

A switching based PID technique for blood glucose control.

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Abstract

Automation of insulin infusion by closed loop control method is the center of attention for many researchers for the last few decades. The main idea behind the insulin automation is artificial pancreas for the accurate measurements of glucose level so the key role is played by the control strategy used to design control algorithm. This paper proposes a Proportional Integral Derivative (PID) algorithm based on switching technique to control and maintain the glucose level. We have used mathematical models like Havoroka model and Meal Simulation model to deal with the dynamics of insulin and glucagon. Simulation results show that the PID control algorithm performs well in many situations such as insulin sensitivity. To check the effectiveness of the control scheme the glucose profile of patient is generated by using MATLAB. The presented control techniques found to be better as compared to traditional method of insulin injection and are helpful in reducing the risks of hypoglycemia.

Keywords: Automated insulin infusion, Artificial pancreas, PID, Root locus, Havoroka model, Meal simulation model.

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Introduction

Diabetes is an incurable disease affecting number of people throughout the world. According to a survey by 2034, the number of diabetic patients will increase up to 44.1 million. Such circumstances are the reason of motivation of control engineers to present effective and advanced solution [1,2]. In diabetes control, Pancreas plays an important role in maintaining the blood glucose level and is responsible for the production of hormones and enzymes which help in breaking down of food. In pancreas there are α -cells which are responsible for the production of glucagon while β -cells are responsible for the production of insulin. The demolishing of α -cells and β -cells results in hypoglycemia and hyperglycemia respectively [3,4].

In order to avoid the elongation of hyperglycemic issues the victim is dependent on insulin infusion along with the problem of self-monitoring as the patient has to monitor his/her blood glucose level throughout the life. Diabetes requires self-monitoring and management which is neither reliable nor provides an effective control of blood glucose. Thus, the issue of controlling the blood glucose level and the automation of insulin infusion in diabetic patients is an enduring problem.

The Artificial Pancreas plays an important role in the automation of insulin delivery. It comprises of a control strategy for closed loop system, a hypodermic infusion pump and glucose monitoring system. A number of control techniques including Model Predictive Control (MPC) [5,6],

Linear Parameter Varying (LPV) [7], H_{∞} Control [8,9] have been tested in clinical trials.

We will not discuss these techniques in detail as they have been reviewed in many survey articles recently [10,11]. The PID control strategy has been used widely in industrial control systems as well as in bio-medical field because Proportional Integral Derivative (PID) controller is irresistible for controlling blood glucose as it replicates the responses of first and second phase which are used to secrete insulin by β -cells in pancreas against continuously monitored glucose.

In an artificial pancreas glucose levels of the patients are continuously being monitored and insulin is being injected according to need of patient apart from using rupture techniques for blood glucose monitoring but due to inter-patient changeability and sensing delays a tuning method is necessary, considering specific characteristics of patients to achieve better performance in close loop [12]. Insulin feedback loop is used to keep blood glucose level in normal range by injecting estimated amount of insulin in patient to achieve safe control of hypoglycemia.

In this paper an improved blood glucose control technique has been developed using PID controller and effects of Proportional, Derivative and Integral controllers are discussed. This paper is organized as follows: The Physiological model is described in section II, Controller design is presented in section III, section IV and V comprises of Simulation results and discussion. Finally the conclusion is drawn in section VI.

Physiological Model

Several physiological models are used to describe insulin and glucose dynamics [13-15]. In real patients the parameters of models under consideration cannot be estimated as they have their own physiological importance. It is difficult to understand such complex models therefore for research purposes it is necessary to convert those complex models into low order models as they are easy to understand as compared to complex ones. Therefore using black box approach a low order model is identified by considering three different glucose concentrations 90, 120 and 150 mg/dl. By the frequency response of these concentrations we are able to get three linear models for every patient [16].

