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(54) FULLY AUTOMATED CONTROL SYSTEM FOR TYPE 1 DIABETES

VOLLAUTOMATISCHES KONTROLLSYSTEM FÜR DIABETES TYP 1

SYSTEME DE CONTROLE ENTIEREMENT AUTOMATISE DU DIABETE DE TYPE 1

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Description

BACKGROUND

[0001] Type 1 diabetes is a chronic, life-threatening disease that is caused by failure of the pancreas to deliver the hormone insulin, which is otherwise made and secreted by the beta cells of the pancreatic islets of Langerhans. Insulin opens receptors on the cell surfaces, thereby regulating inflow of blood glucose, an essential cell nutrient. With the resulting absence of endogenous insulin, people with type 1 diabetes cannot regulate their blood glucose to euglycemic range without exogenous insulin administration. However, it is critical to provide accurate insulin dosing, so as to minimize and whenever possible eliminate low or high blood glucose levels. Both high glucose levels, known as hyperglycemia, and low glucose levels, known as hypoglycemia, can have debilitating and deleterious consequences. Hypoglycemia may result in a coma and can cause acute complications, including brain damage and paralysis. While severe hyperglycemia can also result in a coma, mild chronic hyperglycemia potentially results in long-term, deleterious, and even life-threatening complications, such as vascular disease, renal complications, vision problems, nerve degeneration, and skin disorders.

[0002] In practice, it has been necessary for people with type 1 diabetes to monitor their blood glucose and administer exogenous insulin several times a day in a relentless effort to maintain their blood glucose near euglycemic range. This is a demanding, painstaking regimen. Even those who successfully adhere to the regimen are burdened by it to varying degrees and often still struggle with maintaining good glycemic control. Those who do not follow a regimen are at risk for severe complications.

[0003] US 2003/0208113 A1 discloses a system for assisting a person to maintain a blood glucose level between predetermined limits. The system comprises an electronic device comprising a display, a clock, a memory, and a processor. The system comprises a software program executable by the processor of the electronic device, adapted to receive nutritional data of food consumed by the person, adapted to calculate the blood glucose level for the person using the nutritional data and a glycemic response model for the person, and further adapted to present the blood glucose level to the person on the display of the electronic device.

[0004] US 2004/0028707 A1 discloses a method for administration of a substance into the dermis of a mammal.

[0005] US 4 280 494 A discloses an automatic feedback controlled administration of drugs. Z. Trajanoski et al., "Neural predictive controller for insulin delivery using the subcutaneous route", IEEE Transactions on Biomedical Engineering, Volume 45, Issue 9, Sept. 1998, pages 1122 - 1134 discloses a neural predictive controller for closed-loop control of glucose using subcutaneous tissue glucose measurement and subcutaneous infusion of monomeric insulin analogs. The control strategy is based on off-line system identification using neural networks and nonlinear model predictive controller design. Additional action from the patient at meal time is necessary.

[0006] US 6 852 104 B1 discloses an apparatus for delivering a bolus of a medical agent to a patient. The apparatus comprises a pump mechanism, a data input device, and a processor in data communication with the keypad and arranged to control the pump mechanism. The processor is programmed to receive data specifying a bolus amount through the data port, receive data regarding duration through the data port, receive a percentage through the data port, the percentage defining a portion of the bolus amount to deliver immediately upon executing a deliver command and a remainder of the bolus amount to deliver over the duration upon executing a deliver command, and execute the deliver command thereby controlling the pump mechanism to deliver the bolus.

SUMMARY

[0007] It would be desirable to reduce the burdens associated with monitoring blood glucose levels and administering exogenous insulin, as well as to better regulate blood glucose levels of those with type 1 diabetes and avoid the complications of hyper- and hypoglycemic conditions.

[0008] According to the invention, a controller and method as defined by the independent claims are provided. The dependent claims define embodiments.

[0009] A disclosed closed-loop control system automatically commands delivery of insulin based on glucose measurements. Since slight overdosing of insulin is possible during online operation of such a system, an agent having a counter-regulatory effect to insulin action, such as a hormone known as glucagon, is also made available for delivery by the system.

[0010] In a disclosed automated control system for type 1 diabetes, an adaptive algorithm utilizing model predictive control (MPC) is employed. An input-output subject model is used in conjunction with the MPC algorithm to regulate blood glucose online, where the subject model is recursively adapted, and the delivery of insulin is based solely on online glucose concentration measurements. An MPC signal is synthesized by optimizing an objective function that regulates glucose concentration to a preset reference set point while simultaneously minimizing both the control signal aggressiveness and local insulin accumulation in the subcutaneous space or "depot" that receives the infused insulin. A math-

ematical formulation describing the subcutaneous accumulation of administered insulin is derived based on nominal temporal values pertaining to the pharmacokinetics (time-course of activity) of insulin in human, in terms of its absorption rate, peak absorption time, and overall time of action. The MPC algorithm also provides control action with an integral effect, and in essence minimizes overall drug consumption. The control algorithm provides the automated glucose-control system with self-learning capability that enables it to operate under unrestricted activity of the subject.

[0011] The subject model may be an empirical subject model, which may initially be constructed based on a system identification process performed on input-output data obtained from open-loop glycemic control of the subject. The controller may be further operative to generate the insulin control signal to provide a basal rate of delivery of insulin when the model-predictive control algorithm reveals no need for a corrective dose of insulin.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The foregoing and other objects, features and advantages of the invention will be apparent from the following description of particular embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

Figure 1 is a block diagram of a fully automated control system for type 1 diabetes in accordance with the present invention;

Figure 2 is a functional block diagram of a controller in the system of Figure 1;

Figure 3 is a flow diagram depicting the operation of the system of Figure 1, including details of the operation of the controller of Figure 2; and

Figure 4 is a flow diagram depicting a particular implementation of a control step of Figure 3.

DETAILED DESCRIPTION

[0013] Figure 1 illustrates an automated control system 10 for regulating the blood glucose level of an animal subject (subject) 12, which maybe a human. The subject 12 receives doses of insulin from a delivery device 14, which may be an infusion pump coupled by a catheter to a subcutaneous space of the subject 12 for example. As described below, the delivery device 14 may also deliver a counter-regulatory agent such as glucagon for more effective control of blood glucose level under certain circumstances. In the present description, reference is made to glucagon specifically, but it is to be understood that this is for convenience only and that other counter-regulatory agents may be used. For the delivery of both insulin and glucagon, the delivery device 14 is preferably a mechanically driven infusion mechanism having dual cartridges for insulin and glucagon respectively

[0014] A glucose sensor 16 is operatively coupled to the subject 12 to continually sample a glucose level of the subject 12. Sensing may be accomplished in a variety of ways. A controller 18 controls operation of the delivery device 14 as a function of a glucose level signal from the glucose sensor 16 and subject to user-provided parameters. One feature of the disclosed technique is its ability to perform without receiving explicit information regarding either meals that the subject 12 has ingested or any other "feedforward" information. One necessary user-provided initialization parameter is the weight of the subject 12. Another user-provided parameter is a "setpoint" which, as described below, establishes a target blood glucose level that the system 10 strives to maintain.

[0015] Figure 2 shows a functional block diagram of the controller 18, specifically a high-level depiction of a control algorithm that is executed by software/firmware within the controller 18. As shown, a dose control signal u(t) is generated by an objective function optimizer 20 which receives as one input a setpoint signal r(t+k), which may be constant (independent of time). The dose control signal u(t) controls the operation of the insulin-glucagon delivery device (delivery device) 14 of Figure 1. The input dose control signal u(t) is also provided to a subject model 22 which, as described in more detail below, explicitly models the response of the subject 12 to delivery of insulin and/or glucagon. The subject model 22 also receives an actual glucose level signal y(t) from sensor 16, and generates a predicted future glucose level signal $\hat{y}(t+k|t)$ that is used in the operation of the objective function optimizer 18.

[0016] During operation, the dose control signal u(t) and actual glucose level signal y(t) are continually fed into the subject model 22, thereby internally updating the subject model 22 and generating updated output predictions $\hat{y}(t+k|t)$. By comparison with desired future reference setpoint values r(t+k), the objective function optimizer 20 computes future error signals which are used to synthesize the dose control signal u(t) in an optimizing fashion based on a model predictive control (MPC) algorithm. An amount of insulin or glucagon corresponding to the input signal u(t) is physically administered to the subject 12 via the delivery device 14 and is also passed to the subject model 22. The glucose sensor 16 provides the latest measurement y(t) to complete the cycle, which is then executed anew.

[0017] The function of the subject model 22 is to predict future blood glucose levels based on current and past values of the signals u(t) and y(t). There are a variety of models that can be employed. The following describes one particular

embodiment for the subject model.

