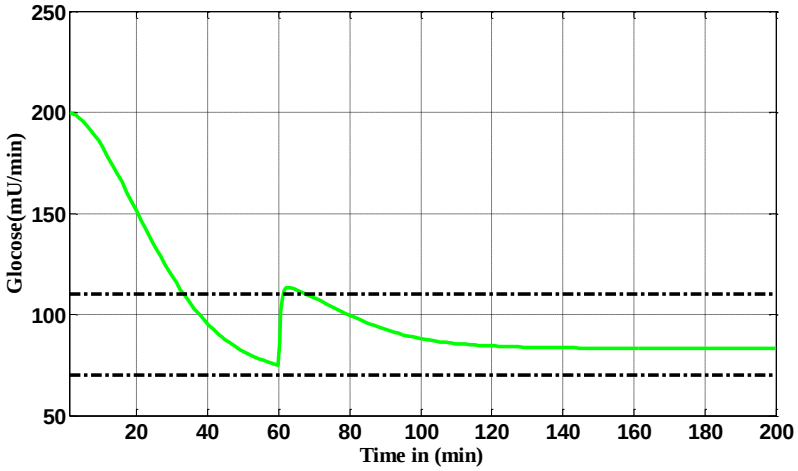

Figure 8. The closed-loop glucose level response for patient2 model with meal disturbance.

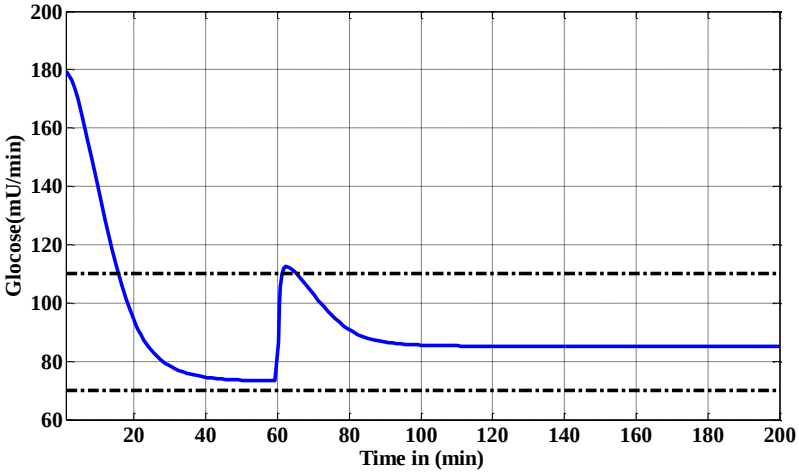

Figure 9. The closed-loop glucose level response for patient3 model with meal disturbance.

The glucose level is suddenly increased then gradually returned to the normal boundary of the glucose level due to DEO-PID within 20 min. The DEO-PID generates a fast insulin action to track the sudden glucose level increment, as shown in **Fig. 10** for patient1, **Fig. 11** for patient2, and **Fig. 12** for patient3. The maximum level of the insulin control action is 16.8 mU/min, and the minimum level is 7mU/min.

