SELF-ORGANIZING FUZZY LOGIC CONTROL FOR THE GLUCOREGULATORY SYSTEM

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ABSTRACT

A self-organizing fuzzy logic controller (SOFLC) used to regulate the glucose concentration and possibly the insulin concentration in the blood of the human subject is presented. A linear stochastic fourth order model, which simulates a type-I diabetic or nondiabetic subject was used. A large enough sample period was selected to suit the basic slow dynamic feature of the glucoregulator system. Two types of external mechanical device, open loop and closed loop types were used as glucose or insulin delivery systems. The controller has been tested successfully against the measurement noise and severe load disturbances. The results obtained suggest the application of the proposed controller in controlling type-I diabetes or for the purpose of operating glucose tolerance test.

Keywords: Self-organizing fuzzy logic controller, Adaptive fuzzy logic controller, Glucoregulatory system

INTRODUCTION

In healthy individuals, blood glucose concentration is finely regulated via complex feedback mechanisms, which involve several hormones and substrates. Failure to regulate blood glucose in a normal fashion results in a family of diseases, generally referred to as diabetes, where some impairment occurs in the system involving glucose and hormone insulin [1]. One of the most important test used in classifying subjects into categories of normal and abnormal glucose metabolism is the so called glucose tolerance test. In this test, blood glucose concentration is raised to a predetermined level and maintained at that level for several hours by glucose infusion. The infusion rate required to maintain that level and the decay characteristics, after infusion is terminated, are used as a measure of the subject glucose metabolism [2].

In recent years, much research effort has been devoted to attempting to achieve optimal control of blood glucose concentration using external mechanical devices. Two types of devices have been developed:-

1. Open loop systems, in which insulin and/or glucose is infused according to a pre-programmed schemes, that is, independent of the actual glucose concentration.
2. Closed loop systems, in which insulin and/or glucose is infused on basis of a continuous measurement of blood glucose.

Fuzzy logic control has become one of the most important fields in artificial intelligence and process control application. Fuzzy logic controller is a rule-based controller, which uses information in the same manner as human experts. The static fuzzy logic controller has a fixed rule base. The main problems of this controller are the derivation of the controller rule base and the fixed structure of the controller may cause deterioration in the system response if the change in the parameters of the process under control occurs.

The SOFLC is studied as one of the adaptive fuzzy controllers. Their idea is to try to identify which rule is responsible for the current poor control performance and then to replace it with better rule. This requires both a mechanism for determining which rule is incorrect and one for determining an improved rule to take its place.

A fourth order mathematical model of the diabetic subject [3] is employed, in which it assumed that the lake of glucose-controlled insulin provision is the only essential difference between the diabetic and nondiabetic states. A SOFLC has been proposed to control the glucregulatory system.

MATHEMATICAL MODEL OF THE GLUCOREGULATION SYSTEM

A method involving an individually identifiable and physiologically relevant model of gluco-insulin relationships in vivo, together with its validation and application, was described by Fischer *et al.* [3]. The transfer characteristics could be described by a fourth-order differential equation. Four state variables proved sufficient for a complete description of the controlled metabolic plant's behavior. The compact matrix form can represent this system:

$$\dot{X} = AX + BU \qquad (1)$$

$$Y = CX \qquad (2)$$

Where X is the vector of the four state variables x,u,y and z defined by the deviation from the fasting level of glucose concentration, overall endogenous glucose balance, plasma insulin concentration and peripheral insulin dependent glucose utilization respectively. U is defined by the input vector given by :-

$$U = [G_{exg} \quad I_{exg} \quad b_o]^T \qquad (3)$$

Where:

G_{exg}: exogenous input of glucose

I_{exg} : exogenous input of insulin

and b_o : endogenous glucose provision.

The transition matrix A and matrix B are given by: -

$$A = \begin{bmatrix} 0 & 1 & 0 & -b_3 \\ 0 & -k_o & -b_1 b_3 & b_1 b_3 \\ a_1 & a_2 & -k_1 & -a_2 b_3 \\ 0 & 0 & k_2 & -k_3 \end{bmatrix}$$

$$B = \begin{bmatrix} 1 & 0 & 0 \\ -b_1 & 0 & b_1 \\ a_2 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad (4)$$

(Please see the definition and value of each variable in the list of symbols at the end of the paper).