[0018] An option for the subject model is one of an empirical form, which may be obtained by system identification performed on input-output data generated from open-loop glycemie control of the subject. The subject model could be of a single-Input single-output, auto-regressive moving average with exogenous input (ARMAX) structure, with the representation

$$A(z^{-1})\,y_t = z^{-d}\,B(z^{-1})\,u_t + C(z^{-1})\,w_t, \qquad (1)$$

where u_t denotes the (input) insulin-glucagon doses, y_t denotes the (output) glucose concentration deviation from the reference set point, w_t is a white Gaussian noise sequence, d is the inherent system time-delay (dead-time), z^{-1} plays the role of the unit delay shift operator, and the scalar polynomials A, B, C are given by

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \ldots + a_n z^{-n},$$

$$B(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots + b_m z^{-m},$$

$$C(z^{-1}) = 1 + c_1 z^{-1} + c_2 z^{-2} + \ldots + c_p z^{-p},$$

[0019] The model's orders and delay may be determined beforehand from the offline system identification analysis. The identified model is then employed in the online integrated control system, except that the model parameters are not statically stipulated, but are dynamic (free), in the sense that they are recursively updated. Recursive (online) parameter estimation of a model such as (1) may be facilitated by re-writing the model in regressor form, namely as

$$y_t = \theta^T \psi_t + w_t, \qquad (2)$$

where the the regressor ψ_t and θ are respectively given by

$$\begin{aligned} \psi_t &:= [-y_{t-1} \ldots -y_{t-n}\ u_{t-d} \ldots u_{t-d-m}\ w_{t-1} \ldots w_{t-p}]^T \\ \theta &:= [a_1 \ldots a_n\ b_0 \ldots b_m\ c_1 \ldots c_p]^T. \end{aligned} \qquad (3)$$

With online parameter estimates packed in a time-varying version of vector 0, namely θ_t, and the estimate $w_t := y_t - \psi_t^T \theta_t$ used in ψ_t, one popular recursive estimation scheme is the Extended Least Squares , which follows the scheme

$$\theta_t = \theta_{t-1} + \frac{P_{t-1}\psi_t}{1 + \psi_t^T P_{t-1} \psi_t}\, e_t \qquad (4)$$

$$P_t = P_{t-1} - \frac{P_{t-1}\psi_t \psi_t^T P_{t-1}}{1 + \psi_t^T P_{t-1} \psi_t}, \qquad (5)$$

where $e_t := y_t - \psi_t^T \theta_{t-1}$, and P_0 is taken to be a positive definite matrix. Another option for recursive parameter estimation is the Recursive Maximum Likelihood estimation method, which is similar to the Extended Least Squares, except that $\varphi_t := \psi_t / C(z^{-1})$ is used in lieu of ψ_t. Other recursive (online) parameter-estimation schemes may also be used, such as the Instrumental Variable method, the Gradient estimation method, or alternate versions of these estimators that use a forgetting factor, to mention but a few options known to those skilled in the art. Regardless of the scheme used, the adaptive subject model can be used to make online predictions of glucose concentrations and can be inherently employed by the controller block in generating the control signal.

[0020] The function of the objective function optimizer 20 is to generate the insulin and glucagon control signals u(t) in an optimized fashion based in part on the predicted blood glucose levels $\hat{y}(t+k|t)$ from the subject model 22. There

are a variety of optimization techniques that can be used. The following describes one particular embodiment of the objective function optimizer 20, which is also referred to as the "controller block" in the following description. The embodiment described below uses a model-predictive control (MPC) strategy.

[0021] The controller block may use one or more of the many MPC strategies, which all (1) make use of a mathematical model to predict the output at future time instants (horizon), (2) compute the control signal that optimizes an objective function at each step, and (3) employ a receding horizon strategy. The latter aspect refers to *repeatedly* displacing the prediction horizon towards the future, while only applying the *first* control signal in the calculated sequence at each step.

[0022] One popular MPC algorithm, compatible with an ARMAX subject model, is the Generalized Predictive Control (GPC) algorithm, which optimizes the mutli-stage quadratic cost function given by

$$J_{GPC} = \sum_{k=N_d}^{N_m} \delta_k \left\| C\left(r_{t+k} - y_{t+k}\right)\right\|^2 + \sum_{k=0}^{N_u} \lambda_k \left(\Delta u_{t+k}\right)^2, \qquad (6)$$

where N_d and N_m are respectively the minimum and maximum (output) prediction costing horizon limits, N_u the control horizon bound, δ_m the weighting on prediction error, and λ_n the weighting on control signals. Some general guidelines in GPC implementation include (1) $N_d \geq$ d, since earlier outputs are not influenced by the current input signal, (2) the output horizon, $N_y := N_m - N_d$, covering a substantial portion of the response rise time due to $u(t|t)$, and (3) $N_y \geq N_u$, with $N_u = 0$ or square horizons, i.e $N_y = N_u$, popularly enforced.

[0023] For control action with integral effect, predictor and control design are based on

$$A(z^{-1})\, y_t = z^{-k}\, B(z^{-1})\, u_t + C(z^{-1})\, w_t/\Delta, \qquad (7)$$

with the corresponding Diophantine separation identity given by

$$\frac{C}{A\Delta} = E_k + z^{-k}\, \frac{F_k}{A\Delta}, \qquad (8)$$

where F_k is the remainder polynomial corresponding to the *monic* quotient polynomial E_k, the former and latter of respective orders n and k-1 in z^{-1}, or specifically, $F_k = f_0 + f_1 z^{-1} + \ldots + f_n z^{-n}$ and $E_k = 1 + e_1 z^{-1} + \ldots + e_{k-1} z^{-(k-1)}$. The best predictor $\acute{y}_{t|t-k}$ is then defined to satisfy

$$y_t = \hat{y}_{t|t-k} + E_k\, w_t, \qquad (9)$$

which yields

$$C\, \hat{y}_{t+k|t} = G_k\, \Delta\, u_{t+k-d} + F_k\, y_t, \qquad (10)$$

where $G_k := E_k B$. Note that G_k is order (m+k-1) in z^{-1}, and can be written as $G_k = g_0 + g_1 z^{-1} + \ldots + g_{m+k-1} z^{-(m+k-1)}$, with $g_0 = b_0$, since E_k is monic $\forall$ k. To implement the GPC aglorithm, we re-write (.10) as

$$C\, \hat{y}_{t+k|t} = \sum_{i=0}^{k-d} g_i\, z^{-i} \Delta\, u_{t+k-d} + \left(G_k - \sum_{i=0}^{k-d} g_i\, z^{-i}\right) \Delta\, u_{t+k-d} + F_k\, y_t, \qquad (11)$$

where the first term on the right-hand side contains the only k-d future-terms (containing the sought control signal) for any k. Taking $N_d = d$ and $N_y + 1 = N_u + 1 =: N$, i.e. square prediction and control horizons of N steps, we apply (11) over $k = d \rightarrow (N_y + d)$, and pack term contributions in the matrix-form equation given by

$$\boldsymbol{y} = \boldsymbol{G}\, \boldsymbol{u} + \boldsymbol{G'}\, \boldsymbol{u} + \boldsymbol{F}\, y_t, \qquad (12)$$

where

$$\boldsymbol{y} = \begin{bmatrix} C\,\hat{y}_{t+d|t} \\ C\,\hat{y}_{t+d+1|t} \\ \cdot \\ \cdot \\ \cdot \\ C\,\hat{y}_{t+N+d-1|t} \end{bmatrix}_{N\times 1} \quad \boldsymbol{G} = \begin{bmatrix} g_0 & 0 & 0 & \cdot & \cdot & \cdot \\ g_1 & g_0 & 0 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & 0 \\ g_{N-1} & g_{N-2} & \cdot & \cdot & \cdot & g_0 \end{bmatrix}_{N\times N} \quad \boldsymbol{u} = \begin{bmatrix} \Delta u_t \\ \Delta u_{t+1} \\ \cdot \\ \cdot \\ \cdot \\ \Delta u_{t+N-1} \end{bmatrix}_{N\times 1}$$

$$\boldsymbol{G'u} = \begin{bmatrix} (G_d - \sum_{i=0}^{0} g_i z^{-i})\,\Delta u_t \\ (G_{d+1} - \sum_{i=0}^{1} g_i z^{-i})\,\Delta u_{t+1} \\ \cdot \\ \cdot \\ \cdot \\ (G_{N+d-1} - \sum_{i=0}^{N-1} g_i z^{-i})\,\Delta u_{t+N-1} \end{bmatrix}_{N\times 1} \quad \boldsymbol{F} = \begin{bmatrix} F_d \\ F_{d+1} \\ \cdot \\ \cdot \\ \cdot \\ F_{N+d-1} \end{bmatrix}_{N\times 1}.$$

[0024] The last two quantities in (12) are available at time *t*, as they are either directly measurable or depend only on past measurements, and can be grouped into a vector f, leading to:

$$\boldsymbol{y} = \boldsymbol{G}\,\boldsymbol{u} + \boldsymbol{f}, \tag{13}$$

With δ_m = 1 and $\lambda_n = \lambda$, (6) can be re-written as

$$J_{\mathrm{GPC}} = (\boldsymbol{G} + \boldsymbol{f} - \boldsymbol{r})^T (\boldsymbol{G} + \boldsymbol{f} - \boldsymbol{r}) + \lambda \boldsymbol{u}^T \boldsymbol{u}, \tag{14}$$

where *r* is the vector holding future set points as $r = [Cr_{t+d}\ Cr_{t+d+1}\ \ldots\ Cr_t{+}N{+}d{-}1]^T$. Further manipulation of (14) leads to

$$J_{\mathrm{GPC}} = \tfrac{1}{2}\,\boldsymbol{u}^T \boldsymbol{H} \boldsymbol{u} + \boldsymbol{b}^T \boldsymbol{u} + \boldsymbol{f}_0, \tag{15}$$

where

$$\boldsymbol{H} = 2(\boldsymbol{G}^T \boldsymbol{G} + \lambda \boldsymbol{I}); \qquad \boldsymbol{b}^T = 2(\boldsymbol{f} - \boldsymbol{r})^T \boldsymbol{G}; \qquad \boldsymbol{f}_0 = (\boldsymbol{f} - \boldsymbol{r})^T (\boldsymbol{f} - \boldsymbol{r}).$$