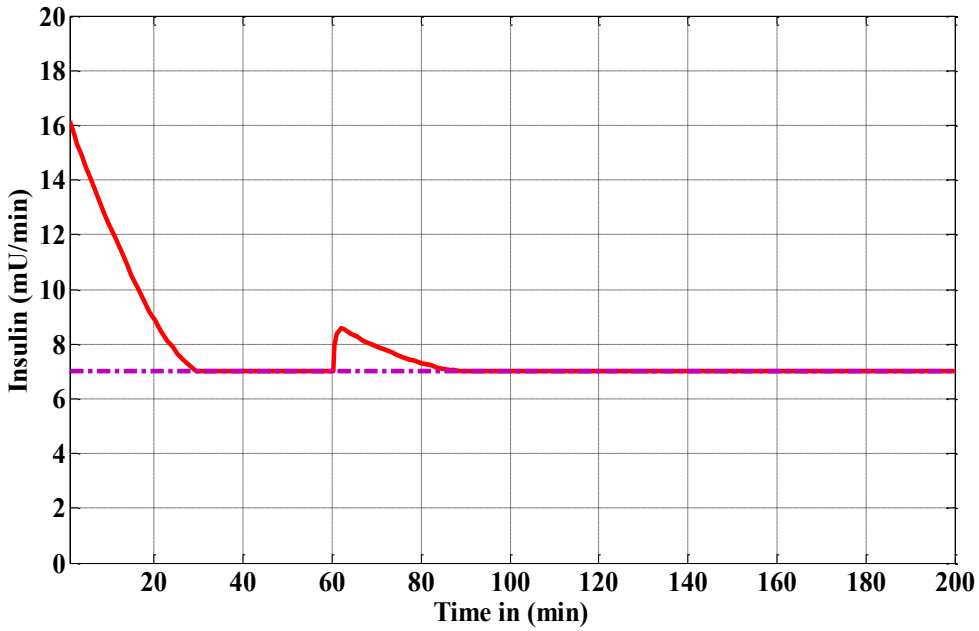

Figure 10. Patient1 Insulin control action of the DEO-PID controller under meal disturbance effect.

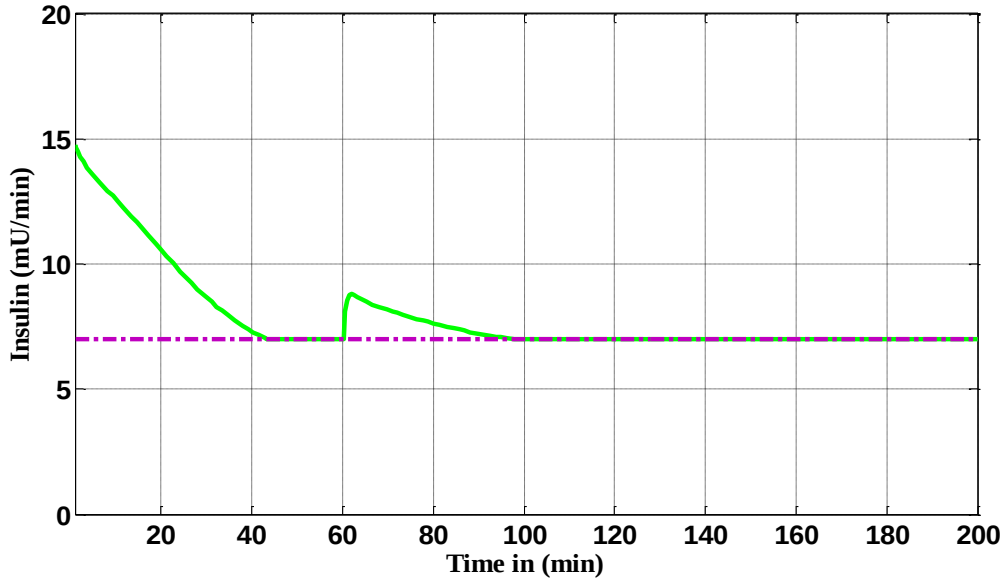

Figure 11. Patient2 Insulin control action of DEO-PID controller with meal disturbance effect.

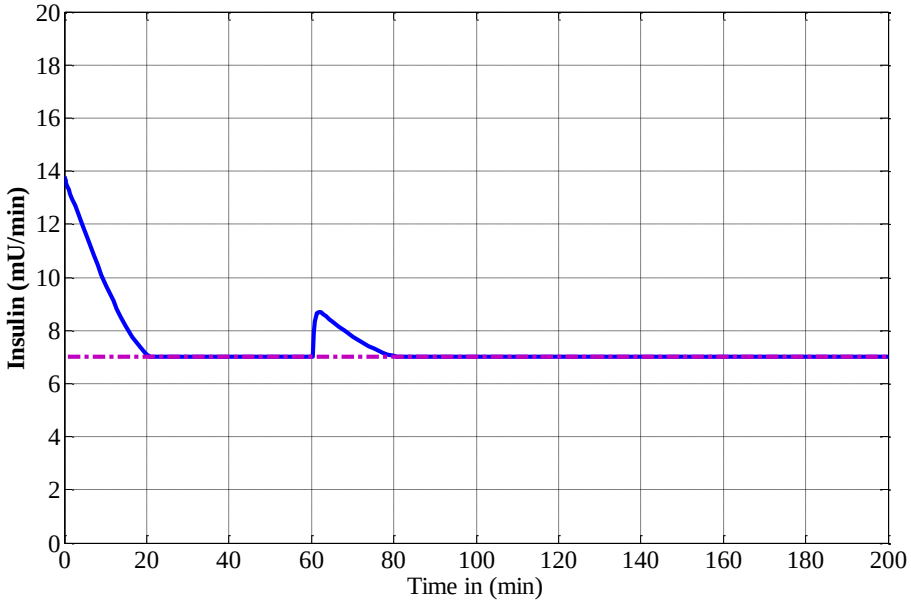

Figure 12. Patient3 Insulin control action of DEO-PID controller under meal disturbance effect.