For the normal human subject, matrix A is (asymptotically) stable, i.e the real parts of the eigenvalues are negative. The mathematical model of the uncontrolled metabolic system (diabetic state) has the same last structure but with the control constants a_1=0 and a_2=0. For the diabetic subject matrix A is unstable, i.e some of the real parts of the eigen values are positive.

THE SELF-ORGANIZING CONTROLLER

The SOFLC is an adaptive fuzzy logic controller [4,5,6]. The adaptive FLC's are capable of modifing their parameter upon an evaluation of their performance and therefore the control policy is adapted according to the changes in the process and its environment. There are three basic groups of adaptive FLC's classified according to the parameters adjusted in order to provide optimal performance: -

- Adaptation of the scaling factors.
- Adaptation of the definition of membership functions.
- Adaptation of the control rules.

Since the control rules are of higher importance in the design of any FLC especially for systems that are not controlled by human. This paper is concerned with the third type, which is called Self - Organization Fuzzy Logic Controller.

Description of the SOFLC

The SOFLC is a simple static [7] fuzzy logic controller incorporates performance feedback as shown in Figure 1. Each of the two blocks added to the simple FLC to form the SOFLC are discussed below in detail.

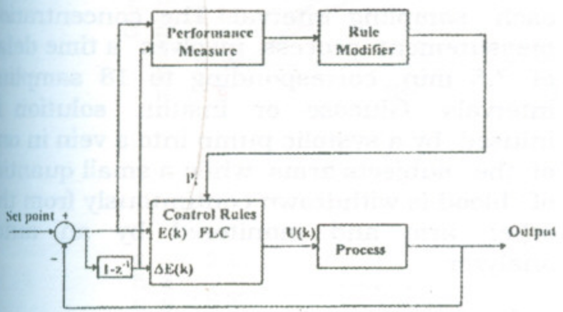

Figure 1 Self-organizing fuzzy controller

The Performance Measure

The performance monitor consists of a performance measure that specifies the basic regulatory control requirements, namely a sufficiently fast approach to set-point y_{sp}, good damping when close to the set-point and a measure of tolerance around the set-point. The requirements with respect to this performance measure can be expressed as a set of rules that define the performance of the system at each sampling time k, given the values of the error and change-of-error. For example:-

if e is VERY LARGE and Δe is NEGATIVE VERY LARGE then P is SATISFACTORY

if e is VERY LARGE and Δe is VERY LARGE then P is VERY POOR

Where:

$e = G_e \, . \, e_c(k)$

$\Delta e = G_{ce} \, . \, \Delta e_c(k)$

$e_c(k) \;\; = y_{sp} - y(k)$

$\Delta e_c(k) = e_c(k) - e_c(k-1)$

$e_c(k)$, ($e_c(k)$ are defined as the crisp values of error and change of error and G_e, G_{ce} are their scaling factors. And P is the performance measure.

For use in the adaptive controller, the output of the performance monitor is not given as a value of the performance, but as a value for the correction required at the process-output to obtain good performance. For example, the rules given above can be rewritten, as rules describing the changes required achieving good performance: -

if e is VERY LARGE and Δe is NEGATIVE VERY LARGE then C is ZERO

if e is VERY LARGE and Δe is VERY LARGE then C is NEGATIVE VERY LARGE

Where C is the required correction. In other words, if the process output is a long way from set-point, but is moving rapidly towards set-point, then no change is required as the process is already moving as fast as possible towards its set-point. If, on the other hand, the error is large and is growing rapidly, then a large change is required to get the process at least moving towards its set point. The decision table shown in Table 1 describes the entire performance monitor. The table entries are the required changes in the process-output. (Notation: Z = zero, S = small, M = medium, L = large, V = very, P = positive, N = negative)