[0025] The unconstrained vector u minimizing J_{GPC} can be found by inspection of (15), and is given by

$$\boldsymbol{u}_{\mathrm{GPC}} = -\boldsymbol{H}^{-1}\boldsymbol{b} = (\boldsymbol{G}^T \boldsymbol{G} + \lambda \boldsymbol{I})^{-1} \boldsymbol{G}^T (\boldsymbol{r} - \boldsymbol{f}). \tag{16}$$

Since $G^TG \geq 0$, (16) gives a unique solution, provided $\lambda > 0$. Only the first control move is of interest at *t*, namely

$$\Delta u_t = [1\ 0\ 0\ \ldots\ 0]\,(\boldsymbol{G}^T \boldsymbol{G} + \lambda \boldsymbol{I})^{-1} \boldsymbol{G}^T (\boldsymbol{r} - \boldsymbol{f}). \tag{17}$$

[0026] The control increment or move in (17) is thus zero if the current situation and desired outcome coincide, that is if *r* - *f* = 0, as it should. Finally, to deal with non-square horizons, which would only be permissible for $N_u < N_y$, *G* is replaced G_{Nu}, where G_{Nu} is composed of the first N_u+1 columns of *G*, and u is replaced by u_{Nu}, which contains the first N_u+1 elements of *u*, with everything else kept the same. Note that the Generalized Minimum Variance (GMV) control, with $N_y = N_u = N - 1 = 0$, is a special instance of GPC with square horizons.

[0027] In the case of subcutaneous drug administration, drug accumulation in the subcutaneous depot (typically that of insulin) can be augmented to the raw control cost function of (6), and viewed as an additional control objective in the optimization process. The resultant online control signal simultaneously (1) optmizes the controller's aggressiveness, (2) minimizes insulin accumulation in the subcutaneous depot, and (3) regulates glucose concentration to a preset set point target value. The mathematical formulation governing the subcutaneous accumulation of administered insulin can be derived based on nominal temporal values pertaining to its pharmacokinetics (time-course of activity), in terms of its absorption rate, peak absorption time, and overall time of action (perfusion intro plasma). If *p*(*t*) is the concentration, in

mU/dl, of the drug in plasma as it is absorbed from the subcutaneous depot, its evolution can be taken to be governed by

$$p(t) = K\,U_0\,(e^{-\alpha_1 t} - e^{-\alpha_2 t}). \tag{18}$$

where U_0 is the subcutaneous-drug impulse dose in units (U), and K, α_1, and α_2 are positive constants. A measure of the pending effect of the accumulated amount of insulin in the SC depot can be taken to be the difference between the total area ($\int_0^\infty p(t)\,\mathrm{d}t$, i.e. a measure of the total action over time due to dose U_0) and $\int_0^t p(t)\,\mathrm{d}t$, i.e. a measure of the expanded portion of U_0. With the measure of the lingering effect of the outstanding quantity of insulin in the SC depot denoted by $q(t)$, we arrive at

$$q(t) := \int_0^\infty p(t)\,\mathrm{d}t - \int_0^t p(t)\,\mathrm{d}t = \frac{K\,U_0}{\alpha_1\,\alpha_2}\,(\alpha_2\,e^{-\alpha_1 t} - \alpha_1\,e^{-\alpha_2 t}), \tag{19}$$

As a discrete-time model, this can be written as

$$\begin{aligned} q_k &= (e^{-\alpha_1 T_s} + e^{-\alpha_2 T_s})q_{k-1} - e^{-(\alpha_1+\alpha_2)T_s} q_{k-2} + \frac{K}{\alpha_1\,\alpha_2}\,(\alpha_2 - \alpha_1)u_{k-d_q} \\ &\quad + \frac{K}{\alpha_1\,\alpha_2}\,(\alpha_1\,e^{-\alpha_1 T_s} - \alpha_2\,e^{-\alpha_2 T_s})u_{k-d_q-1} \\ &=: -a_{1q}\,q_{k-1} - a_{2q}\,q_{k-2} + b_{1q}\,u_{k-d_q} + b_{2q}\,u_{k-d_q-1}, \end{aligned} \tag{20}$$

where T_s is the sampling period. Incidently, IV dosing may be perceived as bypassing the SC depot, i.e. for an IV drug dose, $q(t) = 0$ in (19) and $q_k = 0$ in (20), as if there were zero peak ($\alpha_2 \to \infty$) and zero depletion or consumption times ($\alpha_1 \to \infty$) from the SC depot into plasma, with coinciding values for α_1 and α_2. Before augmenting (20) to the original discrete-time model of (1), whose inherent units are mg/dl, we non-dimensionalize (20) and re-scale it to switch its inherent units from mU min/dl to mg/dl, so that control signal computation (optimization) is performed on an overall homogenous (augmented) system. An overall scaling factor to operate on (20) can be obtained from the steady-state effect of an impulse dose on blood glucose, taken to vary as per a scaled integration of (18). As such, the scaling factor, $s_f = \frac{y_\infty\,\alpha_1\,\alpha_2}{U_0\,K(\alpha_2-\alpha_1)}$ [1], in mg/(mU min), where y_∞ is the steady-state excursion (offset from reference) in blood glucose per unit impulse dose U_0, can be used. The steady-state blood-glucose value, y_∞, can be approximated from the pharmacodynamics of insulin, which is available in the literature. Augmenting the scaled q_k-system of (20) to the original y_k-system of (1), we obtain the single-input multiple-output model given by

$$\boldsymbol{A}(z^{-1})\,\boldsymbol{y}_k = z^{-d}\,\boldsymbol{B}(z^{-1})\,u_k + \boldsymbol{C}(z^{-1})\,\boldsymbol{w}_k, \tag{21}$$

where $\boldsymbol{y}_k = [y_k\ s_f\,q_k]^T$, $\boldsymbol{w}_k$ is a vector of two white-noise sequences, and

$$\begin{aligned} \boldsymbol{A}(z^{-1}) &= \boldsymbol{I}_{2x2} + \boldsymbol{A}_1\,z^{-1} + \boldsymbol{A}_2\,z^{-2} + \ldots + \boldsymbol{A}_n\,z^{-n}, \\ \boldsymbol{B}(z^{-1}) &= \boldsymbol{B}_0 + \boldsymbol{B}_1\,z^{-1} + \boldsymbol{B}_2\,z^{-2} + \ldots + \boldsymbol{B}_m\,z^{-m}, \\ \boldsymbol{C}(z^{-1}) &= \boldsymbol{I}_{2x2} + \boldsymbol{C}_1\,z^{-1} + \boldsymbol{C}_2\,z^{-2} + \ldots + \boldsymbol{C}_p\,z^{-p}, \end{aligned}$$

with

$$\boldsymbol{A}_1 = \begin{bmatrix} a_1 & 0 \\ 0 & a_{1q} \end{bmatrix},\quad \boldsymbol{A}_2 = \begin{bmatrix} a_i & 0 \\ 0 & a_{2q} \end{bmatrix}\quad \boldsymbol{A}_i = \begin{bmatrix} a_i & 0 \\ 0 & 0 \end{bmatrix}\quad \forall\, i > 2,$$

[1] Scaling factor s_f provides the proper unit conversion, but can be scaled further by a unitless factor.

$$B_0 = \begin{bmatrix} b_0 \\ s_f b_{1q} \end{bmatrix}, \quad B_1 = \begin{bmatrix} b_0 \\ s_f b_{2q} \end{bmatrix}, \quad B_i = \begin{bmatrix} b_i \\ 0 \end{bmatrix} \ \forall i > 1,$$

$$C_i = \begin{bmatrix} c_i & 0 \\ 0 & 0 \end{bmatrix} \ \forall i > 0,$$

where, for simplicity, the same system delay d of (1) can be assumed between q_k and u_k. Coupling between the two systems, via the same input signal, is relevant when solving for the optimal control signal, whereby matrix G is merely extended to give an analogous matrix, G_e, for the new system, the latter constructed as:

$$G_e = \begin{bmatrix} g_0 & 0 & 0 & \cdot & \cdot & \cdot \\ g_{0q} & 0 & 0 & \cdot & \cdot & \cdot \\ g_1 & g_0 & 0 & \cdot & \cdot & \cdot \\ g_{1q} & g_{0q} & 0 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & 0 \\ g_{N-1} & g_{N-2} & \cdot & \cdot & \cdot & g_0 \\ g_{(N-1)q} & g_{(N-2)q} & \cdot & \cdot & \cdot & g_{0q} \end{bmatrix}_{2N \times N},$$

where the g_{iq}-entries pertain to the g_k-system and are the analogues of the g_i-entries in the y_k-system. Vector f is also adjusted accordingly to yield an extended version, f_e, which is twice in length. The GPC signal is again given by (17), except that G_e (or its first N_u + 1 columns for non-square horizons) and f_e are used in lieu of G and *f* respectively, in addition to using a trivially extended version, r_e, for *r*. The GMV control is recovered by setting $N_y = N_u = N - 1 = 0$.