Basal insulin (Ib) which is responsible for particular glucose level at steady state is measured. After obtaining, basal insulin is added with sinusoidal insulin. By setting the sampling time at 10 min, this signal is injected and glucose variation is captured. An algorithm of Subspace identification was used to obtain a third order system [17,18]. By considering these models a discrete time transfer function is defined as described in equation (1) shown below,

$$X_0(z) = \frac{c_0 z^{-3}}{(1 - z^{-1} p_1)(1 - z^{-1} p_2)(1 - z^{-1} p_3)} \rightarrow (1)$$

Where P1=0.965, P2=0.95 and P3=0.93 are the poles of the system and C0=0.932. In order to limit traditional nature of the controller, an individualized transfer function is obtained using 1800 rule [14]. 1800 rules are used for measuring value of insulin needed. There is always need to correct for hypoglycemic excursions despite optimal basal therapy.

$$X_{0,j}(z) = \frac{c r_j z^{-3}}{(1 - z^{-1} p_1)(1 - z^{-1} p_2)(1 - z^{-1} p_3)} \rightarrow (2)$$

Where rj=1800/TDIj. TDIj is the total daily insulin of patient with index j and c is a constant which can be obtained as,

$$c = \frac{60}{100}(1 - p_3)(1 - p_2)(1 - p_1)T_s \rightarrow (3)$$

Ts represents the sampling time of the system. Thus is adjusted to each patient and by using individualized transfer function traditionalism of controller can be avoided.

Controller Design

In order to control diabetes, several PID control techniques were developed which are explained in many research articles and survey papers. Most of these techniques are based on simulations and some are applied practically on animals & humans. A lot of research has been done using only PD controllers whereas integral action is ignored as it is responsible for overdosing and low blood sugar levels. Some researchers also used integral action to adjust sudden changes in patients (e.g. Insulin sensitivity).

The rate at which insulin is injected by pump into hypodermic tissues is calculated by PID controller. The noise effect

reduction is achieved by filtering the glucose concentration with standard first order filter [19]. PID technique for diabetes demands high proportional and derivative action as compared to integral action. This can be achieved by putting upper and lower limits on the integral term which makes the effect of integral action negligible as compared to derivative and proportional terms. Integral action is necessary as it is responsible to eliminate steady state error when insulin sensitivity changes. Detail analysis and implementation of PID strategies can be found in figures 1 and 2 [20].

In order to design a control strategy system's parameters are given i.e. natural frequency $\omega_n=0.02$ and damping ratio $\xi=0.707$. The PID controller is designed to remove the difference between set point value of glucose and present value of glucose. Firstly Proportional action of the controller is tuned and by the results of this action, K_p is determined along with Controller derivative time constant TD. The derivative and integral gain was determined by considering different meal challenges and by finding the best response of the controller against these meal challenges. Finally all the gains of PID are re-evaluated to ensure that after meal hypoglycemia did not happen. The finely tuned PID controller deals with hypoglycemia and hyperglycemia when switch at proper interval. Each gain of PID controller is tuned to minimize,

- Integral Absolute error.
- High glucose values.
- Low glucose values.

The blood glucose controller consists of two parts:

- A. PID controller
- B. Insulin feed-back loop (IFL)

The block diagram of overall closed loop system with PID controller is shown below:

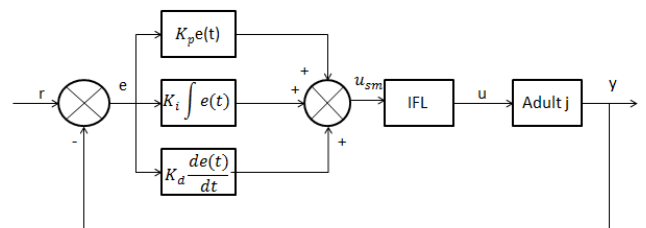


Figure 1. Block diagram of closed loop using PID controller.

In the block diagram 'r' is the reference input and 'e' is the error signal which is calculated by subtracting reference input level from present glucose level of patient under consideration. This error signal is then feed to controller block i.e. PID. The controller block sense the error signal and feed patient with required amount of insulin through insulin feedback loop IFL. A.

PID controller

The controller which is generally used in industrial processes is PID controller. Its transient response is very fast and having

large power to overcome the steady state error. The three control actions of the PID controller are proportional, integral and derivative. In PID, the system's output is feed backed to input through closed loop. If the output of the system have some difference between the reference point then PID controller modify the input according to the difference in the reference point and output.

The PID controller consists of three parameters which have different actions and functions. The output of the system due to proportional parameter of controller depends on the present change in the error. The system's output due to the integral parameter depends on the past error and the output due to the derivative parameter depends on the future error. By using all these control actions i.e. PID we get a good performance control technique. In order to get the desired output of the system we adjust the values of these three parameters. Proportional Integral (PI), Proportional Derivative (PD) and Proportional Integral Derivative (PID) are the combination of these three parameters and explained in equation (4) [21].