Table 1 Performance monitor decision table

E \ CE	NVL	NL	NM	NS	NVS	Z	PVS	PS	PM	PL	PVL
NVL	Z	Z	Z	Z	Z	PVL	PVL	PVL	PVL	PVL	PVL
NL	Z	Z	PM	PM	PM	PVL	PVL	PVL	PVL	PVL	PVL
NM	Z	Z	PM	PM	PL	PL	PL	PL	PL	PL	PVL
NS	Z	Z	Z	Z	PM	PS	PS	PS	PM	PL	PL
NVS	Z	Z	Z	Z	Z	Z	Z	Z	PS	PM	PL
Z	Z	Z	Z	Z	Z	Z	Z	Z	NS	NM	NL
PVS	Z	Z	Z	Z	Z	NS	NS	NS	NM	NL	NL
PS	Z	Z	NM	Z	Z	NM	NM	NM	NM	NL	NVL
PM	Z	Z	NM	NM	NM	NL	NL	NL	NL	NL	NVL
PL	Z	Z	NM	NM	NM	NVL	NVL	NVL	NVL	NVL	NVL
PVL	Z	Z	Z	Z	Z	NVL	NVL	NVL	NVL	NVL	NVL

Modification Algorithm

Consider the inputs to the controller to be e(k) and Δe(k), and the input to the process to be u(k). At some instant k the process input rewards is pi(k) and if the process input r samples earlier (delay) contributed most to the present state then the controller output due to the measurements e(k-r) and Δe(k-r) should have been u(k-r)+pi (k) rather than u(k-r). The rule modification can be approached by forming fuzzy sets around the above single values:-

$E(k\text{-}r) = F_z\{e(k\text{-}r)\};$

$\Delta E(k\text{-}r) = F_z\{\Delta e(k\text{-}r)\};$

$U(k\text{-}r) = F_z\{u(k\text{-}r)\};$

$V(k\text{-}r) = F_z\{u(k\text{-}r) + p_i(k)\};$

Where, F_z represents a fuzzification procedure. Therefore, the controller is modified by replacing the rule that most contributed to the process input r samples earlier:-

if < e is E(n-r) and Δe is ΔE(n-r)> Then < u is U(n-r)>

With the new rule:

if < e is E(n-r) and Δe is ΔE(n-r)> Then < u is V(n-r)>

It is apparent that the above procedure can be used to generate rules from an 'empty' controller (with no initial rules). To avoid contradictory rules any rules with similar antecedents to the above must be removed from the rule store. This also removes those rule that most contributed to the control action being rewarded.

To reduce the number of rules generated, the modification algorithm can be adjusted to delete rules unless their antecedents have fuzzy sets displaced along the universe of discourse by more than one support value relative to the antecedent of the rule to be added. This operation can be expressed linguistically as:

Delete all rules that are about the same as the one to be added.

However, this may cause bad response around the desired state, because many of the discrete states of the pervious few samples will be about the same as the present state and therefore the rules generated from them will be deleted. Hence there will be fewer control rules available for control about the origin.

NUMERICAL SIMULATION RESULTS

In the investigation carried out by El-Shal [8], the output was sampled every 25 second and the input was held constant over each sampling interval. The concentration measurement process involves a time delay of 7.5 min. corresponding to 18 sampling intervals. Glucose or insulin solution is infused by a systolic pump into a vein in one of the subjects arms, while a small quantity of blood is withdrawn continuously from the other arm and monitored by an auto-analyzer.

SOFLC of the Gulcoregulatory System (Glucose Tolerance Test)

A SOFLC is proposed to regulate the glucoregulatory system. The controlled output is the glucose concentration and the input is the glucose infusion rate (Gexg). The glucose infusion rate input should take only positive amplitudes due to the physical constraints and hence a minimum value for the glucose infusion rate was used. A triangle membership function with 11 fuzzy sets [PVB, PB, PM, PS, PVS, ZE, NVS, NS, NM, NB, NVB] was used for fuzzifing the error, change of error and the control action [9]. Also a decision table for the performance monitor as shown in Table 1 was used [10,11].