[0028] The following describes the use of constraints on the control signals u(t):

Constraints on input-output signals may be enforced to limit them to allowable, possibly subjective, fields of action. The output constraints are not usually explicitly contemplated, but rather implicitly enforced via optimizing the cost function. In general, the input constraints can be described by

$$u_{min} \leq u_t \leq u_{max}$$

$$\Delta u_{min} \leq \Delta u_t \leq \Delta u_{max}.$$

Input constraints, such as minimum (basal) and maximum (bolus) doses, or their respective rate of change, may be explicitly enforced, possibly by saturation or clipping. The input constraints may be left for the user to initialize, but may at the same time be stipulated to be less than (and occasionally clipped or overridden by) a maximum allowable value, possibly based on the subject's weight.

[0029] Figure 3 illustrates the overall process by which the system 10 of Figure 1 operates. In step 24, the glucose level of the subject 12 is continually sensed by the glucose sensor 16, which generates a corresponding actual glucose level signal y(t). In step 26, the delivery device 14 operates in response to the insulin/glucagon dose control signal u(t) to deliver corresponding doses of insulin and glucagon to a subcutaneous space of the subject 12.

[0030] In step 28, the controller 18 generates the insulin/glucagon dose control signal u(t) as a function of the weight of the subject 12, the setpoint r(t+k), and time-varying glucose levels of the subject 12 as represented by the actual glucose level signal y(t) over time. Specifically, the controller 18 employs a control algorithm including steps 30 and 32 as shown.

[0031] In step 30, a subject model 16 is utilized to explicitly model response of the subject 12 to delivered doses of insulin and glucagon and thereby generate, based on time-varying values of the actual glucose level signal y(t) and the insulin/glucagon dose control signal u(t), a predicted glucose level signal $\hat{y}(t+k|t)$ representing a predicted glucose level of the subject.

[0032] In step 32, the insulin and glucagon dose control signals u(t) are generated based on (a) a difference between the predicted glucose level signal $\hat{y}(t+k|t)$ and the setpoint signal r(t+k) representing desired future levels of the glucose level of the subject 12, and (b) local accumulation of insulin in the subcutaneous space of the subject 12. This latter

value is tracked according to the pharmacokinetics of insulin as described above.

[0033] Figure 4 illustrates a particular implementation of the general step 32 of Figure 3. In particular, the illustrated embodiment utilizes an MPC control strategy as described above. In step 34, the insulin/glucagon control signal u(t) is generated as optimizing an objective function with objectives of (a) a weighted integration of a difference between the actual glucose level signal y(t) and a predetermined setpoint value over a time horizon, and (b) a weighted integration of the insulin/glucagon control signal u(t) over the time horizon.

[0034] In step 36, the model parameters of the subject model 22 are recursively and continually updated to dynamically adapt the subject model 22 to variations in the response of the subject 12 to the delivered doses of insulin and glucagon.

[0035] It will be appreciated that the present invention maybe embodied as an overall system such as shown in Figure 1, as an overall method, as a controller such as shown in Figure 2, and as a method performed by a controller such as shown in Figure 4. With respect to the method performed by a controller, the method may be performed by computer program instructions executed by generic controller hardware including memory, a processing or execution unit, and input/output circuitry. The instructions may be provided to the controller from a computer-readable medium such as semiconductor memory, magnetic memory (e.g. magnetic disk), optical memory (e.g. optical disk such as CD, DVD), etc.

[0036] While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention as defined by the appended claims.

Claims

1. A controller for use in a system for automatic control of blood glucose level of a subject, the controller being operative to generate an insulin dose control signal based on the weight of the subject and time-varying glucose levels of the subject as represented by an actual glucose level signal over time, the actual glucose level signal being generated by a glucose sensor operative to continually sense a glucose level of the subject, the insulin dose control signal for controlling the delivery of doses of insulin to a subcutaneous space of the subject by a delivery device, the controller employing a control algorithm including:

(1) utilizing a subject model to explicitly model response of the subject to delivered doses of insulin and thereby generate, based on time-varying values of the actual glucose level signal and the insulin dose control signal, a predicted glucose level signal representing a predicted glucose level of the subject; and
(2) generating the insulin dose control signal based on the weight and a difference between the predicted glucose level signal and a setpoint signal representing desired future levels of the glucose level of the subject,

characterized in that
the insulin dose control signal is generated further based on local accumulation of insulin in the subcutaneous space of the subject.

2. A system for automatic control of blood glucose level of a subject, comprising:

a glucose sensor operative to continually sense a glucose level of the subject and generate a corresponding actual glucose level signal;
a delivery device operative to deliver doses of insulin to a subcutaneous space of the subject in response to an insulin dose control signal; and
a controller according to claim 1.

3. A system according to claim 2, wherein the controller employs a model-predictive control algorithm by which the insulin dose control signal is generated as a value optimizing an objective function with objectives of (a) a weighted integration of a difference between the predicted glucose level signal and the setpoint signal over a time horizon, and (b) a weighted integration of the insulin dose control signal over the time horizon.

4. A system according to claim 3, wherein the model-predictive control algorithm is an adaptive model-predictive control algorithm which includes recursively and continually updating model parameters to dynamically adapt the subject model to variations in the response of the subject to the delivered doses of insulin.

5. A system according to claim 3 wherein the objective function also has an objective of (c) minimizing the local accumulation of insulin in the subcutaneous space of the subject.

6. A system according to claim 2 wherein the subject model is an empirical subject model.

7. A system according to claim 6, wherein the empirical subject model is of a type initially constructed based on a system identification process performed on input-output data obtained from open-loop glycemic control of the subject.

8. A system according to claim 2 wherein the controller is further operative to generate the insulin control signal to provide a basal rate of delivery of insulin when the model-predictive control algorithm reveals no need for a corrective dose of insulin.

9. A system according to claim 8 wherein the basal rate is determined by a user-provided basal-rate value.

10. A system according to claim 9 wherein the controller employs a default basal-rate value based on the weight of the subject when the user-provided basal-rate value is either absent or greater than a predetermined maximum allowable value.

11. A system according to claim 10 wherein the controller adapts the basal rate online based on the actual glucose level signal over time and the insulin dose control signal.

12. A system according to claim 11 wherein the controller is operative to automatically impose hard constraints on the insulin dose control signal corresponding to maximum allowable doses of insulin.

13. A system according to claim 2 wherein the glucose sensor is integrated with the delivery device.

14. A system according to any one of claims 2 to 13 wherein the controller is operative to generate a counter-regulatory-agent dose control signal as a function of the weight of the subject and the time-varying glucose levels of the subject as represented by the actual glucose level signal over time, and wherein the control algorithm includes generating the counter-regulatory-agent dose control signal based on (a) the difference between the predicted glucose level signal and the setpoint signal, and (b) the local accumulation of insulin in the subcutaneous space of the subject.

15. A system according to claim 14 wherein the delivery device comprises a mechanically driven infusion mechanism and dual cartridges for insulin and counter-regulatory agent respectively.

16. A system according to claim 14, wherein the counter-regulatory agent comprises glucagon.

17. A method for automatic control of the blood glucose level of a subject, comprising:

continually sensing a glucose level of the subject and generating a corresponding actual glucose level signal; and generating an insulin dose control signal for a delivery device based on the weight of the subject and time-varying glucose levels of the subject as represented by the actual glucose level signal over time, by a control algorithm including:

(1) utilizing a subject model to explicitly model response of the subject to delivered doses of insulin and thereby generate, based on time-varying values of the actual glucose level signal and the insulin dose control signal, a predicted glucose level signal representing a predicted glucose level of the subject; and
(2) generating the insulin dose control signal based on the weight and a difference between the predicted glucose level signal and a setpoint signal representing desired future levels of the glucose level of the subject,

characterized in that
the insulin dose control signal is generated further based on local accumulation of insulin in a subcutaneous space of the subject.

18. A method according to claim 17, wherein the control algorithm includes a model-predictive control algorithm by which the insulin dose control signal is generated as a value optimizing an objective function with objectives of (a) a weighted integration of a difference between the predicted glucose level signal and the setpoint signal over a time horizon, and (b) a weighted integration of the insulin dose control signal over the time horizon.

19. A method according to claim 18, wherein the model-predictive control algorithm is an adaptive model-predictive control algorithm which includes recursively and continually updating model parameters to dynamically adapt the

subject model to variations in the response of the subject to the delivered doses of insulin.

20. A method according to claim 19 wherein the objective function also has an objective of (c) minimizing the local accumulation of insulin in the subcutaneous space of the subject.

21. A method according to claim 17 wherein the subject model is an empirical subject model.

22. A method according to claim 21, wherein the empirical subject model is initially constructed based on a system identification process performed on input-output data obtained from open-loop glycemic control of the subject.

23. A method according to claim 17 further comprising generating the insulin dose control signal to provide a basal rate of delivery of insulin when the model-predictive control algorithm reveals no need for a corrective dose of insulin.

24. A method according to claim 23 wherein the basal rate is determined by a user-provided basal-rate value.

25. A method according to claim 24 wherein a default basal-rate value based on the weight of the subject is employed when the user-provided basal-rate value is either absent or greater than a predetermined maximum allowable value.

26. A method according to claim 25 wherein the basal rate is adapted online based on the actual glucose level signal over time and the insulin dose control signal.

27. A method according to claim 26 further comprising automatically imposing hard constraints on the insulin dose control signal corresponding to a maximum allowable dose of insulin.

