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An Improved PID Switching Control Strategy for Type 1 Diabetes

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***Abstract*— In order for an "artificial pancreas" to become a reality for ambulatory use, a practical closed-loop control strategy must be developed and critically evaluated. In this paper, an improved PID control strategy for blood glucose control is proposed and evaluated *in silico* using a physiologic model of Hovorka *et al.* [1]. The key features of the proposed control strategy are: (i) a switching strategy for initiating PID control after a meal and insulin bolus; (ii) a novel time-varying setpoint trajectory, (iii) noise and derivative filters to reduce sensitivity to sensor noise, and (iv) a systematic controller tuning strategy. Simulation results demonstrate that the proposed control strategy compares favorably to alternatives for realistic conditions that include meal challenges, incorrect carbohydrate meal estimates, changes in insulin sensitivity, and measurement noise.**

I. Introduction

People with type 1 diabetes must rely on exogenous insulin for survival. During the past 30 years, a variety of glucose control strategies based on continuous glucose sensing has been reported. Since this literature has been reviewed in recent survey articles [2]–[5], we will not present a detailed review here. In summary, the control strategies include variations of the proportional-integral-derivative (PID) control strategy that is widely used in industrial control applications [6].

This paper is concerned with developing an improved glucose controller that is based on a novel PID controller, bolus injections for meals, and a strategy for switching between them.

II. Physiological Model

Many physiological models have been proposed that describe glucose and/or insulin dynamics [1], [7]–[10]. In this paper, the simulation studies are based on the model developed by Hovorka *et al.* [1] and the modifications reported by Wilinska *et al.* [10]. This model will be referred to as the "Hovorka model". It represents the relationship between input variables, subcutaneous insulin infusion rates (basal and bolus), and the output variable, intravenous glucose concentration. This model also includes a submodel for meal ingestion.

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The normally distributed sensor noise, ϵ had zero mean and a standard deviation of 0.0333, $G_m = G(1+\epsilon)$, where G_m is the measured value.

III. PID Controller Design

The PID controller calculates the insulin infusion rate that is released by the pump into subcutaneous tissues. The velocity form of the PID controller was used [6]. In order to reduce the effect of noise, the measured glucose concentration, G_m, was filtered using a standard first-order filter [6]. Furthermore, a derivative filter was used in the controller itself.

In an initial study, the PID controller was tuned for meal challenges. However, it was not possible to avoid postprandial hypoglycemia unless the reset time was set to very large values (e.g., $\tau_I = 167$ h), which essentially eliminated the effect of integral control action. On the other hand, it is desirable to include integral action to deal with patient variability such as changes in insulin sensitivity. One solution to this problem is to limit the integral term by introducing upper and lower limits. With this constraint, the effect of the integral action for meal challenge is negligible compared to the effects of proportional and derivative actions, but integral action will eliminate steady-state error (offset) in G_m after insulin sensitivities changes. Based on these considerations, a novel controller tuning procedure was employed. First, K_c and τ_D were tuned for meal challenges (correct CHO estimate, and 50% under- and over-estimates) using a nominal value of $\tau_I = 1.67$ h; then τ_I was tuned for insulin sensitivity changes. Finally, the resulting PID controller was re-evaluated for the three meal challenges to ensure that post-prandial hypoglycemia did not occur, even when the insulin bolus was over-estimated by 50%. In each case, the resulting value of τ_I was satisfactory. For each PID controller, K_c and τ_D were tuned to minimize the following objective function,

$$J = \sum_i \left(\text{IAE}_i + w_i\right) + c_1 + c_2, \tag{1}$$

$$\text{with,} \quad \text{IAE} = \sum_k^{t_\infty} |e(k)|\Delta t, \tag{2}$$

$$w_i = \exp\left(-100\left(G_{min,i} - 60\right)\right), \tag{3}$$

$$c_1 = \exp\left(-10000\left(-0.01 - K_c\right)\right), \tag{4}$$

$$c_2 = \exp\left(-10000\left(1500 - \tau_D\right)\right), \tag{5}$$

where index $i = c, u, o$ refers to the response for a correct, under-estimated and over-estimated CHO content of the meal; IAE (mg min/dL) is the discrete version of the integral absolute error, e (mg/dL) is the control error, w_i is the soft constraint to avoid low G values (hypoglycemia); c_1 is the soft constraint to avoid K_c values larger than -0.01 mU dL/mg min; c_2 is the soft constraint to avoid τ_D values larger than 1500 min; t_∞ is the duration of the simulation; Δt is the sampling period (5 min), and $G_{min,i}$ is the minimum value of G_f for the i-th run. Note that when the constraints are not active, the objective function is simply the sum of the IAE values for the three cases.