Figure 2, shows the blood glucose response and the glucose infusion rate to step change (with unity reference). From the figure, it is clear that the designed controller was capable of producing different responses, and with small settling time. Also the controller is succeeded in raising the blood glucose to the required level with zero steady state error. But the critical damped response with settling 100 min. is the more suitable one with scaling factors for the error, derivative of the error and the control input are used with values 1.28 , 90 , 0.0155 respectively.

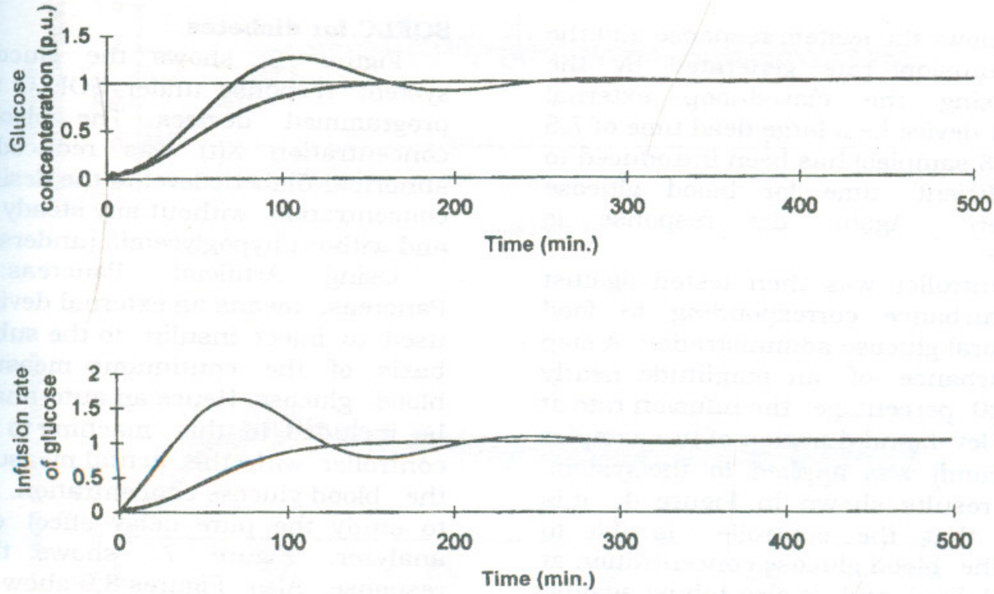

Figure 2 Different system responses under SOFLC (injection with glucose)

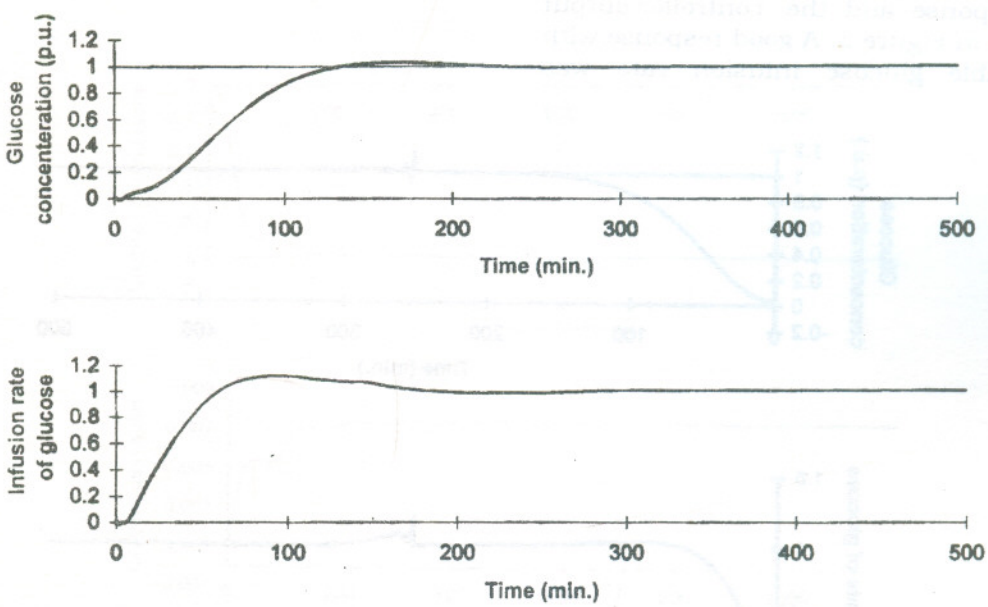

Figure 3 Different system responses under SOFLC (injection with glucose)