28. A method according to any one of claims 17 to 27, further comprising:

generating a counter-regulatory-agent dose control signal for the delivery device as a function of the weight of the subject and the time-varying glucose levels of the subject as represented by the glucose level signal over time.

29. A method according to claim 28, wherein the counter-regulatory agent comprises glucagon.

Patentansprüche

1. Steuerung für die Verwendung in einem System für eine automatische Kontrolle eines Blutzuckerspiegels eines Patienten, wobei die Steuerung betriebsfähig ist, um basierend auf dem Gewicht des Patienten und zeitlich veränderlichen Zuckerspiegeln des Patienten, wie sie durch ein tatsächliches Zuckerspiegelsignal über die Zeit dargestellt werden, ein Insulindosissteuersignal zu erzeugen, wobei das tatsächliche Zuckerspiegelsignal von einem Glukosesensor erzeugt wird, der betriebsfähig ist, um einen Zuckerspiegel des Patienten fortlaufend abzutasten, wobei das Insulindosissteuersignal dazu dient, die Abgabe von Insulindosen an einen subkutanen Raum des Patienten durch eine Abgabevorrichtung zu steuern, wobei die Steuerung einen Regelungsalgorithmus verwendet, der umfasst:

(1) Nutzen eines Patientenmodells, um eine Reaktion des Patienten auf abgegebene Insulindosen explizit zu modellieren und dadurch basierend auf zeitlich veränderlichen Werten des tatsächlichen Zuckerspiegelsignals und dem Insulindosissteuersignal ein Vorhersagezuckerspiegelsignal zu erzeugen, das einen vorhergesagten Zuckerspiegel des Patienten darstellt; und
(2) Erzeugen des Insulindosissteuersignals basierend auf dem Gewicht und einer Differenz zwischen dem Vorhersagezuckerspiegelsignal und einem Sollwertsignal, das erwünschte zukünftige Pegel des Zuckerspiegels des Patienten darstellt,

dadurch gekennzeichnet, dass
das Insulindosissteuersignal ferner basierend auf einer lokalen Akkumulation von Insulin in dem subkutanen Raum des Patienten erzeugt wird.

2. System für die automatische Kontrolle des Blutzuckerspiegels eines Patienten, das aufweist:

einen Glukosesensor, der betriebsfähig ist, um fortlaufend einen Zuckerspiegel des Patienten abzutasten und

ein entsprechendes tatsächliches Zuckerspiegelsignal zu erzeugen;
eine Abgabevorrichtung, die betriebsfähig ist, um als Reaktion auf ein Insulindosissteuersignal Insulindosen an einen subkutanen Raum des Patienten abzugeben; und
eine Steuerung nach Anspruch 1.

3. System nach Anspruch 2, wobei die Steuerung einen modellprädiktiven Regelungsalgorithmus verwendet, durch den das Insulindosissteuersignal als ein Wert erzeugt wird, der eine Zielfunktion mit Zielen (a) einer gewichteten Integration einer Differenz zwischen dem vorhergesagten Zuckerspiegel und dem Sollwertsignal über einen Zeithorizont und (b) einer gewichteten Integration des Insulindosissteuersignals über den Zeithorizont optimiert.

4. System nach Anspruch 3, wobei der modellprädiktive Regelungsalgorithmus ein adaptiver modellprädiktiver Regelungsalgorithmus ist, der ein rekursives und fortlaufendes Aktualisieren von Modellparametern umfasst, um das Patientenmodell an Änderungen der Reaktion des Patienten auf die abgegebenen Insulindosen dynamisch anzupassen.

5. System nach Anspruch 3, wobei die Zielfunktion auch ein Ziel (c) der Minimierung der lokalen Akkumulation von Insulin in dem subkutanen Raum des Patienten hat.

6. System nach Anspruch 2, wobei das Patientenmodell ein empirisches Patientenmodell ist.

7. System nach Anspruch 6, wobei das empirische Patientenmodell einem Typ entspricht, der anfänglich auf der Basis eines Systembestimmungsverfahrens aufgebaut wird, das für Eingangs-Ausgangsdaten durchgeführt wird, die aus einer Zuckersteuerung des Patienten erhalten werden.

8. System nach Anspruch 2, wobei die Steuerung ferner betriebsfähig ist, um das Insulinsteuersignal zu erzeugen, um eine Basalrate für die Insulinabgabe bereitzustellen, wenn der modellprädiktive Regelungsalgorithmus keine Notwendigkeit für eine Korrekturdosis von Insulin offenbart.

9. System nach Anspruch 8, wobei die Basalrate durch einen von einem Benutzer bereitgestellten Basalratenwert bestimmt wird.

10. System nach Anspruch 9, wobei die Steuerung einen Vorgabewert für die Basalrate auf Basis des Gewichts des Patienten verwendet, wenn der vom Benutzer bereitgestellte Basalratenwert entweder nicht vorhanden oder größer als ein vorgegebener maximal zulässiger Wert ist.

11. System nach Anspruch 10, wobei die Steuerung die Basalrate basierend auf dem tatsächlichen Zuckerspiegelsignal über die Zeit und dem Insulindosissteuersignal online anpasst.

12. System nach Anspruch 11, wobei die Steuerung betriebsfähig ist, um automatisch harte Nebenbedingungen für das Insulindosissteuersignal aufzuerlegen, das maximal zulässigen Insulindosen entspricht.

13. System nach Anspruch 2, wobei der Glukosesensor mit der Abgabevorrichtung einteilig ausgebildet ist.

14. System nach einem der Ansprüche 2 bis 13, wobei die Steuerung betriebsfähig ist, um ein Dosissteuersignal für ein gegenregulierendes Mittel als eine Funktion des Gewichts des Patienten und der zeitlich veränderlichen Zuckerspiegel des Patienten, wie sie durch das tatsächliche Zuckerspiegelsignal über die Zeit dargestellt werden, zu erzeugen, und wobei der Regelungsalgorithmus ein Erzeugen des Dosissteuersignals für ein gegenregulierendes Mittel basierend auf (a) der Differenz zwischen dem Vorhersagezuckerspiegelsignal und dem Sollwertsignal und (b) der lokalen Akkumulation von Insulin in dem subkutanen Raum des Patienten umfasst.

15. System nach Anspruch 14, wobei die Abgabevorrichtung einen mechanisch angetriebenen Infusionsmechanismus und Doppelpatronen jeweils für Insulin und ein gegenregulierendes Mittel aufweist.

16. System nach Anspruch 14, wobei das gegenregulierende Mittel Glucagon aufweist.

17. Verfahren für eine automatische Kontrolle des Blutzuckerspiegels eines Patienten, das aufweist:

fortlaufendes Abtasten eines Zuckerspiegels des Patienten und Erzeugen eines entsprechenden tatsächlichen

Zuckerspiegelsignals; und
Erzeugen eines Insulindosissteuersignals für eine Abgabevorrichtung basierend auf dem Gewicht des Patienten und zeitlich veränderlichen Zuckerspiegeln des Patienten, wie sie durch ein tatsächliches Zuckerspiegelsignal über die Zeit dargestellt werden, durch einen Regelungsalgorithmus, der umfasst:

(1) Nutzen eines Patientenmodells, um eine Reaktion des Patienten auf abgegebene Insulindosen explizit zu modellieren und dadurch basierend auf zeitlich veränderlichen Werten des tatsächlichen Zuckerspiegelsignals und dem Insulindosissteuersignal ein Vorhersagezuckerspiegelsignal zu erzeugen, das einen vorhergesagten Zuckerspiegel des Patienten darstellt; und
(2) Erzeugen des Insulindosissteuersignals basierend auf dem Gewicht und einer Differenz zwischen dem Vorhersagezuckerspiegelsignal und einem Sollwertsignal, das erwünschte zukünftige Pegel des Zuckerspiegels des Patienten darstellt,

dadurch gekennzeichnet, dass
das Insulindosissteuersignal ferner basierend auf einer lokalen Akkumulation von Insulin in einem subkutanen Raum des Patienten erzeugt wird.

18. Verfahren nach Anspruch 17, wobei der Regelungsalgorithmus einen modellprädiktiven Regelungsalgorithmus umfasst, durch den das Insulindosissteuersignal als ein Wert erzeugt wird, der eine Zielfunktion mit Zielen (a) einer gewichteten Integration einer Differenz zwischen dem vorhergesagten Zuckerspiegel und dem Sollwertsignal über einen Zeithorizont und (b) einer gewichteten Integration des Insulindosissteuersignals über den Zeithorizont optimiert.

19. Verfahren nach Anspruch 18, wobei der modellprädiktive Regelungsalgorithmus ein adaptiver modellprädiktiver Regelungsalgorithmus ist, der ein rekursives und fortlaufendes Aktualisieren von Modellparametern umfasst, um das Patientenmodell an Änderungen der Reaktion des Patienten auf die abgegebenen Insulindosen dynamisch anzupassen.

20. Verfahren nach Anspruch 19, wobei die Zielfunktion auch ein Ziel (c) einer Minimierung der lokalen Akkumulation von Insulin in dem subkutanen Raum des Patienten hat.

21. Verfahren nach Anspruch 17, wobei das Patientenmodell ein empirisches Patientenmodell ist.

22. Verfahren nach Anspruch 21, wobei das empirische Patientenmodell anfänglich auf der Basis eines Systembestimmungsverfahrens aufgebaut wird, das für Eingangs-Ausgangsdaten durchgeführt wird, die aus der Zuckersteuerung des Patienten erhalten werden.