IV. Control Strategies

A new switching PID control strategy is proposed that consists of meal boluses, a novel PID control algorithm with a time-varying setpoint, and a switching strategy. The proposed strategy (Strategy E) is compared to four alternative strategies (A–D) in Section V. These five control strategies are:

A – Bolus only. This strategy consists of a constant basal insulin infusion rate plus a meal bolus.

B – PID control only. The PID control algorithm of Section III provides a basis for comparison.

C – Bolus plus PID control. The PID controller operates continuously.

D – Bolus plus PID control with switching criteria. The PID controller is not initiated until a switching criterion is satisfied.

E – Bolus plus PID control with switching criteria and a time-varying glucose setpoint.

First, we consider why a switching strategy is desirable. Preliminary simulations for Strategy C indicated that it is detrimental to have the PID controller active during and immediately after an insulin bolus. For this situation, the PID controller senses the increasing glucose level of the post-prandial response and consequently makes the insulin infusion rate greater than its basal value. This additional insulin release leads to hypoglycemia unless the controller is tuned very conservatively. Consequently, the optimal controller settings for Strategy C and the performance index of equations (1)–(5), were the minimum allowable values of K_c and τ_D. Thus, Strategy C was essentially identical to Strategy A, the bolus-only approach, for these conditions. This experience motivated the development of the switching technique that is a key element of Strategies D and E. A simple switching control strategy (wait 1.5 h) has been used in a diabetes MPC application [1].

Improved glucose control for meal challenges and poor CHO estimates can be achieved by starting the PID controller after the meal and bolus occur. However, the specification of the switching time is important. If the PID controller is started too early, hypoglycemia can occur. On the other hand, if the PID controller is switched on too late, the post-prandial glucose peak may be very large and slowly decrease to the setpoint value. Our simulation studies have indicated that an effective switching strategy is obtained if the PID controller is started when one of two criteria is satisfied:

(i) G_f reaches its peak value;
(ii) $G_f > 150$ mg/dL and $\mathrm{d}G_f/\mathrm{d}t > 1.5$ mg/dL min.

The 150 mg/dL threshold was selected because it is the peak value of G for a correct bolus and Strategy A. The rate-of-change limit of 1.5 mg/dL min was chosen to be greater than the maximum rate of change for this same situation.

The rationale for these switching criteria is as follows. When the CHO estimate is either correct or too large, the PID controller switches on when criterion (i) is satisfied. Then the insulin infusion rate starts to decrease because $\mathrm{d}G/\mathrm{d}t < 0$. When the CHO estimate is too small, the bolus is also too small and thus when G reaches the threshold of 150 mg/dL, $\mathrm{d}G/\mathrm{d}t$ is large. Consequently, after the PID controller is switched on, it immediately increases the insulin infusion rate, which is the correct action.

Next, we consider the rationale for using a time-varying setpoint in Strategy E. During the post-prandial period, the blood glucose concentration is expected to increase, and then decrease. Consequently, it is appropriate to have a time-varying setpoint, G_{sp}, that reflects this expected behavior [1], [5]. The following strategy has been devised. When the PID controller is initiated, G_{sp} should be set equal to the current filtered measurement, G_f, and then eventually decrease to the desired value of $G = 80$ mg/dL. However, for the case of a CHO under-estimate, G is still increasing when the PID controller is switched on. Thus, it would be inappropriate to force G_{sp} to decrease right away. Extensive simulations have demonstrated that an appropriate setpoint trajectory is:

$$G_{sp}(k^*) = \begin{cases} 80 \text{ mg/dL} & \text{if } G_f(k^*) \le 80 \text{ mg/dL} \\ \left(G_f\left(k^*\right) - 80\right) \exp\left(-\frac{k^*}{\tau}\right) + 80 & \text{otherwise,} \end{cases} \tag{6}$$

where $k^* = k - k_{sw}$, k (min) is the current sampling instant, k_{sw} (min) is the switching instant, and τ (min) is a design parameter. For $k^* < 0$, $G_{sp} = G_f$. In order to avoid unexpected hypoglycemia, a lower limit of 80 mg/dL was used. The time-varying setpoint trajectory defined in (6) has the following properties:

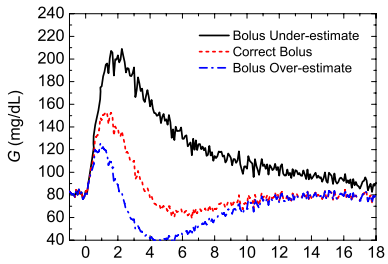
a. It is affected by the actual value of G_f, for every k^*;
b. It varies from $G_f(k^* = 0)$ to 80 mg/dL;
c. As $\tau \to 0$, $G_{sp}(k^*) \to 80$ mg/dL;
d. As $\tau \to \infty$, $G_{sp}(k^*) \to G_f(k^*)$.

V. Simulation Results

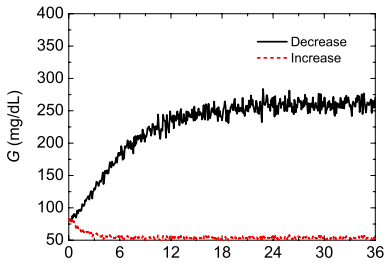
The five glucose control strategies of Section IV were evaluated for two situations:

(i) Meal challenges and either a correct insulin bolus, a 50% under-bolus, or a 50% over-bolus;
(ii) Changes in insulin sensitivity during basal conditions: a 50% increase or a 50% decrease.

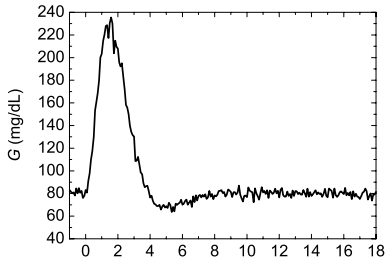
The incorrect boluses represent situations where the diabetic subject incorrectly estimates the CHO content of the meal. The changes in insulin sensitivity were simulated by making the indicated change in all three insulin sensitivities for the



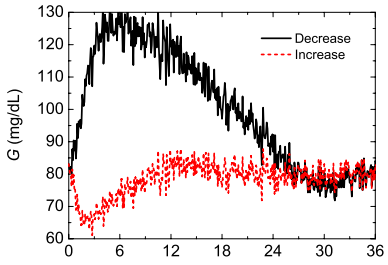
(a) Strategy A: bolus only.



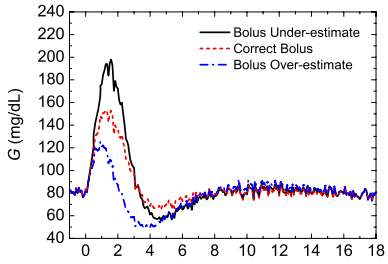
(b) Strategy A: bolus only.



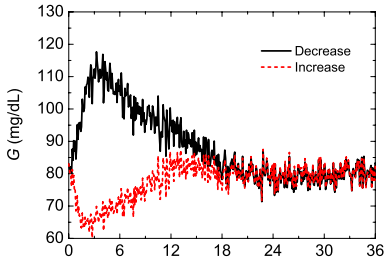
(c) Strategy B: PID control only.



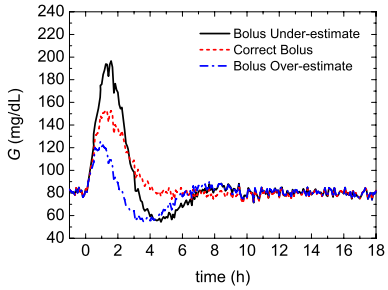
(d) Strategy B: PID control only.



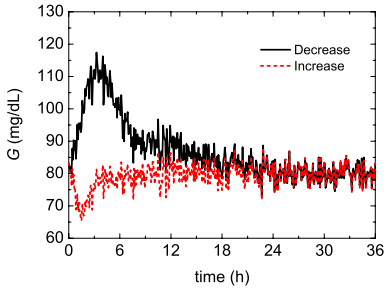
(e) Strategy D: Bolus plus PID control with switching criteria.



(f) Strategy D: Bolus plus PID control with switching criteria.



(g) Strategy E: Bolus plus PID control with switching criteria and time-varying glucose setpoint. ($\tau = 25$ min).



(h) Strategy E: Bolus plus PID control with switching criteria and time-varying glucose setpoint. ($\tau = 25$ min).