Figure 3, shows the system response and the glucose infusion rate generated by the SOFLC using the closed-loop external mechanical device i.e a large dead time of 7.5 minutes (18 samples) has been introduced to allow sufficient time for blood glucose measurement. Again the response is appropriate.

The controller was then tested against load disturbance corresponding to food intake or oral glucose administration. A step load disturbance of an amplitude nearly equal to 20 percentage the infusion rate at the raised level, and duration of two samples (i.e 50 second) was applied to the system. From the results shown in Figure 4, it is concluded that the controller is able to maintain the blood glucose concentration at the desired level and is also robust against sever load disturbances.

To represent the sensor noise a white Gaussian noise with zero mean and a variance of 0.1 was added to the system. The system response and the controller output are shown in Figure 5. A good response with a reasonable glucose infusion rate was obtained.

SOFLC for diabetes

Figure 6, shows the glucoregulatory system response under SOFLC using pre-programmed devices. The blood glucose concentration X(t) was reduced from the abnormal diabetic level to the desired normal concentration without any steady state error and without hypoglycemia (undershoot).

Using Artificial Pancreas: Artificial Pancreas, means an external device which is used to inject insulin to the subject on the basis of the continuous measurement of blood glucose. Hence an auto-analyzer must be included in this machine to provide the controller with the actual measurements of the blood glucose concentration. So we have to study the pure delay effect of the auto-analyzer. Figure 7, shows the system response. Also Figures 8,9 show the system response for the load and the measurement noise disturbances respectively. A good regulation of blood glucose concentration has been achieved.

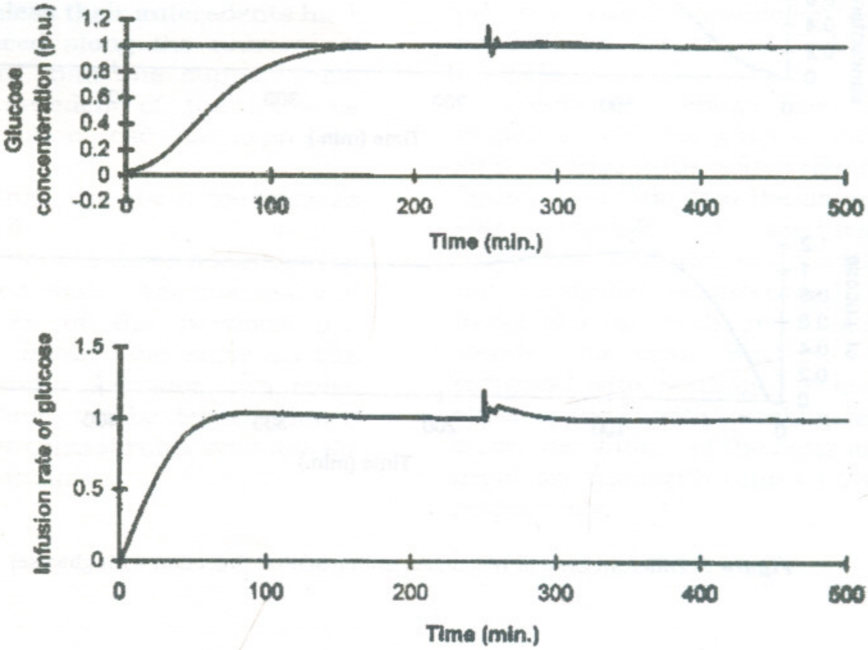

Figure 4 Step load disturbance effect (injection with glucose)