23. Verfahren nach Anspruch 17, das ferner ein Erzeugen des Insulindosissteuersignals aufweist, um eine Basalrate für die Insulinabgabe bereitzustellen, wenn der modellprädiktive Regelungsalgorithmus keine Notwendigkeit für eine Korrekturdosis des Insulins offenbart.

24. Verfahren nach Anspruch 23, wobei die Basalrate durch einen von einem Benutzer bereitgestellten Basalratenwert bestimmt wird.

25. Verfahren nach Anspruch 24, wobei ein Vorgabewert für die Basalrate auf Basis des Gewichts des Patienten verwendet wird, wenn der vom Benutzer bereitgestellte Basalratenwert entweder nicht vorhanden oder größer als ein vorgegebener maximal zulässiger Wert ist.

26. Verfahren nach Anspruch 25, wobei die Basalrate basierend auf dem tatsächlichen Zuckerspiegelsignal über die Zeit und dem Insulindosissteuersignal online angepasst wird.

27. Verfahren nach Anspruch 26, das ferner ein automatisches Auferlegen harter Nebenbedingungen für das Insulindosissteuersignal, das den maximal zulässigen Insulindosen entspricht, aufweist.

28. Verfahren nach einem der Ansprüche 17 bis 27, das ferner aufweist:

Erzeugen eines Dosissteuersignals für ein gegenregulierendes Mittel für die Abgabevorrichtung als Funktion des Gewichts des Patienten und der zeitlich veränderlichen Zuckerspiegel des Patienten, wie sie durch das

tatsächliche Zuckerspiegelsignal über die Zeit dargestellt werden.

29. Verfahren nach Anspruch 28, wobei das gegenregulierende Mittel Glucagon aufweist.

Revendications

1. Dispositif de régulation à utiliser dans un système de régulation automatique d'un taux de glycémie d'un sujet, le dispositif de régulation étant conçu pour produire un signal de régulation de dose d'insuline sur la base du poids du sujet et des taux de glucose variant dans le temps du sujet tels que représentés par un signal de taux de glucose en cours sur une durée, le signal de taux de glucose en cours étant produit par un détecteur de glucose conçu pour détecter en continu un taux de glucose du sujet, le signal de régulation de dose d'insuline pour réguler l'administration de doses d'insuline à un espace sous-cutané du sujet par un dispositif d'administration, le dispositif de régulation employant un algorithme de régulation incluant :

1) l'utilisation d'une modélisation de sujet pour modéliser explicitement une réponse du sujet à des doses d'insuline administrées et par conséquent produire, sur la base de valeurs variant dans le temps du signal de taux de glucose en cours et du signal de régulation de dose d'insuline, un signal de taux de glucose prévu représentant un taux de glucose prévu du sujet ; et
2) la production du signal de régulation de dose d'insuline sur la base du poids et d'une différence entre le signal de taux de glucose prévu et un signal de consigne représentant des taux ultérieurs souhaités du taux de glucose du sujet,

caractérisé en ce que
le signal de régulation de dose d'insuline est en outre produit sur la base d'une accumulation locale d'insuline dans l'espace sous-cutané du sujet.

2. Système de régulation automatique d'un taux de glycémie d'un sujet, comprenant :

un détecteur de glucose conçu pour détecter en continu un taux de glucose du sujet et produire un signal de taux de glucose en cours correspondant ;
un dispositif d'administration conçu pour administrer des doses d'insuline à un espace sous-cutané du sujet en réponse à un signal de régulation de dose d'insuline ; et
un dispositif de régulation selon la revendication 1.

3. Système selon la revendication 2, dans lequel le dispositif de régulation emploie un algorithme de régulation à modèle prédictif par lequel le signal de régulation de dose d'insuline est produit en tant que valeur optimisant une fonction d'objectifs avec des objectifs étant (a) une intégration pondérée d'un différence entre le signal de taux de glucose prévu et le signal de consigne sur un horizon dans le temps, et (b) une intégration pondérée du signal de régulation de dose d'insuline sur l'horizon dans le temps.

4. Système selon la revendication 3, dans lequel l'algorithme de régulation à modèle prédictif est un algorithme de régulation adaptatif à modèle prédictif qui inclut l'actualisation de manière récurrente et en continu de paramètres de modélisation pour adapter de manière dynamique la modélisation de sujet à des variations dans la réponse du sujet aux doses d'insuline administrées.

5. Système selon la revendication 3, dans lequel la fonction d'objectifs présente également un objectif de (c) minimalisation de l'accumulation locale d'insuline dans l'espace sous-cutané du sujet.

6. Système selon la revendication 2, dans lequel la modélisation de sujet est une modélisation de sujet empirique.

7. Système selon la revendication 6, dans lequel la modélisation de sujet empirique est d'un type initialement construit sur la base d'un processus d'identification de système soumis à des données entrée-sortie obtenues depuis une régulation en boucle ouverte de la glycémie du sujet.

8. Système selon la revendication 2, dans lequel le dispositif de régulation est en outre conçu pour produire le signal de régulation d'insuline en vue de fournir un débit basal d'administration d'insuline lorsque l'algorithme de régulation à modèle prédictif ne révèle aucun besoin d'une dose correctrice d'insuline.

9. Système selon la revendication 8, dans lequel le débit basal est déterminé par une valeur de débit basal fournie par un utilisateur.

10. Système selon la revendication 9, dans lequel le dispositif de régulation emploie une valeur de débit basal par défaut sur la base du poids du sujet lorsque la valeur de débit basal fournie par un utilisateur est soit absente soit supérieure à une valeur admissible maximale prédéterminée.

11. Système selon la revendication 10, dans lequel le dispositif de régulation adapte le débit basal en direct sur la base du signal de taux de glucose en cours sur une durée et du signal de régulation de dose d'insuline.

12. Système selon la revendication 11, dans lequel le dispositif de régulation est conçu pour automatiquement imposer des restrictions rigoureuses au signal de régulation de dose d'insuline correspondant à des doses admissibles maximales d'insuline.

13. Système selon la revendication 2, dans lequel le détecteur de glucose est intégré au dispositif d'administration.

14. Système selon l'une quelconque des revendications 2 à 13, dans lequel le dispositif de régulation est conçu pour produire un signal de régulation de dose d'agent de contre-régulation qui est fonction du poids du sujet et des taux de glucose variant dans le temps du sujet tels que représentés par le signal de taux de glucose en cours sur une durée, et dans lequel l'algorithme de régulation inclut la production d'un signal de régulation de dose d'agent de contre-régulation sur la base de (a) la différence entre le signal de taux de glucose prévu et le signal de consigne, et de (b) l'accumulation locale d'insuline dans l'espace sous-cutané du sujet.

15. Système selon la revendication 14, dans lequel le dispositif d'administration comprend un mécanisme de perfusion entraîné mécaniquement et des cartouches doubles pour l'insuline et l'agent de contre-régulation respectivement.

16. Système selon la revendication 14, dans lequel l'agent de contre-régulation comprend du glucagon.

17. Procédé de régulation automatique du taux de glycémie d'un sujet, comprenant :

la détection en continu d'un taux de glucose du sujet et la production d'un signal de taux de glucose en cours correspondant ; et
la production d'un signal de régulation de dose d'insuline pour un dispositif d'administration sur la base du poids du sujet et des taux de glucose variant dans le temps du sujet tels que représentés par le signal de taux de glucose en cours sur une durée, par un algorithme de régulation incluant :

1) l'utilisation d'une modélisation de sujet pour modéliser explicitement une réponse du sujet à des doses d'insuline administrées et par conséquent produire, sur la base de valeurs variant dans le temps du signal de taux de glucose en cours et du signal de régulation de dose d'insuline, un signal de taux de glucose prévu représentant un taux de glucose prévu du sujet ; et
2) la production d'un signal de régulation de dose d'insuline sur la base du poids et d'une différence entre le signal de taux de glucose prévu et un signal de consigne représentant des taux ultérieurs souhaités du taux de glucose du sujet,

caractérisé en ce que
le signal de régulation de dose d'insuline est en outre produit sur la base d'une accumulation locale d'insuline dans un espace sous-cutané du sujet.

18. Procédé selon la revendication 17, dans lequel l'algorithme de régulation inclut un algorithme de régulation à modèle prédictif par lequel le signal de régulation de dose d'insuline est produit en tant que valeur optimisant une fonction d'objectifs avec des objectifs étant (a) une intégration pondérée d'un différence entre le signal de taux de glucose prévu et le signal de consigne sur un horizon dans le temps, et (b) une intégration pondérée du signal de régulation de dose d'insuline sur l'horizon dans le temps.

19. Procédé selon la revendication 18, dans lequel l'algorithme de régulation à modèle prédictif est un algorithme de régulation adaptatif à modèle prédictif qui inclut l'actualisation de manière récurrente et en continu de paramètres de modélisation pour adapter de manière dynamique la modélisation de sujet à des variations dans la réponse du sujet aux doses d'insuline administrées.

20. Procédé selon la revendication 19, dans lequel la fonction d'objectifs présente également un objectif de (c) minimalisation de l'accumulation locale d'insuline dans l'espace sous-cutané du sujet.