Fig. 1. Control strategy comparison for meal challenges (left) and insulin sensitivity changes (right).

Hovorka model [1]. In order to provide a fair comparison of Strategies A–E, each PID controller was tuned using the method in Section III. The glucose sampling period was 5 min.

Results for meal challenges. The simulation results for a 75 kg patient and a 60 g CHO meal challenge are shown in the left side of Fig. 1 and in Table I. Results for Strategy C are not included in Fig. 1 because they are identical to those for Strategy A, as indicated in Table I and discussed in Section IV. Table I includes several metrics: the maximum and minimum glucose concentrations for each response, G_{max} and G_{min}, and the settling time t_s. The settling time was defined to be the time at which the glucose concentration entered and remained with the desired range, 75 to 85 mg/dL.

Figure 1 and Table I indicate that the new switching control strategies (D and E) are superior to the standard control strategies (A, B, and C) for these meal challenges due to their smaller IAE values, shorter settling times, and smaller G_{max}

TABLE I

RESULTS FOR MEAL CHALLENGES REJECTION*.

Control Strategy	Bolus Estimation	IAE (10^{-4}) (mg min/dL)	G_{max} (mg/dL)	G_{min} (mg/dL)	t_s (h)
A	correct	1.40	150	64	10.2
	under	4.69	202	80	>18
	over	1.68	122	**40**	>18
B	-	1.97	228	67	6.7
C	correct	1.40	150	64	10.2
	under	4.69	202	80	>18
	over	1.68	122	**40**	>18
D	correct	1.08	150	68	6.2
	under	1.71	192	**58**	7.1
	over	1.10	122	**51**	12.8
E	correct	0.99	150	78	3.9
	under	1.61	192	**56**	8.5
	over	0.79	122	**56**	8.4

*Glucose values under 60 mg/dL are reported in boldface.

values for the under-estimated bolus. Strategy E provides the best control based on these criteria.

Results for insulin sensitivities changes. The simulation results for the two insulin sensitivity changes during basal conditions and no meal are shown in the right side of Fig. 1. As described in Section IV, the tuning procedure for each controller determined the optimal value of τ_I for insulin sensitivity changes. The simulation results in Fig. 1 are for the optimal value of τ_I for that specific change in insulin sensitivity (e.g., τ_I equal to 2.60 and 3.68 h for Strategy E and insulin sensitivity decrease and increase, respectively).

The results in Fig. 1 demonstrate that Strategies A and C are not able to cope with these sensitivity changes and result in undesirable glucose excursions, which include hypoglycemia. For Strategy B and the 50% decrease in insulin sensitivity, G eventually returns to the desired value of 80 mg/dL but only after a large, slow response. Strategy E provides the best response to the insulin sensitivity changes based on its small IAE values and short settling times. The total insulin utilization is essentially the same for all five control strategies (not shown).

VI. DISCUSSION OF RESULTS

The simulation results demonstrate that an insulin bolus for a meal challenge is required in order to avoid the large glucose peak that occurs when a bolus is not used (Strategy B). However, the bolus-only approach (Strategy A) results in poor glucose control for incorrect boluses and for insulin insensitivity changes. Thus, a combination of insulin boluses for meals and PID control is desirable. But for meal challenges, the PID controller should be switched on at an appropriate time after the bolus is introduced (Strategies D and E); otherwise, it will result in insulin overdosing and hypoglycemia unless it is tuned very conservatively, as was necessary for Strategy B.

For this simulation study, the proposed Strategy E gave the best performance for both meal challenges and changes in insulin sensitivity. Furthermore, Strategy E is quite robust, as indicated by additional simulation results.

The reason that Strategy E outperforms the other four strategies is that the combination of the switching criterion and the time-varying glucose setpoint allows more aggressive controller settings to be used without sacrificing robustness.

VII. CONCLUSIONS

A new glucose control strategy has been proposed based on a novel combination of insulin boluses for meals and an improved PID control algorithm. The key features of the control strategy are (i) a switching strategy for determining when to initiate PID control action after a meal, (ii) a novel time-varying trajectory for the glucose setpoint, and (iii) a limit on the integral control action that greatly reduces the possibility of insulin over-dosing. The new control strategy has been compared to four alternatives in a simulation study based on Hovorka's physiological model [1], [10], and was shown to be superior for both insulin sensitivity changes and meal challenges with poor CHO estimates.

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