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \rightarrow (4)$$

Where u (t) represents the overall control function of PID controller and K_p , K_i and K_d represents proportional, integral and derivative gain respectively. K_p represent the present gain of the error, K_i represent the past error and K_d represent the future error. Table I N shows the effect of different gains of PID controller.

Table 1. Effects of k_p , k_d and k_i using pid controller.

Response	Rise time	Overshoot	Settling time	Steady error	state
KP	Decrease	Increase	No effect	Decrease	
KI	Decrease	Increase	Increase	Eliminate	
KD	No effect	Decrease	Decrease	No effect	

Insulin feedback loop

The insulin feedback loop (IFL) is second part of an automated blood glucose control and it is responsible for injecting the required amount of insulin. Up till now this part of blood glucose control is used as precise way to imitate typical insulin discharge. By using this technique basal metabolic or insulin rate can be arranged in various sections in 24 h time. By adjusting insulin availability on the basis of hourly cycle (24 h), the diabetic patient can tackle the health situations and change related to metabolism such as diet, exercise, changing work routine etc. [22]. The injection (subcutaneous) is said to be as the safest way of injecting the insulin dose in the body. The risk in insulin therapy is the over dosage of insulin in blood plasma and high IOB (Insulin on Board) level in patient's body. Therefore, it is necessary that estimation of Insulin on board is made and employ to prevent this over dosage issue [23,24]. For this purpose IFL is attached at the

output of PID controller and when the desired and present level of blood glucose is same no insulin is injected into the patient through IFL.

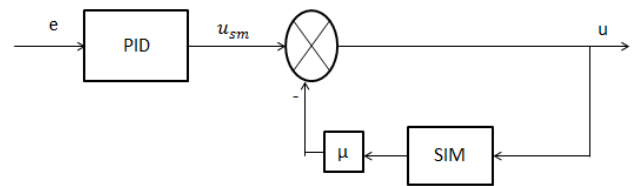


Figure 2. Block diagram of PID with IFL.

Subcutaneous insulin model (SIM) proposed by ‘Meal simulation model’ given in Appendix A is employed to get arithmetic mean of population for all of its specifications. Tuning gain μ is used along with SIM block and its value is determined by compensating response between slow (high μ) and fast (low μ) when the closed loop stability is made sure

Results

To investigate the performance of feedback controlled insulin infusion system, the predefined model is analyzed in open loop, following the closed loop without controller and then a controlled strategy is developed and implemented using PID controller. This section includes results of open loop analysis, closed loop analysis and effect of gains of PID on the closed loop system.

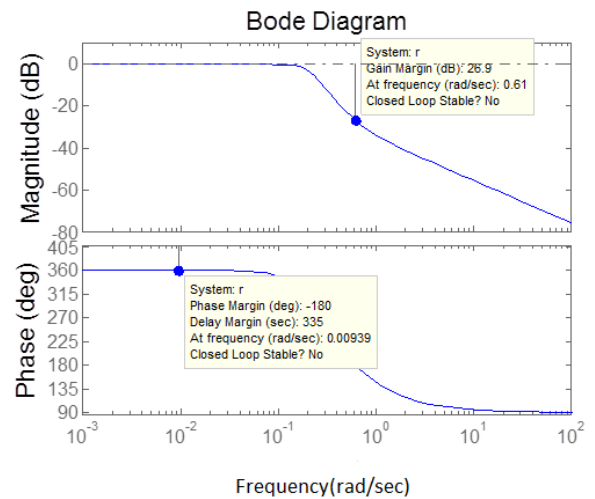


Figure 3. Bode plot of system without controller.

Open loop results

Open loop system is not following the BIBO (Bounded Input Bounded Output) stability criteria as for bounded input (which in our case is step) system has unbounded output. The frequency response also showed system has no closed loop stability as shown in Figure 3. Root locus of the system showed one of the poles is in right half plane as shown in figures 3 and 4 so the system is unstable. Figure 5 shows the

step response of the system without using controller and its evident from the graph that the system is not stable.

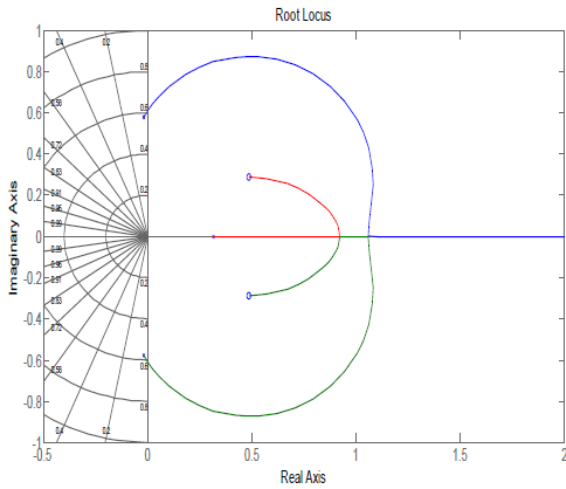


Figure 4. Root locus of system without controller.