21. Procédé selon la revendication 17, dans lequel la modélisation de sujet est une modélisation de sujet empirique.

22. Procédé selon la revendication 21, dans lequel la modélisation de sujet empirique est initialement construite sur la base d'un processus d'identification de système soumis à des données entrée-sortie obtenues depuis une régulation en boucle ouverte de la glycémie du sujet.

23. Procédé selon la revendication 17, comprenant en outre la production du signal de régulation de dose d'insuline en vue de fournir un débit basal d'administration d'insuline lorsque l'algorithme de régulation à modèle prédictif ne révèle aucun besoin d'une dose correctrice d'insuline.

24. Procédé selon la revendication 23, dans lequel le débit basal est déterminé par une valeur de débit basal fournie par un utilisateur.

25. Procédé selon la revendication 24, dans lequel une valeur de débit basal par défaut sur la base du poids du sujet est employée lorsque la valeur de débit basal fournie par un utilisateur est soit absente soit supérieure à une valeur admissible maximale prédéterminée.

26. Procédé selon la revendication 25, dans lequel le débit basal est adapté en direct sur la base du signal de taux de glucose en cours sur une durée et du signal de régulation de dose d'insuline.

27. Procédé selon la revendication 26, comprenant en outre l'imposition automatique de restrictions rigoureuses au signal de régulation de dose d'insuline correspondant à une dose admissible maximale d'insuline.

28. Procédé selon l'une quelconque des revendications 17 à 27, comprenant en outre :

la production d'un signal de régulation de dose d'agent de contre-régulation pour le dispositif d'administration qui est fonction du poids du sujet et des taux de glucose variant dans le temps du sujet tels que représentés par le signal de taux de glucose sur une durée.

29. Procédé selon la revendication 28, dans lequel l'agent de contre-régulation comprend du glucagon.

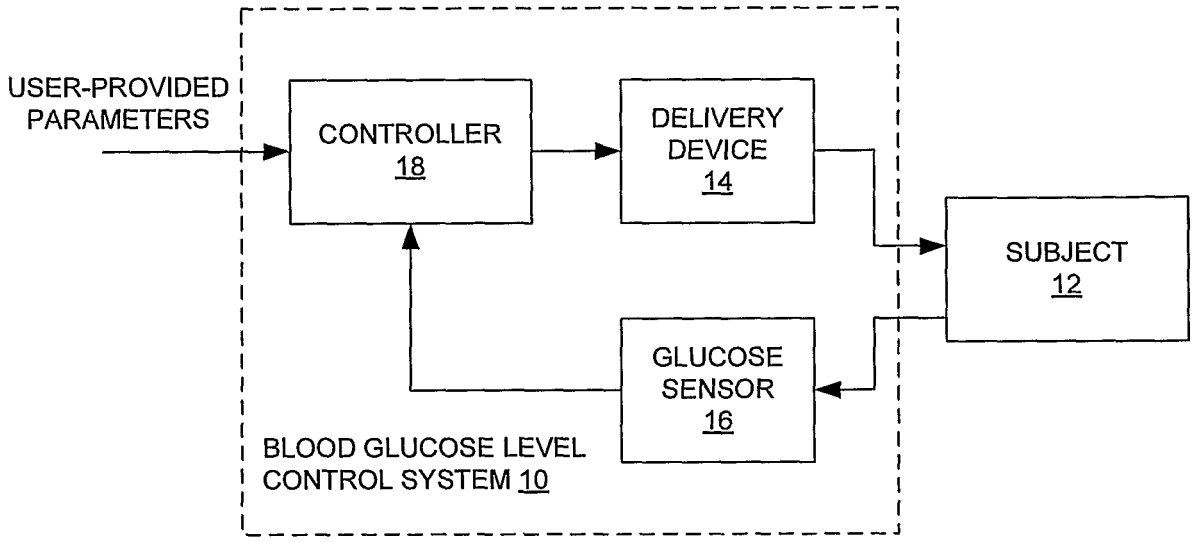
USER-PROVIDED PARAMETERS
CONTROLLER 18
DELIVERY DEVICE 14
SUBJECT 12
GLUCOSE SENSOR 16
BLOOD GLUCOSE LEVEL CONTROL SYSTEM 10

Fig. 1

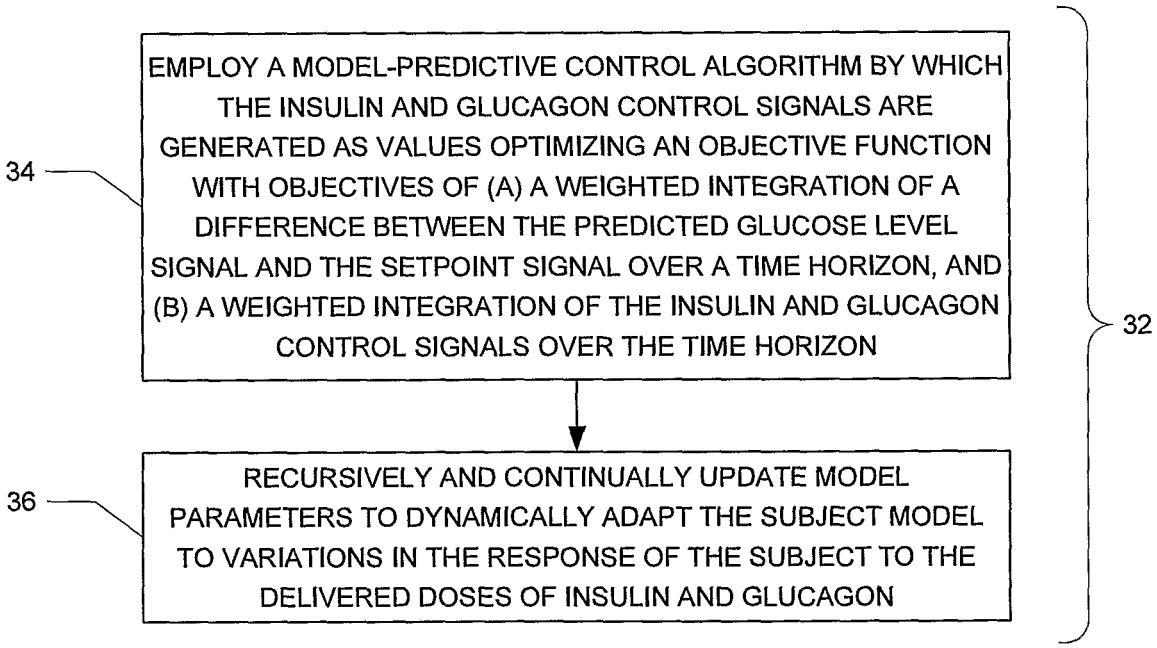
34
EMPLOY A MODEL-PREDICTIVE CONTROL ALGORITHM BY WHICH THE INSULIN AND GLUCAGON CONTROL SIGNALS ARE GENERATED AS VALUES OPTIMIZING AN OBJECTIVE FUNCTION WITH OBJECTIVES OF (A) A WEIGHTED INTEGRATION OF A DIFFERENCE BETWEEN THE PREDICTED GLUCOSE LEVEL SIGNAL AND THE SETPOINT SIGNAL OVER A TIME HORIZON, AND (B) A WEIGHTED INTEGRATION OF THE INSULIN AND GLUCAGON CONTROL SIGNALS OVER THE TIME HORIZON
36
RECURSIVELY AND CONTINUALLY UPDATE MODEL PARAMETERS TO DYNAMICALLY ADAPT THE SUBJECT MODEL TO VARIATIONS IN THE RESPONSE OF THE SUBJECT TO THE DELIVERED DOSES OF INSULIN AND GLUCAGON
32

