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The Application of PID Control in Closed-Loop Blood Glucose Management for Type 1 Diabetes

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Abstract. In recent years, diabetes has become a serious global public health issue, and the number of patients continues to grow, causing serious social and economic burdens. Type 1 diabetes patients require life-long insulin treatment, and they are also prone to risks of hypoglycemia. Diabetes is not a directly life-threatening disease, but it can significantly increase the risk of heart disease, kidney disease, and stroke. Therefore, traditional manual insulin injection methods often cause changes in blood sugar levels during treatment, which can lead to high or low blood sugar. Thus, how to effectively and steadily control insulin has become a key research area. PID control is easy to implement, convenient to operate, and capable of real-time control, and it has been widely applied in blood glucose control systems. Through a review of the relevant literature, this paper introduces the application of PID control in closed-loop blood glucose regulation and its adaptability in the insulin-glucose system, as well as the pros and cons of various PID control methods. The conclusion indicates that PID control can effectively control blood glucose changes.

Keywords: Type 1 Diabetes, Artificial Pancreas, Closed-loop Glucose Regulation, PID Control, PID Optimization

1. Introduction

Diabetes has emerged as a significant global health issue in the last few years, and the rising prevalence of diabetes among adults has created a substantial social and economic burden on the healthcare system [1,2]. Among the different types of diabetes, type 1 diabetes (T1D) is a particularly difficult form of the disease because, in this case, the body does not produce any insulin, and the only treatment available to the patient is lifelong insulin therapy. This kind of treatment is often injected manually, and there is a high possibility of under-dosage or overdose. Due to this, they are extremely susceptible to episodes of hypoglycemia [3,4]. In order to minimize these risks, scientists and researchers have slowly moved away from the traditional and manual insulin infusion technique to the more advanced closed-loop control system, Artificial Pancreas. The main goal of this system is to provide more stable glucose control than the traditional method and has shown promising results in this aspect [2,3]. Nevertheless, the capacity of any closed-loop system to guarantee safe and stable maintenance of glucose is also limited due to physiological variations between people and unpredictable extraneous factors, such as changes in diet and physical activity. In addition, more sophisticated control algorithms are more theoretically accurate but will be

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complex, making them impractical. In this regard, the proportional-integral-derivative (PID) control algorithm has become one of the significant alternatives. Due to its comparatively low complexity, high sturdiness and low computational intensity, it can be used in the regulation of blood glucose. As the interest in optimisation of PID control has increased, numerous recent studies have utilised the application of intelligent optimisation algorithms in order to improve its dynamic characteristics and reliability in real-world scenarios [5,6]. Thus, this paper explores PID control methods used in closed-loop glucose and insulin level control in type 1 diabetes patients. The evidence is that the review will discuss the use of the PID control in the glucose and insulin dynamic system, performance comparison among various PID control strategies, and the technical issues facing the performance of the strategies in real-life applications. It further seeks to recapitulate the theoretical foundation, parameter optimisation methods and implementation plans as evidenced in the contemporary literature. In addition, the assessment involves simulated virtual patients and actual clinical information to discuss the advantages and disadvantages of the various strategies and what can be done to improve the strategies in the future.

2. The adaptability of PID control in the glycemic system

2.1. Control principles and modeling methods

The proportional, integral and derivative components make up the controller of the PID, and it is applied to correct the errors in the system and control the dynamic processes as shown in Figure 1 [5]. The PID controller is simple and easy to understand, which makes it easy to use in engineering. Hence, PID control is used in industrial processes and in processes with slow variations [7].

