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Automatic meal planning using artificial intelligence algorithms in computer aided diabetes therapy

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Abstract— **Paper presents the review of the computer aided diabetes therapy introducing GIGISim (Glucose-Insulin and Glycemic Index Web Simulator) e-learning tool based on the glucose and insulin plasma levels simulation models and genetic algorithms optimization. Together with the system, recently reported solutions assisting diabetes therapy were summarized and their functionality presented. Artificial intelligence is applied in GIGISim tools to improve patients' management and health awareness. Interactive, diabetes-dedicated simulators, supported with genetic algorithms (GA) have a great deal of educational potential for patients and their families, and may also offer a means of training for health-care professionals. It is generally believed that evolutionary algorithms (EA), which GA are a particular class of, perform consistently well across all types of optimization problems, in this case the optimization of the diabetes meal plan.**

Keywords: Tele-health system, Tele-education, web tools, glucose-insulin models, interactive simulation, diabetes therapy, evolutionary computing.

I. Introduction

In this paper we present the newly developed, diabetes dedicated, educational tools compared to existing approaches and solutions. Glucose-Insulin and Glycemic Index Web Simulator (GIGISim) serves as a graphical simulator of postprandial glucose profiles of diabetic individuals, and can be accessed via Internet. Results are based on human carbohydrate metabolism model and influenced by user's diet – meals and food products can be entered into the system and possible glucose and insulin fluxes simulated.

Despite the introduction of many therapeutic aids such as intelligent insulin pumps and injectors, blood glucose tests, insulin dose algorithms and new pharmacological formulas the metabolic care of most patients is still insufficient, mainly because of the number of therapy recommendations that should be taken under consideration and lack of the education. A meal and insulin dose planning requires experience from patients, their families and physicians - patients should correlate their insulin regime with blood glucose variations and daily diet. Type II diabetes should often modify eating habits to lose weight and improve their body's sensitivity to insulin.

According to our surveys, patients often ignore the importance of basic nutritional meal assessment, despite the necessity of the properly balanced diet. Several investigators have pointed out the possibility of using the glucose and insulin plasma levels simulation models, to help diabetes interpret human carbohydrate metabolism influenced by a diet, and insulin-treatment. This approach to the diabetes education was proved to be effective and numbers of mathematical models of the diabetes mellitus metabolism have been previously reported in literature [8][9].

GIGISim is equipped with two major tools: glucose-insulin simulator and Meal Planner, which, using the simulation results and GA optimization prepare a meal plan that is adapted to users taste and ensures proper blood glucose limits. Patient may provide a choice of favorite food products, and optimization tool will report back combinations of products and meals which cause the lowest possible glucose rise.

II. Diet Assessment as a part od diabets theraphy

One of the most important aspects to be considered when planning dietetic education is to emphasize how patient's diet may affect blood glucose level. American Diabetes Association (ADA) basically recommends controlling the amount of carbohydrates in meals[1] but recent research [2] together with the statement of the Canadian Diabetes Association -"Guidelines for the Nutritional Management of Diabetes Mellitus in the New Millennium" [3], introduce glycemic index (GI) as a highly important factor, directly related to glycemic control. GI value, estimated experimentally, describes the potential of the product to raise blood glucose. Lowering the GI of the diet may improve blood glucose control, help in weight loosing and normalize appetite [4], which was proved for non-diabetes, type I and type II diabetes [5]. Thus, many educational centers for diabetes include lectures on GI in their program and patients are encouraged to consider GI among other dietetic rules that should be taken into account when preparing a proper diabetes meal.

The glycemic index (GI) is a ranking of carbohydrates on a scale from 0 to 100 according to the extent to which they raise blood sugar levels after eating. The GI value of a food is calculated experimentally by feeding around 10 healthy people a portion of the considered food, containing 50 grams of digestible carbohydrate. Then the effect on their blood glucose is measured over the next two hours. The area under their blood glucose level curve (AUC) is then compared with the reference AUC measured the other day for the same amount of pure glucose sugar. GI value is the average of the 10 values obtained by dividing food's AUC by reference one.