Table 4. shows the best values of DEO-PID controller parameters with meal disturbance effects for the patient1, patient2 and patient3 models. Based on Eq. (7), the remote insulin level x (t) responses for patient1, patient2, and patient3 models are shown in **Figs. 13, 14,** and **15,** respectively, with the meal disturbance effect.

Table 4. The best values of DEO-PID controller parameters for three patients types with meal disturbance effects.

Type of patient	K_p	K_i	K_d
Patient1	-0.0797	-0.98653 e-07	1.0386
Patient2	-0.0682	-2.4462e-07	3.0326
Patient3	-0.0597	-3.4653 e-06	2.110

To confirm the effectiveness of this work, the simulation results of the proposed adaptive DEO-PID controller were compared with other types of controller results that are taken from **(Sharma, et al., 2016)** and **(Hassan, et al., 2017)** as shown in **Table 5**. The plasma insulin level I (t) for patient1, patient2 and patient3 models with the meal disturbance effect are shown in **Figs. 16, 17**, and **18**, respectively, based on Eq. (6).

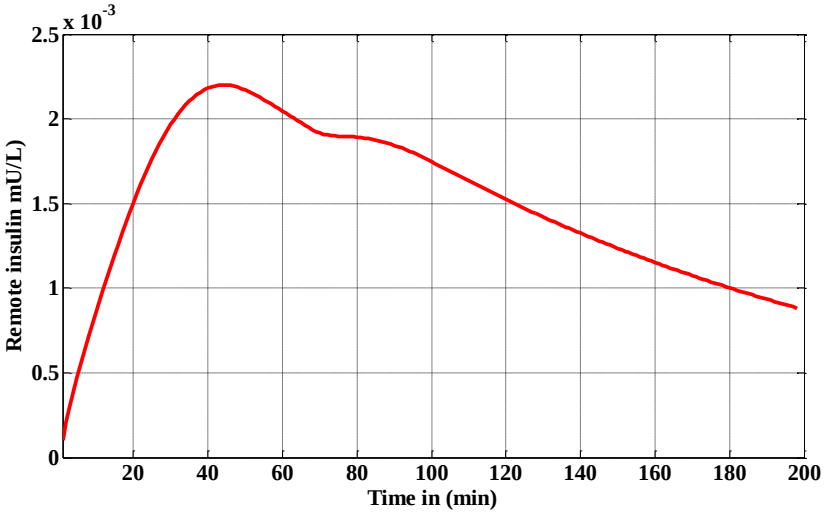

Figure 13. The X(t) remote insulin level with meal disturbance for patient1 model**.**

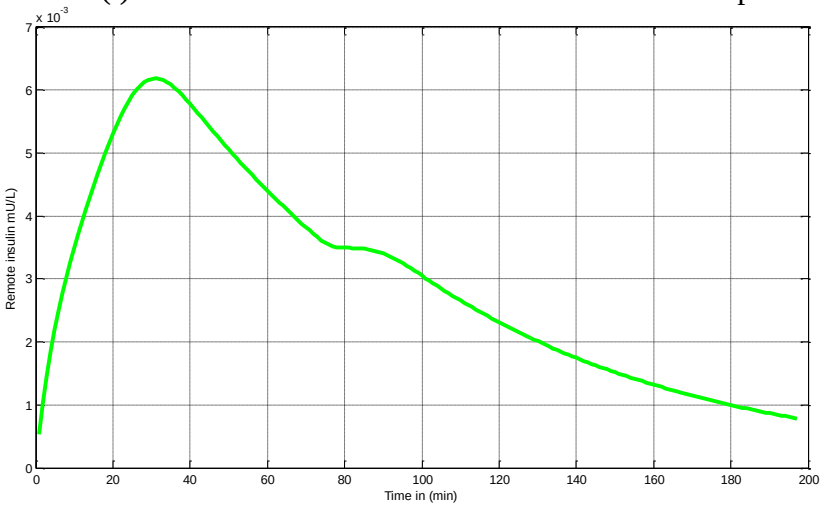

Figure 14. The X(t) remote insulin level with meal disturbance for patient2 model

