In Silico Evaluation of Fuzzy Logic Controller for Artificial Pancreatic β-Cell

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Introduction

Fuzzy logic (FL) provides a powerful vehicle to incorporate human reasoning in the control algorithm. Unlike traditional Proportional Integral Derivative (PID) and Model Predictive Control (MPC) controllers, FL need not be based on the explicit mathematical model of a process. A controller designed using FL can implement human reasoning into the control algorithm. However, similar to PID and MPC controllers, FL controllers may incorporate real-time methods for adapting the controller to the changing conditions of the system being controlled. FL controllers also allow a medical expert to communicate control in a manner they understand, can easily visualize, and readily adapt to the conditions of their patients.

Objective

To evaluate the feasibility of a fuzzy logic based controller for an artificial pancreas

Methods

FL control uses a Dosing Rules Matrix that visually portrays insulin dosing covering all blood glucose situations. The matrix allows dosing to be customized as a function of any combination of Blood Glucose (BG), BG rate and BG acceleration without the mathematical constraints required by other methods. It also provides an intuitive mechanism for significant physician input, allowing individual customization. It is also well suited to the control in non-linear, or poorly behaved systems, such as the human glucoregulatory system.

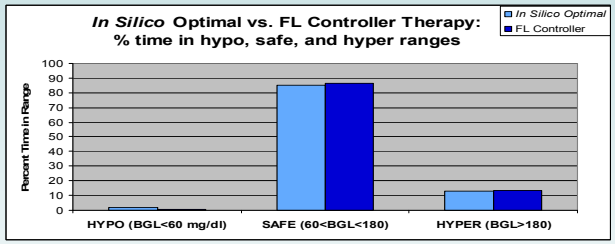
Dosing rules are customized as a function of BG, BG rate, and BG acceleration/deceleration. Five segments are used for BG; 5 segments for BG rate, and BG acceleration is divided into 3 intervals. Therefore, this 3-axis space is divided into 75 subspaces, and a different insulin dose value is given in each subspace. Standard FL methods are used to produce an insulin dose. Finally, a personalization factor, which is proportional to total daily dose (TDD), is introduced to scale the insulin dose for a particular patient.

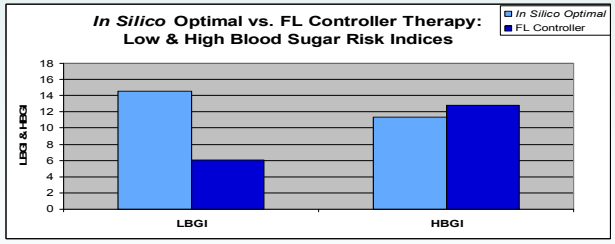
Dosing Rules Matrix

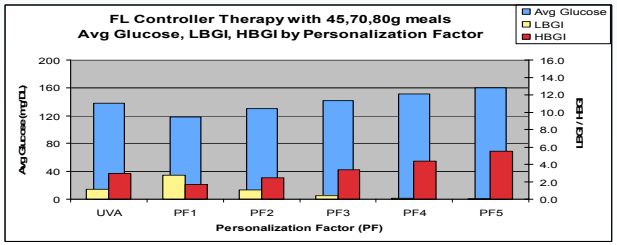
Subcutaneous insulin infusion rates. Units of insulin. 5 min sample time

BGL Rate: Very Negative, Negative, Zero Positive, Very Positive	VN			N			Z			P			VP		
BGL Acceleration: Negative, Zero Positive	N	Z	P	N	Z	P	N	Z	P	N	Z	P	N	Z	P
BGL Trajectory: previous two sample times	↘	↘	↘	↘	↘	↘	→	→	→	↗	↗	↗	↗	↗	↗
> 250 mg/DL	0.00	0.00	0.00	0.13	0.17	0.83	0.17	0.30	1.00	0.50	0.90	1.17	0.53	1.50	1.67
180-250 mg/DL	0.00	0.00	0.00	0.10	0.13	0.27	0.13	0.27	0.67	0.27	0.73	0.90	0.30	1.40	1.50
120-180 mg/DL	0.00	0.00	0.00	0.07	0.10	0.13	0.10	0.13	0.27	0.13	0.50	0.57	0.17	1.00	1.17
80-120 mg/DL	0.00	0.00	0.00	0.23	0.03	0.03	0.03	0.07	0.10	0.03	0.10	0.13	0.03	0.13	0.17
< 80 mg/DL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.02	0.03	0.03	0.04	0.05

Results







Methods (continued)

The FL method is compared with *in silico* optimal therapy using the adult population from the FDA approved UVa /Padova simulator. All ten subjects followed the same daily pattern of 3 meals and 2 snacks at 7am, noon, 4pm, 6pm, and 11pm of 45g, 70g, 5g, 80g, and 5g, respectively.

Results

Ten patients were studied. The average percentage time in hypoglycemia (BGL< 60 mg/dl), safe range (60<BGL<180 mg/dl), and hyperglycemia (BGL>180) were 2.1%, 85.0%, and 12.9%, respectively, under the *in silico* optimal therapy, and 0.3%, 86.5%, and 13.2%, under the proposed method. The low blood glucose index (LBGI) and high blood glucose index (HBGI) were 14.5 and 11.3 for the *in silico* optimal therapy and 6.1 and 12.8 for the proposed method. With the use of personalization factors (PFs), HBGI and LBGI levels were transposed, while keeping average glucose levels close to *in silico* optimal therapy levels.

Conclusion

The proposed method can reduce hypoglycemia with negligible risk of hyperglycemia. Moreover this method depends only on CGM input and is tuned based on TDD. It does not rely on carbohydrate knowledge, which is usually poorly estimated by patients with T1DM, nor does it rely on any other user intervention. Despite this lack of user input it provides comparable performance to *in silico* optimal therapy. When coupled with PFs, adjustments to HBGI and LBGI levels are possible appropriate to a particular subject. Its simplicity and effectiveness makes the FL method an excellent candidate for future artificial pancreatic β-cell.

Future Research

FL can be readily modified to accept adaptive and predictive components. These two areas are the focus of our future research, which will be evaluated using *in silico* simulations.

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