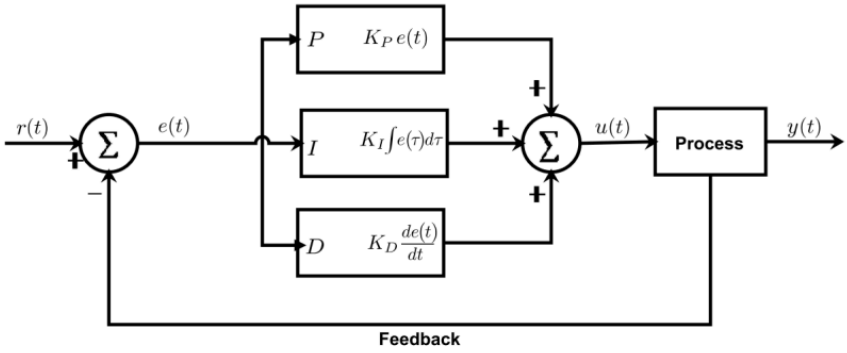

Figure 1. Control structure of PID

The artificial pancreas system also still uses PID control, although more sophisticated control algorithms such as model predictive control (MPC) exist. This happens to be the case mostly due to its simplicity; it can process in real time and does not need an accurate model of the process [1,8].

The glucose-insulin system, inherently, is a nonlinear feedback system, where the insulin infusion influences the glucose level in the blood, and the dynamics of the system as a whole are characterised by this cycle. An example of a simplified mathematical model of this process has been the traditional Bergman minimal model and has been applied to the design of controllers [1,3]. This model, however, does not provide a thorough description of the process. To solve this problem, more elements have been added to the models which includes gastrointestinal glucose absorption, meal errors, and the impact of physical exercise [1,2]. These elements are trying to present a more realistic explanation of the process. As the glucose regulation process as a whole can be considered a

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system with insulin as the input and blood glucose as the output, PID control can naturally be applied to this system and function within a single-input, single-output system architecture [8]. Despite the presence of hardware constraints such as delays and noise in insulin pumps and glucose sensors, studies have demonstrated that properly designed PID controllers can provide effective glucose control [1,4].

2.2. Control performance and adaptability analysis

In closed-loop control systems, controller performance is evaluated using multiple metrics to ensure blood glucose remains within a safe target range. These include the steady-state error, overshoot, settling time, and the percentage of time for which glucose concentrations remain between 70 and 180 mg/dL [1,4,9]. Of these, the avoidance of hypoglycemia is considered the most important requirement, as most clinical trials emphasize that the acute risk of danger is much more likely to occur during episodes of hypoglycemia than during episodes of hyperglycemia [2,4].

A PID controller that uses fixed parameters can be applied to control glucose concentrations adequately; however, there are a number of limitations that limit its efficiency. The first one is the high variability of insulin sensitivity and metabolism in various individuals, and it is not appropriate to establish a set parameter to apply to all patients [2]. It can also be noted that the presence of sensor noise and delays associated with the measurement in continuous glucose monitoring systems directly influences the derivative and integral variables of the PID controller. This can cause oscillation in the insulin delivery or huge corrections on misguided feedback [1,4]. Even large perturbations, like eating or physical activity, cause problems in glucose regulation, because a traditional PID controller might not be able to react fast and precisely enough to counter the abrupt alterations in glucose level [10]. According to the literature, despite the fact that PID control is typically relevant to the dynamics of glucose and insulin, the application of a standard and unmodified PID controller is insufficient in a realistic and highly variable physiological scenario [2,11]. This has facilitated the realisation of new strategies that alter and expand the conventional PID controller. These are the parameter optimisation, adaptive adjustment and intelligent or hybrid PID control designs. The combination of these developments suggests the way research work can be conducted in the future to enhance the reliability, safety, and individuality of the controller.

3. Optimization and application of PID control in blood glucose regulation

3.1. Control evolution and method improvements

The blood glucose systems started with control strategies based on the fixed-parameter PID control, and slowly evolved into more flexible and intelligent control strategies. Initially, PID controllers were mostly used due to their simplicity and low prices. Meanwhile, the parameters of PID control could be determined by simple rules, including Ziegler-Nichols, CHR, and ITAE, and those rules could offer simple control performance. Nonetheless, the conventional PID control usually experiences challenges in responding to the various insulin sensitivities of patients or tremendous variations in glucose levels caused by food consumption and exercise activities [7,8]. Thus, certain changes were implemented, like anti-windup, derivative filtering, and feedforward compensation, to remove delays and stabilise the controller.