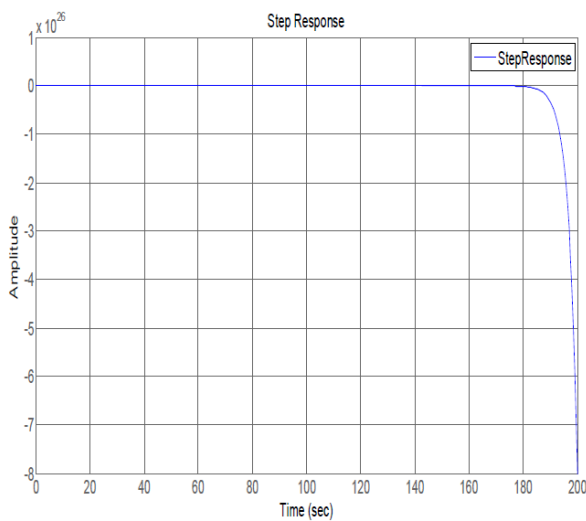


Figure 5. Step response of the system without controller.

Closed loop results

The closed loop results include effect of Proportional, Derivative and Integral actions on system. Figure 6 shows the frequency response analysis of closed loop system. It system is stable as it meets the Bode plot stability criteria i.e. both the phase margin and gain margin are greater than 0 (means positive). Figure 7 shows the step response using only proportional controller. The step response of the system has following the input but this controller adds more oscillations in the step response as shown in the plot of Figure 7. The proportional controller made system response faster as rise time is decreased and also decreased the steady state error. Figures 8 and 9 show the step response using proportional derivative controller. As derivative controller increases the damping ratio so the step response obtained using Proportional Derivative (PD) controller has less oscillations as well as less

overshoot. The proportional derivative controller made system response fast as proportional action is responsible for less rise time and derivative action decreases system settling time but steady state error is still there so in order to eliminate it integral action is necessary Figure 9 shows the step response using proportional integral controller. By adding integral controller the steady state error in the system is no more but due to integral effect the overshoot is added in the system. The settling time of the response is increased due to absence of derivative action while rise time is less due to proportional action. After observing actions of different gains of PID it is noticed that proportional, derivative and integral all three actions are necessary in order to achieve desired and optimal response. Figure 10 shows the step response using proportional derivative integral controller. The system has all the desired characteristics which can help in making automated insulin infusion system.

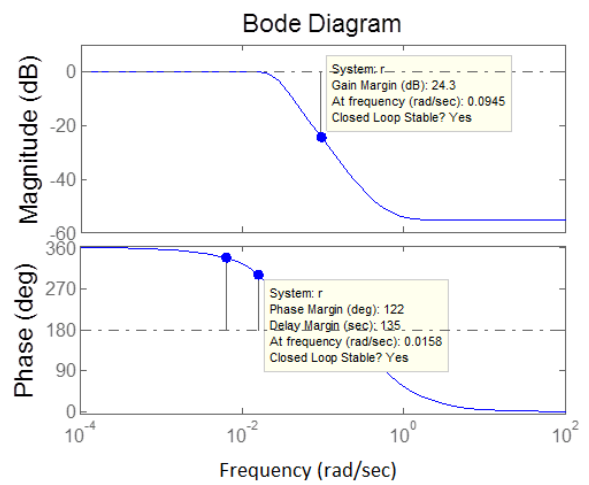


Figure 6. Bode plot of system with controller.

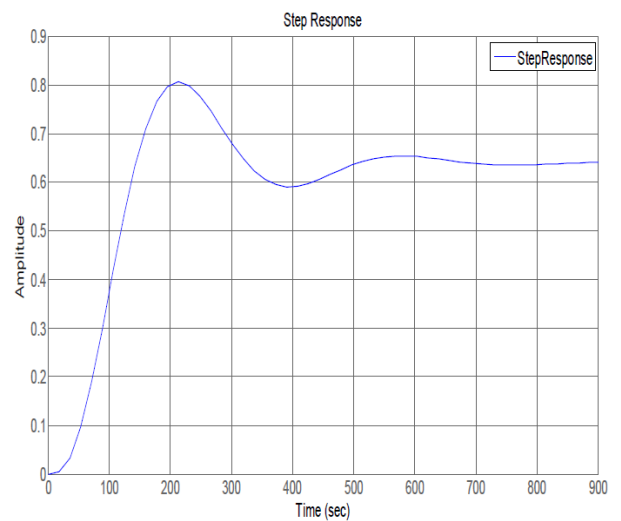


Figure 7. Step Response using Proportional Controller.