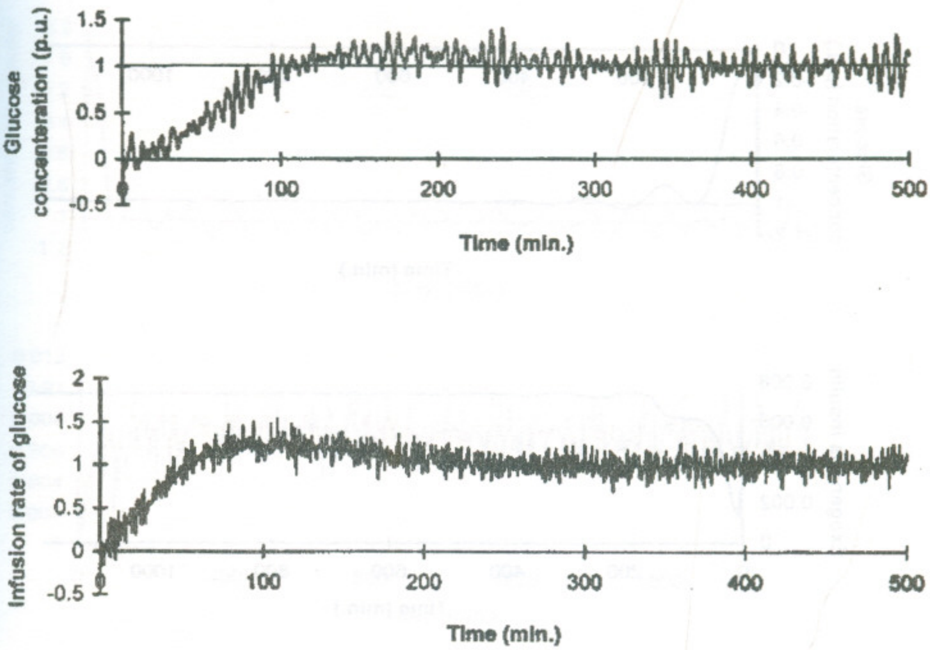

Figure 5 Measurement noise effect, N (0, 0.1)

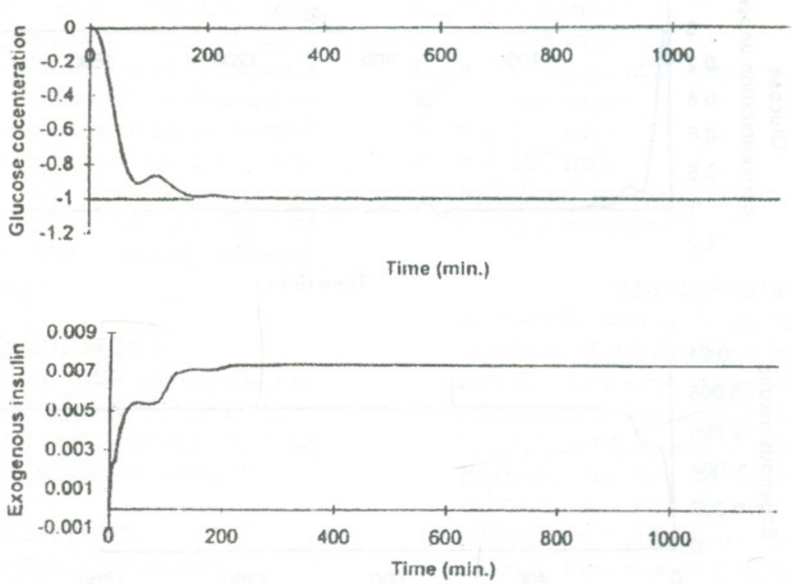

Figure 6 SOFLC for the diabetic subject (preprogrammed case)