With the further development of intelligent optimization techniques, PID control has begun to adopt swarm intelligence algorithms or evolutionary algorithms such as PSO, GA, and GOA. These algorithms can optimize the parameters of PID control through simulation, making our controller

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more adaptable to the nonlinear characteristics of the blood glucose system. This can improve the control level and reduce the degree of blood glucose fluctuations and hypoglycemia [12,13]. However, they require a large amount of computing power and cannot adapt to changing situations in real time. Hybrid PID control methods such as fuzzy PID control, fractional-order PID control, and complex-order PID control have also become increasingly popular [9,14]. They all have flexibility and powerful features, just like fuzzy PID, and can be changed at any time; but unlike fractional-order and complex-order PID, they are very gentle when dealing with any disturbances.

3.2. Clinical applications and scenario expansion

The closed-loop insulin delivery system controlled by PID has been tested via virtual simulation studies and small-scale clinical trials. The research found that the PID-based method can control the blood glucose level in the body after subcutaneous injection (SC) of insulin [1,2]. But SC infusion is always late and the reaction is late or too much, especially after meals or if there are large individual metabolic variations. As for unforeseen exercise or an unannounced meal that the person does not inform you of will cause a sudden change in blood sugar level and it is common for PID control systems to be unable to react promptly and accurately to such sudden fluctuations.

As SC insulin absorption can be quite slow, other methods of delivering insulin have also been studied. For intraperitoneal insulin infusion, the pharmacokinetic process is faster and has a more direct relationship with lowering blood glucose levels. Therefore, it can be used in PID controllers with time-varying or personalized characteristics, which can respond to sudden changes in blood glucose levels [15]. It is found that IP-based system may be the solution to problem associated with SC-PID.

However, in clinical practice, unpredictable phenomena such as spontaneous physical activity, declining meal announcements, and the threat of night hypoglycemia have to be considered even in an optimised PID system. These problems have led to the emergence of other control layers which operate in conjunction with the PID algorithm. The system is now commonly fitted with safety modules and glucose prediction algorithms to interrogate real-time sensor data, forecast future glucose levels and control the rate of insulin infusion accordingly. Taking into account the influence of factors like diet and exercise, these additional modules can lower the likelihood of hypoglycemia, especially if the insulin pump cannot completely stop the release rate. And as blood sugar levels start to drop, this situation becomes more pronounced [2,4]. The safety and prediction module has a variety of different control functions, making it more suitable for use in PID control systems. This system can ensure that patients maintain stable blood sugar levels not only on normal days, but also during more uncertain situations (such as after meals (post-meal) or during sleep (nighttime)).

3.3. Solution evaluation and performance comparison

The comparison of various PID control strategies via virtual patient simulations is also prevalent in recent literature. These data indicate that, in terms of indicators such as steady-state error, recovery time, and the time within the effective range [3,6,9]. However, improved PID strategies still cannot compete with more advanced strategies such as MPC, particularly when the control problem becomes more complex or dynamic.

Despite these drawbacks, improved PID controllers also retain significant advantages in practical applications. They are very simple to operate and run, and are also easy to implement. Moreover, they are very applicable in real life. Therefore, precisely because of this, there are many types of blood sugar control systems that can utilize them, especially when the cost is low and the

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implementation is easy [1]. The evolution of PID control from simple tuning rules to more intelligent and hybrid approaches has enabled more recent approaches to PID control to address more complex scenarios that are more representative of real-world clinical practice.