Foods with a high GI are those which are rapidly digested and absorbed and result in marked fluctuations in blood sugar levels. One of the unique aspects of GI is that the various combinations of the same food products may result in various glucose level changes. Carbohydrates that breakdown quickly during digestion have the highest GI (quick, rapid glucose rises). Those that break down slowly, releasing glucose steadily into the blood have low glycemic indexes. GI values of basic food products may be found in databases but the total GI value of the meal composed of many products is not always a simple weighted sum of GI components. Glycemic Index, and therefore glucose rises in human blood depend on the type of carbohydrate on the one side, and on the other side on the presence of a starch, fat and proteins that have the ability to slow the absorption process from guts and therefore slow down glucose uptake to the blood.

The process may be illustrated using the example of 4 food products:

- Product I (low GI < 25);
- Product II (moderate GI);
- Product III (high GI);
- Product IV (very low GI)

- combined into two meals named in the example: A and B. The result of glucose level changes, after consumption of all possible combination of the products I-IV in both meals were simulated with GIGISim and results presented in figures 1-3.

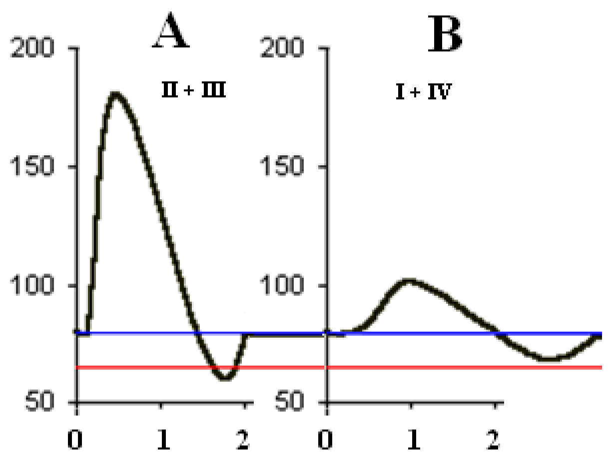

Figure 1. GIGISim simulation of glucose fluxes (mg/dl) in time (h) for given meal combiantion A: product II and III, meal B: produc I and IV

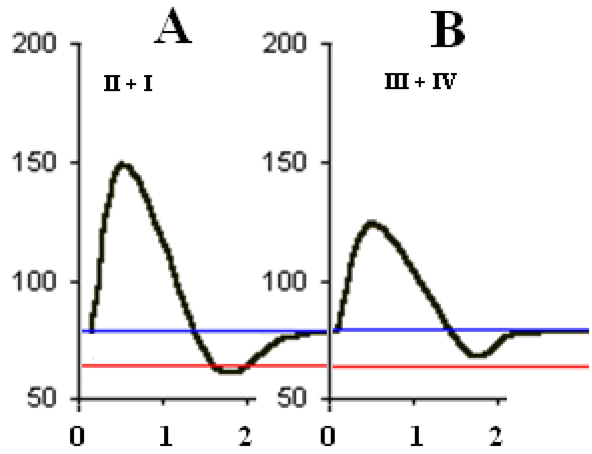

Figure 2. GIGISim simulation of glucose fluxes (mg/dl) in time (h) for given meal combiantion A: product II followed by I, meal B: produc III followed by IV

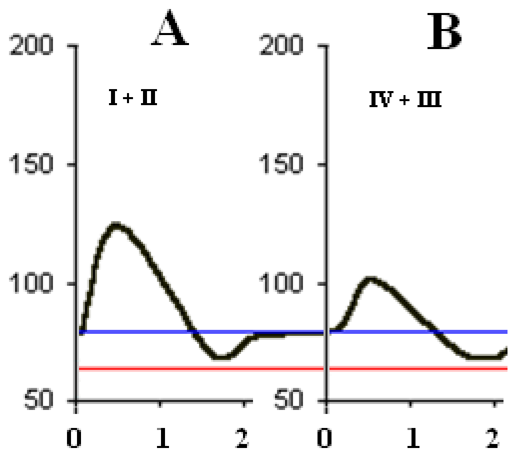

Figure 3. GIGISim simulation of glucose fluxes (mg/dl) in time (h) for given meal combiantion A: product II followed by I, meal B: produc III followed by IV