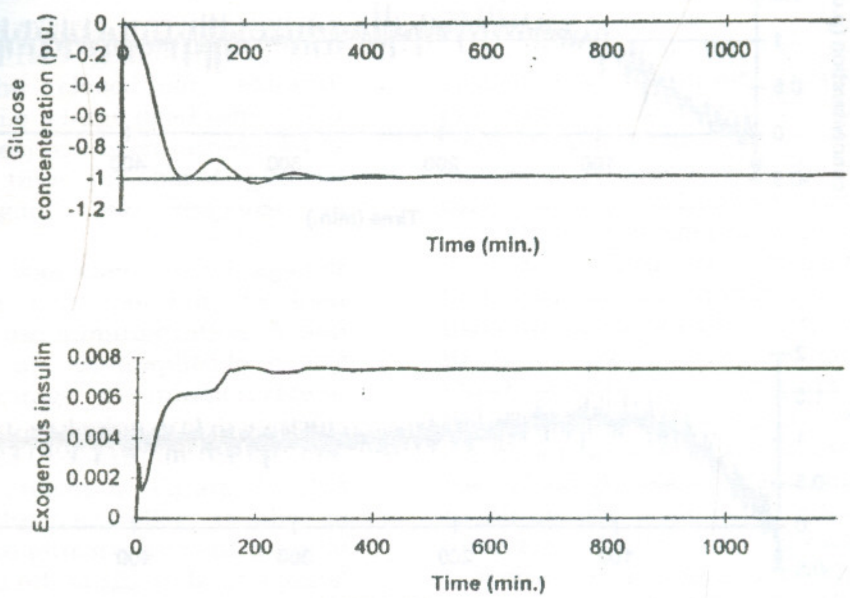

Figure 7 System response using artificial pancreas

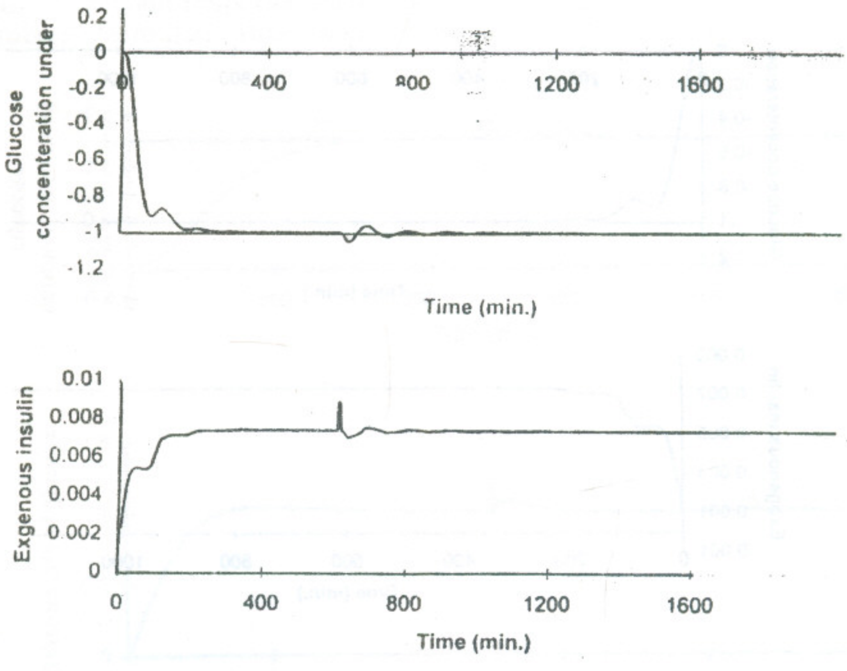

Figure 8 Step load disturbance effect

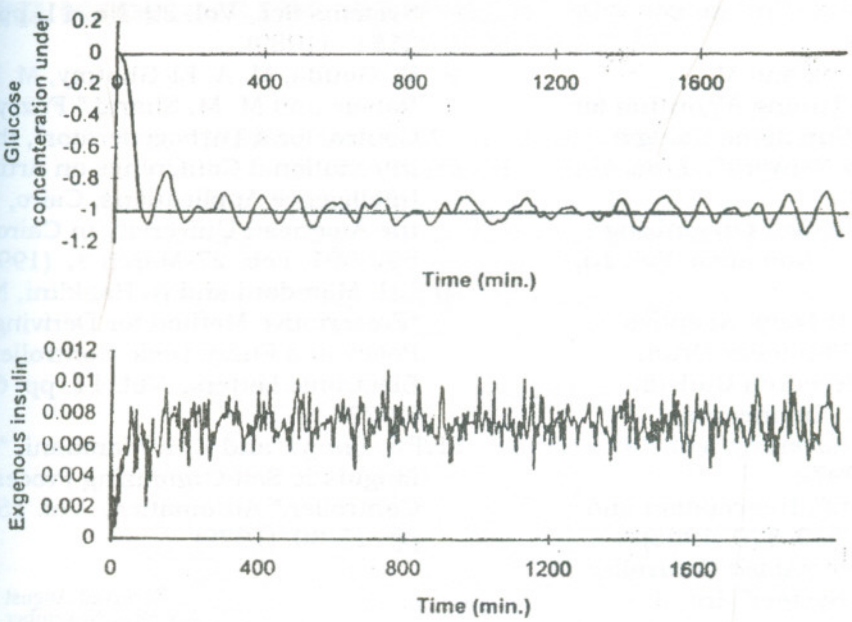

Figure 9 Measurement noise effect, N (0, 0.11)

CONCLUSIONS

An open loop and closed loop electromechanical devices were used successfully for the regulation of blood on a fourth order model. A SOFLC was used as the control algorithm needed to inject proper rates of external glucose or insulin. The results show that, in the presence of disturbances due to food intake or measurement noise the control scheme works with high efficiency.

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NOMENCLATURE

b_0 Endogenous glusoe provision.
b_1 Amplification constant.
b_2, k_0 ,
k_1, k_2 Rate constants.
b_3 Dose-effect ratio
a_1, a_2 Natural Pancreas control parameters

and

b_0 = 8.0 mg . kg $^{-1}$
b_1 = 0.018 min^{-1}
b_2 = 0.094 min^{-1}
b_3 = -1.74 mg . mU^{-1}. min^{-1}
k_0 = 0.056 min^{-1}
k_1 = 0.350 min^{-1}
k_2 = 0.150 min^{-1}
a_1 = 19.6 mU(mmol/l)$^{-1}$. min^{-1}
a_2 = 198.2 mU(mmol/l)$^{-1}$

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التحكم اللفظى ذاتى الإنضباط لتنظيم الجلوكوز فى الكائن الحى