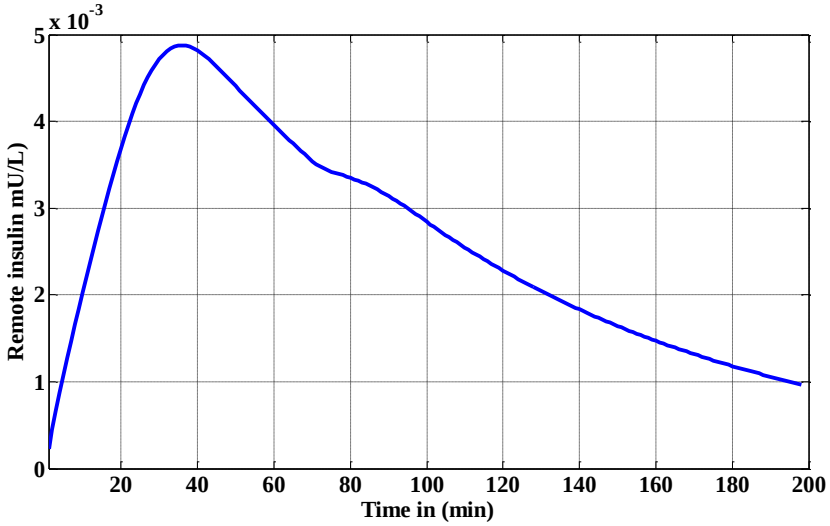

Figure 15. The X(t) remote insulin level with meal disturbance for patient3 model.

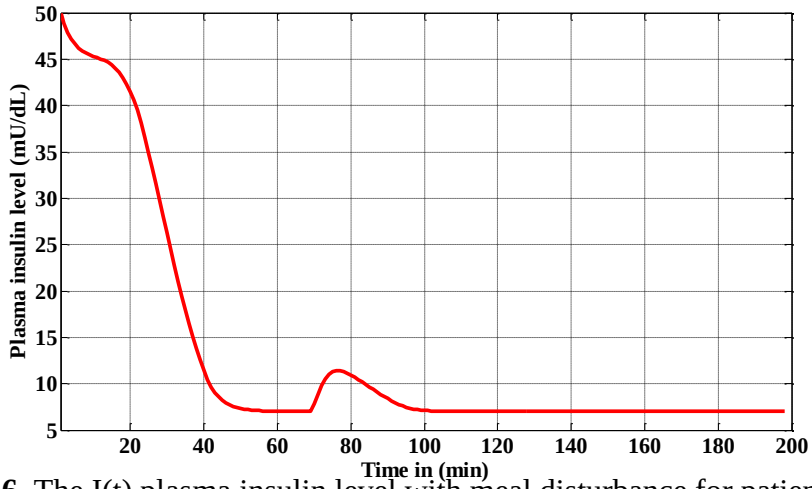

Figure 16. The I(t) plasma insulin level with meal disturbance for patient1 model

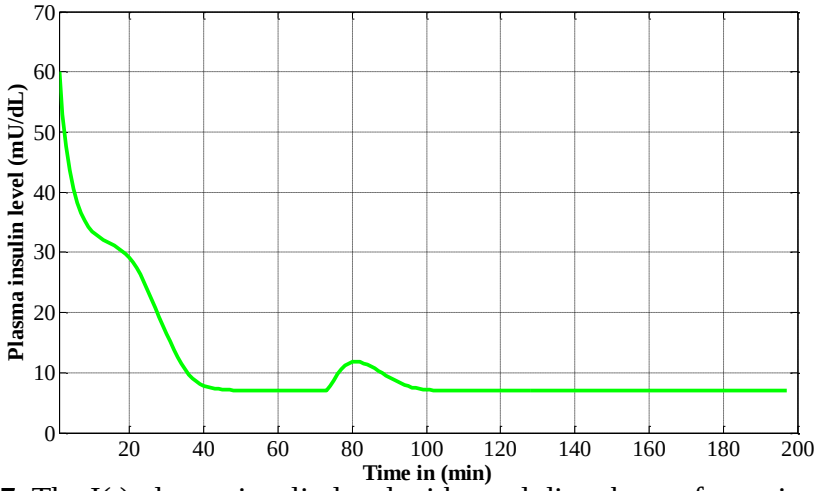

Figure 17. The I(t) plasma insulin level with meal disturbance for patient2 model.