As we can observe in Fig. 1-3 glucose amplitude depends not only on the GI of the product but also on the applied meals combination and products order (see Fig 2 and 3.). Meals with low GI have the ability to lower the GI of the following courses (example: vegetable salad with very low GI, eaten as a starter lowers the total GI of the meal and result in lower fluctuations in blood sugar levels).

Although the impressive number of software is available for diabetes there are no solutions which would help consumers to identify the effect of GI and plan meals in the way they could easily avoid dangerous blood rises only by changing the order or the combination of food products in the diet plan. The example introduced in our previous paper [6] showed some advantages of the visualization method over numeric value estimation of a meal. The blood glucose variation graphic simulation is far more meaningful and educative than figures and calculations. Automated diet planning may increase the comfort of life and therapy as it searches for most safe combinations of favorite patients' products. This is why we demonstrate the usefulness of GIGISim and emphasize the educational role of this tool.

III. Computer-Aided Diabetes Education: A Review

Several investigators have pointed out the possibility of using glucose and insulin plasma levels simulation models, to help diabetes interpret human carbohydrate metabolism [7][8][9]. This approach to diabetes education was proved to be effective and numbers of mathematical models of the diabetes mellitus metabolism have been previously reported in literature.

The well known example of AIDA software [10], available since 1996, provides a simulation of glucose and insulin levels in the blood based on the glucose-insulin kinetics model. Authors have proved educational advantage of visualization methods like AIDA simulation in comparison to traditional lectures.

Although the mentioned software is well featured we believe that a graphic visualization of glucose and insulin with relation to a diet is the biggest advantages of GIGISim over presented software. Total effect on blood glucose variations is emphasized on plots and patients treated with insulin analogues, may benefit by adapting insulin types (long lasting, short lasting) to the pattern of blood glucose response which is correlated to GI, especially if used with Meal Planner tool which provides easy way to plan diet with possibly lowest glucose rise, using patients' choice of products.

IV. Proposed Approach - The GIGISim Model

To develop a new algorithm of GI simulation we have extended and utilized existing mathematical model based on pharmacokinetic diagrams of glucose and insulin. First output of algorithm is the plasma glucose level related to the declared meal ingredients, second is the insulin concentration which is however not used in the further GA calculations.

Although many researchers had focused on modeling the physiological process of digestion and absorption of the food in the gut compartment, which is challenging due to the complexity of the above processes, in this paper we propose a simple procedure to simulate GI effect using existing mathematical model of glucose and insulin dynamics in the blood compartment. Results were obtained with the basic model reported in [16]. Model equations were modified to optimize GIGISim specific simulation algorithm and are presented in the equations 1 - 4. The x variable stands for glucose kinetics and y stands for insulin:

$$\frac{dx}{dt} = -\nu xy - \lambda x - \mu(x-\theta) + Q_L, \quad x > \theta \qquad (1)$$

$$= -\nu xy - \lambda x + Q_L, \quad x \leq \theta \qquad (2)$$

$$\frac{dy}{dt} = -\alpha y, \quad x \leq \Phi \qquad (3)$$

$$= \beta(x - \Phi) - \alpha y, \quad x > \Phi \qquad (4)$$

The parameters values [16] employed in this model are estimated for a normal adult: $\theta = 2.5$ [mg / ml], $\mu = 7200$ [ml / h], $\lambda = 2470$ [ml / h], $\nu = 139000$ [1/ (mU * h)], $\varphi = 0.51$ mg ml-1 , $\beta = 1430$ [mU*ml / h], $\alpha = 7600$ [ml / h]. The outline of the proposed compartmental model is presented in Fig. 4.