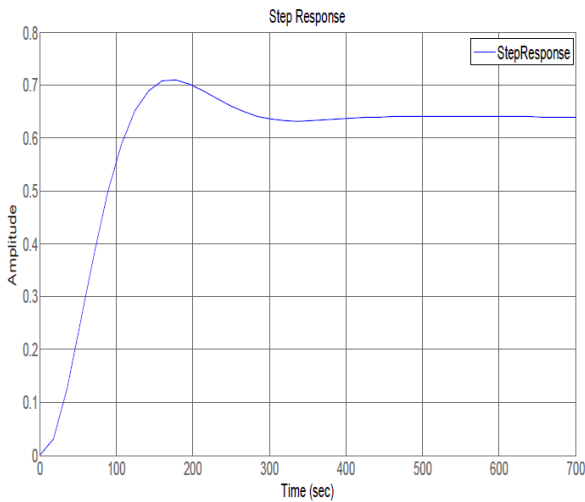


Figure 8. Step response using proportional derivative controller.

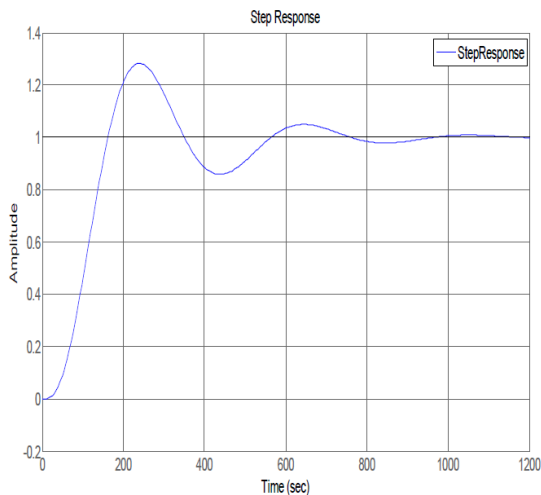


Figure 9. Step response using proportional integral controller.

Insulin sensitivity variations

Insulin sensitivity variations occur during basal conditions is shown in Figure 12. The corresponding insulin summaries are described in [25-29]. The desired range (i.e. 70-100 mg/dL) of blood glucose is achieved using PID controller but this desired range is achieved after long and slow response. The glucose level rises up and then finally returns to desired value of 70 mg/dL. The glucose level for different meal challenges and poor estimation of carbohydrate content of a diabetic patient can be improved using PID controller with specific switching time. The glucose concentration in blood depends upon the intake food as after eating, the concentration of glucose in blood is increased and it is necessary for the controller to sense the glucose level and inject the desire amount of insulin. This can only happen when the controller is finally tuned. The switching time of PID is very important as early switching may result in low blood sugar and for late switching after meal

glucose peak is very high and will slowly reach at set point value.

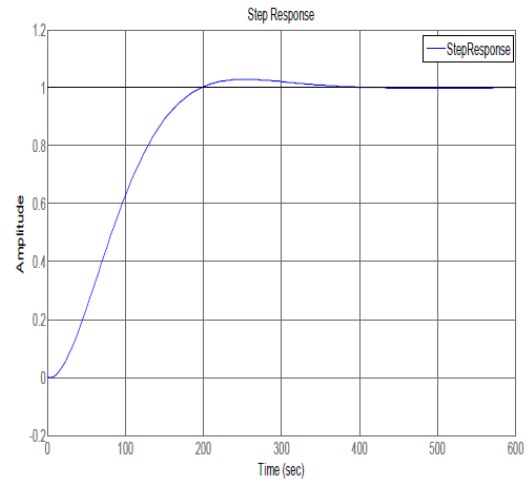


Figure 10. Step response using PID controller.

Discussion

In order to maintain glucose concentration in normal range in human body, Proportional, Integral, Derivative control based technique is designed and implemented. This Implementation is simulation based analysis on the basis of comparison of effects of Proportional controller, Proportional Derivative controller, Proportional Integral controller and Proportional Integral Derivative controller. This comparative analysis clarifies the effect of each controller in maintaining the glucose concentration in normal range.