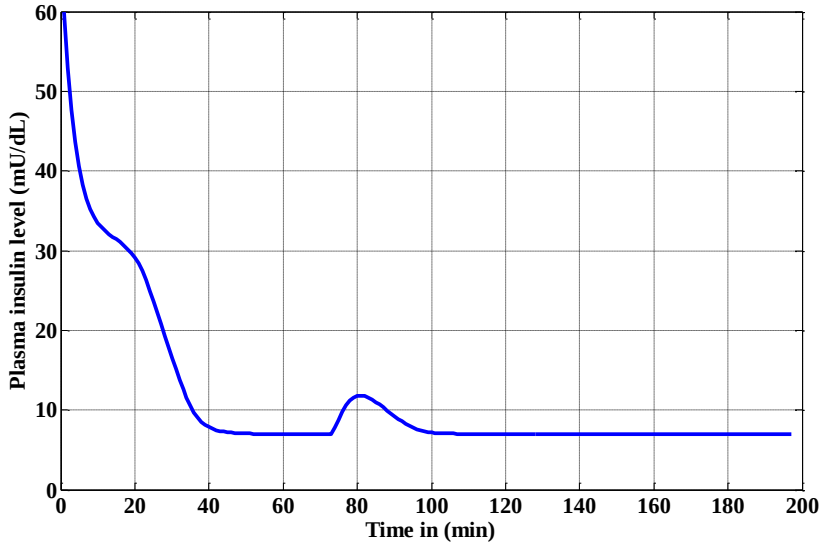

Figure 18. The I(t) plasma insulin level with meal disturbance for patient3 model.

Table 5. Comparison simulation results between the proposed DEO-PID and other types.

Type of controller	Tuning algorithm	Steady-State Error	Overshoot (%)	Controller Parameter Numbers
Nonlinear backstepping, **Hassan, et al.,2017**	Try and Error	0	0%	Three Fixed Parameters Values
PID Ziegler-Nichols , **Sharma, et al., 2016**	Ziegler-Nichols	0	20%	Three Fixed Parameters Values
The proposed work	Off-line Dolphin Echolocation	0	0%	Three Adaptive Parameters Values

5. CONCLUSIONS

In this paper, an offline adaptive DEO-PID controller has been designed and simulated for the Bergman minimal model for blood glucose monitoring and controlling system. The three different patient models were taken as a linear model to solve the problem statement to track and stabilize the glucose level response in diabetes patients. Therefore, the DEO-PID controller was proposed as a control strategy, which has an excellent ability for solving the problem statement as follows:

- The glucose level is excellently tracked to the desired level and stabilized at a normal physiological level successfully without overshooting.
- The best and smooth value of insulin control action was generated to enhance the dynamic behavior of the Glucose control system in diabetes patients.
- The offline tuning control parameters of the proposed controller based on DEO leads to generate smooth insulin action without the spike and no saturation state. Thus, a high tracking precision of the glucose level was obtained.
- The maximum span tracking glucose error level reached approximately zero value.
- The proposed time domain specification cost function has contributed to reducing the number of iteration and number of function evaluations.
- The gradual decreased of the meal disturbance effects within appropriate time verified the robustness of the proposed controller. Finally, the experimental work of the proposed controller will be implemented in the future.

NOMENCLATURE

$\dot{G}$ = The derivative of Plasma glucose compartment level G(t) in (mg/dl)/min.
$\dot{I}$ = The derivative of the remote insulin compartment level in (mU/dL)/min.
$\dot{X}$ = The derivative of the remote insulin (mU/L)min.
$D(t)$ = Glucose absorption rate to blood *via* food intake (meal) in mg/dl
e(s) = Error signal in mg/dl.
$G(t)$ = The Plasma glucose compartment level G(t) in mg/dl.
G_0 = The glucose initial level in (mg/dl).
Gb=The base level for the glucose before injection in (mg/dL)
h = Threshold value in (mg/dl).
$I(t)$ = remote insulin compartment level in mU/dL.
I_0 = Insulin initial level in µU/ml.

Ib = The base level for the insulin before injection in µU/ml.
Kd = Derivative gain.
Ki = Integral gain.
Kp = Proportional gain.
n = Decay rate of plasma insulin in 1/min.
P_1 = Insulin independent constant in1/min.
P_2 = Decrease rate of tissue's glucose up taking in (1/min).
P_3 = Enhanced glucose up taking capability (insulin base) in (µU/ml)/ min^2
U(s) = The Laplace transform of the input (insulin) in (mU/min).
u(s) = The control signal in (mU/min).
U(t) = The input (insulin) in (mU/min).
X(t) = The remote insulin mU/L.
Y = Insulin secretion of ß cells in µUm/ml/ min^2/(mg/dl).

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