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ملخص البحث

فى هذا البحث تم استخدام التحكم اللفظى ذاتى الإنضباط لتنظيم نسبة السكر فى الدم للكائن الحى. وللمحاكاة تم إستخدام نظام خطى رباعى الرتبة لتمثيل النظام. ونظرا لخاصية بطئ ديناميكية النظام قد تم إختيار زمن العينة كبير.

وتنقسم طريقة التحكم من حيث العنصر المستخدم فى عملية الحقن الى نوعين أحدهما نظام تحكم المسار المفتوح والأخر نظام تحكم المسار المغلق. وفى هذا النوع تتم عملية حقن الجلوكوز او الإنسولين عن طريق برنامج محدد وموضوع مسبقا. وفى النوع الثانى تتم عملية الحقن بناءا على عملية قياسات مستمرة لنسبة السكر فى الدم. وفى هذه الحاله لابد ان نأخذ فى إشارات العشوائية وزمن التأخير الناتجين عن عملية القياسات وعن استخدام الحساس.

وفى هذا البحث تم هاتين الطريقتين إما لعمل إختبار التفاوت الجلوكوزى أو لضبط مستوى السكر فى الدم عند الحد الطبيعى أثناء وبعد إجراء العمليات الجراحية والتى لايستطيع المريض فيها أن يأكل بصورة طبيعية أو لضبط مستوى السكر فى الدم عند مرضى السكر وقد تم تطبيق طريقة التحكم اللفظى ذاتى الإنضباط. وباستخدام تغيير قواعد التحكم اللفظية بناء على معدل الأداء كخوارزم لتحديد معدل الحقن اللازم من الجلوكوز أو الانسولين.

وقد تم إختبار المحاكى بنجاح وإثبات فاعليته ويعتبر من أنسب الطرق القادرة على تنظيم السكر فى الدم ومحاكاة الوظائف الحيوية للبنكرياس الطبيعى فى الإنسان.