This research analyzed the effects of different components of PID one by one and concluded that PID controller incorporated in artificial pancreas gives best response as it has very less overshoot percentage. Only proportional (P) controller reduced the rise time of the system but it did not eliminated the steady state error, only reduced it a little. Following a P controller, Proportional Integral (PI) controller was designed and it was tuned to control glucose level. It was done by using root locus method and desired requirements were met. When different controllers were implemented, the fact that each of them has its own merits and demerits was evident. The PI controller removed the steady state error but added overshoot which can cause hyperglycemia in real time. From Figure 9 it is evident that overshoot is added and elimination of which is vital for controlling diabetes. In order to remove this overshoot, a Proportional Derivative (PD) controller was designed and implemented which solves the issue of increased overshoot percentage and also increased the system stability but added oscillations so the need of using all the gains of Proportional Integral Derivative (PID) controller in order to achieve the best results. The PID controller was successfully implemented to control the concentration of glucose is blood. The Root locus of system using PID controller in Figure 11 shows that the system is stable as there is no pole in the right half plane.

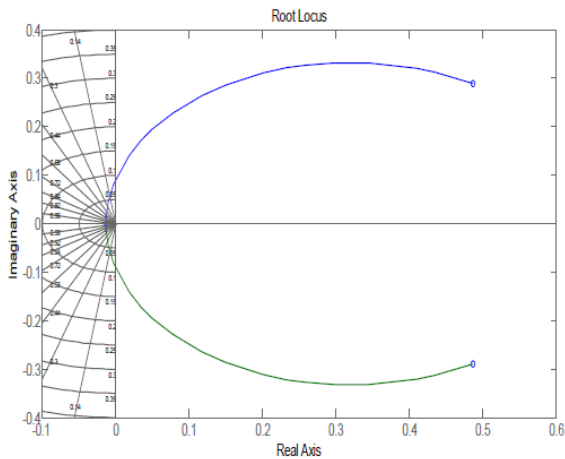


Figure 11. Root locus using PID controller no pole in right half plane.

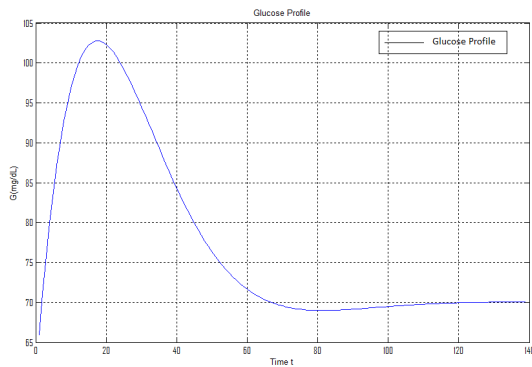


Figure 12. Glucose profile using PID controller.

Table 2. Controller characteristics.

Parameters	Values
Kp	-0.00253
Ki	-1.5815×10 ⁻⁵
Kd	-0.09936
Td	39.43

The Glucose profile shown in Figure 12 reveals that by using PID controller the glucose level is maintained in normal range.

When the PID controller is started set point is equal to current measured value of glucose and then finally it reaches to the desired value of glucose i.e. 70 mg/dL after few seconds.

Switching time is very important while using PID controller as late and early switching may result in hyperglycemia and hypoglycemia respectfully.

The comparative analysis of these controllers evince that the combined result of all the gains provides the best control of diabetes (Table 2).

Conclusion

In the field of bio-medical, automated insulin delivery is one of the major applications of control strategies. Maintaining glucose level in normal range i.e., 70 mg/dl-100 mg/dl is vital in human body. For the automation of insulin infusion system simulations of Proportional Integral Derivative controller has been evinced which shows the encouraging and desired results for insulin infusion. The effects of individual controllers that are Proportional, Integral, Derivative and their combinations are also discussed for comparative analysis. From the discussion of all the combinations of P, I and D, the effects of each one of them shows that PID gives the best and fastest response. The glucose profile of diabetic patient shows that by using PID controller the glucose level is being maintained. In this research the simulation results obtained using PID controller uplifts the clinicians and control engineers to implement this advanced and safe infusion technique in real time in order to automate the insulin delivery. In the sphere of bio-medical control patois this prototypical model will result in minimization of clinical work in the field of diabetes.

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