4. Current challenges and future developments

4.1. Existing challenges in PID-based blood glucose control

Although a lot of research has proved that PID control with a closed loop could achieve effective glucose control, implementing this strategy in clinics is very hard. One major cause of it being difficult is that there are big variations in people and how their bodies work, plus those changes happen as time goes by. Insulin sensitivity, the rate at which the body absorbs glucose, and the speed of metabolism all differ greatly between individuals, and even in the same person, they can vary based on the daily conditions. Therefore, it is impossible to obtain a stable control result over a very long time with the PID parameter (fixed and decided beforehand) [2,15].

Another problem arises from the restriction of continuous glucose measuring system. CGM signals generally have noise and because of physiological and algorithm reasons there will be a few minute's delay. With this sort of delay and noise for input into a PID Controller, the integral part of that controller will tend to accumulate error, and the derivative part will tend to amplify noise in the signal. Thus, it becomes unstable, and it will be oscillated with too much insulin [1,4] Moreover, practical clinical conditions introduce uncertainties in the control process. The blood sugar level may experience sudden and unpredictable fluctuations due to unrecorded diet, irregular meal times, changes in physical activity, or emotional stress. These sudden changes in blood glucose will often cause a sharp rise or fall in the amount of blood glucose. Studies have shown that most cases of hypoglycemia and hyperglycemia are caused by such unexpected events. In such situations, the normal insulin secretion system has difficulty making rapid adjustments to respond to the sudden changes in blood sugar levels and secrete insulin in a timely manner.

4.2. Future directions in PID-based blood glucose regulation

In response to these problems, the future methods of PID control of blood glucose were inclined toward adaptive, personal, and intelligent control. Recent studies are trying to give evidence to the assimilation of artificial intelligence and PID control, and this has been significantly addressed. As an example, the approaches to reinforcement learning, real-time optimisation, and adaptive estimation have been suggested to adapt the PID control parameters on a process basis and reduce the effects of individual variability and time-dependent dynamics of the system [5,11]. Meanwhile, the current trends in artificial pancreatic systems are leaning towards the concept of personalised closed-loop control and digital twin. An individual model can further be designed and modified with time, and this has assisted the PID controller in responding to the physiological variations of the patient. This method has shown its possibility in virtual patient simulation and long-term simulation [2,9]. And to further improve the PID control method, other new research trends are the multimodal data fusion and predictive assistance. Predictive models can help control PID by combining CGM data with meal, exercise and past glucose patterns data. This will ensure the PID control technique remains simple as well as render the system more robust and secure [1,4,6].

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5. Conclusion

This paper discusses the application of PID control to closed-loop blood glucose regulation and discusses its theory, optimisation techniques and its application in artificial pancreas systems. It starts with an analysis of the dynamism of the interactions between glucose and insulin, which is modelled. This paper reveals why PID control can naturally be applied to this nonlinear interaction system, where the insulin infusion volume is the driving variable and the blood glucose level is the output result. It describes the evolution of classical PID controllers using the means of intelligent optimisation and subsequently incorporates hybrid architectures that add more control components. And the comparisons made on these developments are on performance, safety and feasibility of implementation in engineering. The various important issues that arise when implementing PID control in the clinical environment have also been identified. There are significant differences in the physiological states of patients among themselves and at different time points. Issues such as sensor delay, noise in blood glucose measurement, and interference caused by inconsistent lifestyle behaviors have all been mentioned. To address these issues, various methods have been proposed, such as adaptive adjustment, intelligent optimization, supervised security layer, and multi-model control structure, aiming to make the PID-based system more powerful in practical applications. Besides, the continuous importance of PID control in the research of artificial pancreas is elaborated. Its simple operation, rapid real-time response, and compatibility with the devices already used in the medical field are features that facilitate its continued use, although more advanced methods are being developed. It is believed that by integrating methods related to AI, patient-specific models, and multimodal information, the performance of PID can be further enhanced, and the creation and clinical application of closed-loop artificial pancreas technology can be promoted.

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