Fig. 4

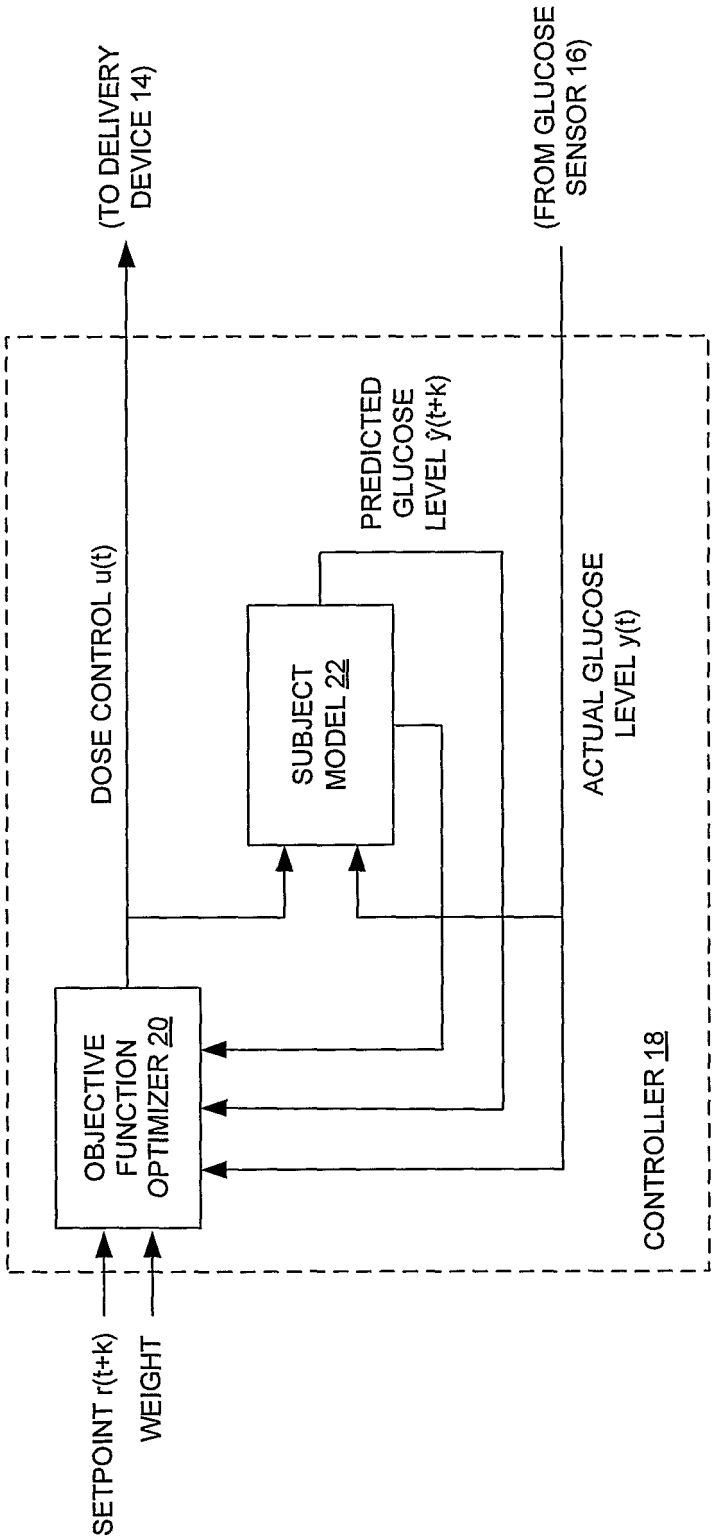
(TO DELIVERY DEVICE 14)
(FROM GLUCOSE SENSOR 16)
DOSE CONTROL u(t)
PREDICTED GLUCOSE LEVEL ŷ(t+k)
SUBJECT MODEL 22
ACTUAL GLUCOSE LEVEL y(t)
OBJECTIVE FUNCTION OPTIMIZER 20
CONTROLLER 18
SETPOINT r(t+k)
WEIGHT

Fig. 2

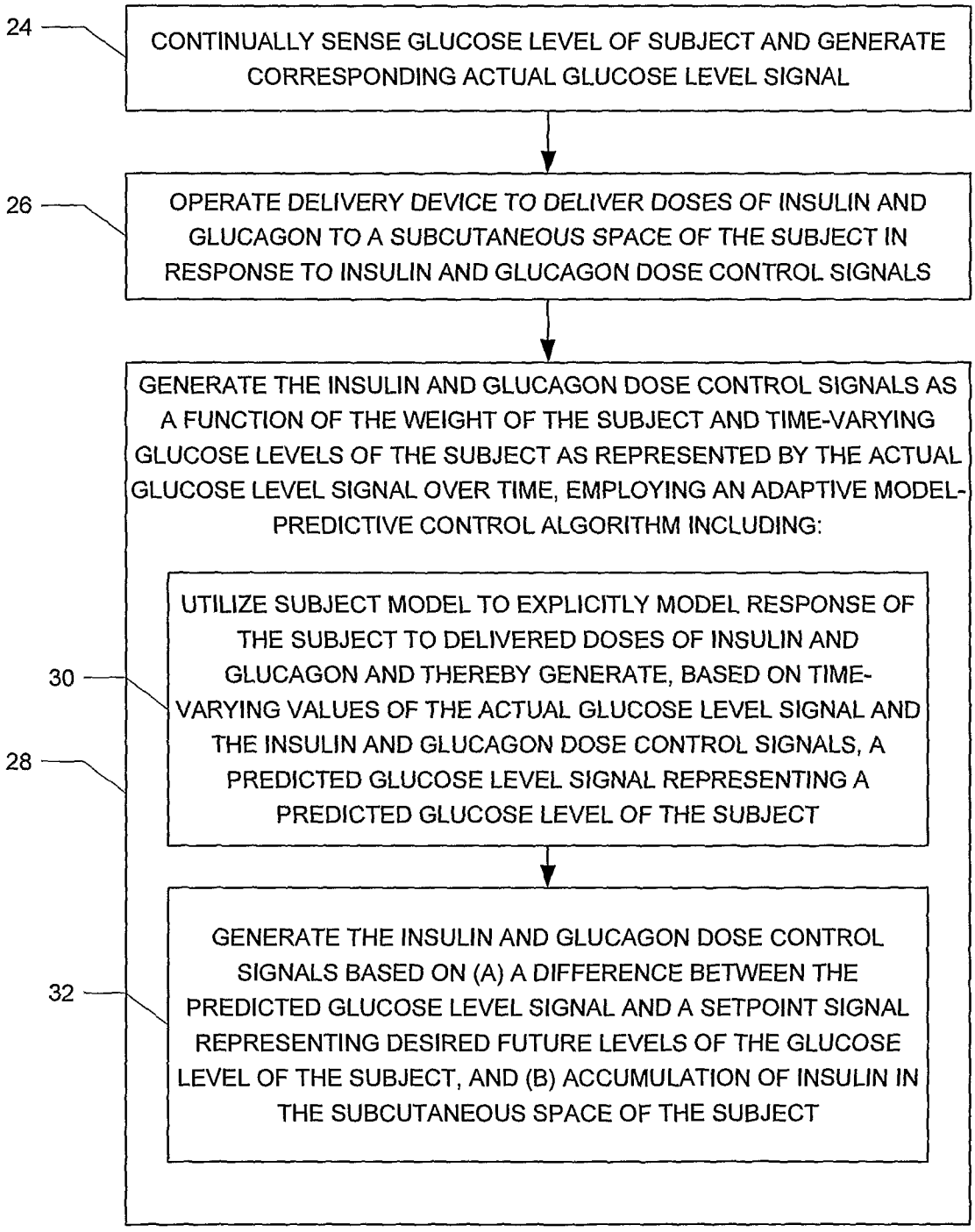
24
CONTINUALLY SENSE GLUCOSE LEVEL OF SUBJECT AND GENERATE CORRESPONDING ACTUAL GLUCOSE LEVEL SIGNAL
26
OPERATE DELIVERY DEVICE TO DELIVER DOSES OF INSULIN AND GLUCAGON TO A SUBCUTANEOUS SPACE OF THE SUBJECT IN RESPONSE TO INSULIN AND GLUCAGON DOSE CONTROL SIGNALS
GENERATE THE INSULIN AND GLUCAGON DOSE CONTROL SIGNALS AS A FUNCTION OF THE WEIGHT OF THE SUBJECT AND TIME-VARYING GLUCOSE LEVELS OF THE SUBJECT AS REPRESENTED BY THE ACTUAL GLUCOSE LEVEL SIGNAL OVER TIME, EMPLOYING AN ADAPTIVE MODEL-PREDICTIVE CONTROL ALGORITHM INCLUDING:
30
28
UTILIZE SUBJECT MODEL TO EXPLICITLY MODEL RESPONSE OF THE SUBJECT TO DELIVERED DOSES OF INSULIN AND GLUCAGON AND THEREBY GENERATE, BASED ON TIME-VARYING VALUES OF THE ACTUAL GLUCOSE LEVEL SIGNAL AND THE INSULIN AND GLUCAGON DOSE CONTROL SIGNALS, A PREDICTED GLUCOSE LEVEL SIGNAL REPRESENTING A PREDICTED GLUCOSE LEVEL OF THE SUBJECT
32
GENERATE THE INSULIN AND GLUCAGON DOSE CONTROL SIGNALS BASED ON (A) A DIFFERENCE BETWEEN THE PREDICTED GLUCOSE LEVEL SIGNAL AND A SETPOINT SIGNAL REPRESENTING DESIRED FUTURE LEVELS OF THE GLUCOSE LEVEL OF THE SUBJECT, AND (B) ACCUMULATION OF INSULIN IN THE SUBCUTANEOUS SPACE OF THE SUBJECT

Fig. 3

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- **Z. TRAJANOSKI et al.** Neural predictive controller for insulin delivery using the subcutaneous route. *IEEE Transactions on Biomedical Engineering,* September 1998, vol. 45 (9), 1122-1134 **[0005]**

专利名称(译)	1型糖尿病全自动控制系统		
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外部链接	Espacenet		

摘要(译)

利用模型预测控制（MPC）的增强自适应算法被开发用于1型糖尿病中的闭环葡萄糖控制。线性经验输入 - 输出主题模型与MPC算法一起用于在线调节血糖，其中主题模型被递归地调整，并且用于递送胰岛素的控制信号和诸如胰高血糖素的反调节剂仅基于在线葡萄糖浓度测量。通过优化增强的目标函数来合成MPC信号，该目标函数使皮下贮库中的局部胰岛素积累最小化并控制信号侵略性，同时将葡萄糖浓度调节至预设的参考设定点。控制所施用的胰岛素的皮下积累的数学公式是基于与人体内胰岛素的药代动力学（活动的时间过程）有关的标称时间值，就其吸收速率，峰值吸收时间和总体作用时间而言。 MPC算法也被制定为提供具有整体效果的控制动作，并且实质上最小化总体药物消耗。当用作1型糖尿病的自动化集成葡萄糖控制系统中的调节剂时，控制算法为系统提供自学习能力，使其能够在受试者的不受限制的活动下操作。