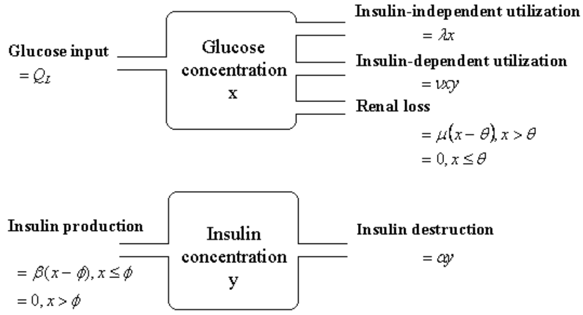

Figure 4. Glucose and insulin compartment system and kinetics in the presented model.

To obtain a desired response from the glucose-insulin model (output), that is the curve with the AUC that reflects the GI effect on the blood glucose (GI is one of the input parameters) an inverse problem should be solved, which in the case of this nonlinear physiological system is particularly difficult to solve with standard methods [17].

The solution we propose gives satisfying result for the needs of GIGISim simulation. Output system signal match real medical signal and have smooth, biologically interpretable profile. The basic idea is to regard the process of obtaining a curve with specific AUC as the optimization problem. Then any heuristic method may be used, to minimize the error measured as the difference between the actually processed AUC (calculated for two hours, for randomly chosen set of input values) and reference AUC. In this work the Matlab Optimization Toolbox was used and all possible GI values preliminarily simulated for the purpose of further GA processing in MealPlanner.

V. Proposed Approach - The GIGISim Web Application

One of the main advantages of using GIGISim is the possibility to create personalized profiles and perform simulations based on adapted model. Information on age, BMI and possible diabetes is used to personalize simulation result by choosing model parameters from predefined sets. More advanced method includes patient's results of Oral Glucose Tolerance Test as one of the algorithm inputs, adapting dynamically the set of model parameters. Adaptation components have been added to personalize simulation – both the algorithm and adaptation method where reported in previous papers about GIGISim [6, 19, 20].

Genetic algorithms (AI) in an intelligent Meal Planner individualize nutritional recommendations, to satisfy the person's taste preferences and lifestyle and to provide optimal blood glucose control. The tool analyzes the data base containing over 1000 products to find and suggest optimal daily diet plan based on nutrient requirements. Practical use of this tool was highlighted in section 2, where the best combination of proposed products was found for user, and their impact on blood glucose visualized.

The application is implemented in ASP.NET 2.0 web technology to provide more advanced and comfortable user interface, and to assure easier migration to mobile platform. System will be broadly and freely accessible in WWW providing demo-simulations and facilities for online users, news on diabetes care, newsletters or discussions. Registered users and physicians will have the access to the patient-profiled simulations and data, report generator and statistical analysis. Online communication between patient and his physicians will be also handled.

At this stage of development we plan also to implement the simple GIGISim simulation software designed for mobile devices. That would give patients the unique chance to simulate glucose behavior pattern offline, after a meal and take results in to account while planning everyday activities.

VI. Optimization problem in Meal Planner tool

To define GA [14][15] one should established primary facts as: coding, fitness function, methods of crossover and mutation, appropriate probabilities for these operators, stopping criteria. GA is used to optimize the combination of food products in planned meal and is defined by following settings:

a) Definition and implementation of the genetic representation: chromosome is represented by an ordered vector v containing set of P_i values of:

$P_i = [Product_{GI}; Product_{AMOUNT}; Product_{TIME}]$

Each chromosome represents full daily diet plan described by set of P_1 to P_n products. Classification of products to each meal order of service ($Product_{TIME}$) and amounts of product ($Product_{AMOUNT}$) vary between chromosomes and change during turns.

b) Fitness function is defined as a distance between safe, base level of blood glucose and maximum level of glucose observed in simulation calculated for period of 3hours for each meal "virtually" consumed. Meal is in every turn formed from products in the chromosome.

c) Genetic operators:

- Crossover: method (arithmetic), probability (0,8);
- Mutation: method (uniform), probability (0,2).

As in all GAs stopping criteria should be carefully chosen and for the need of our experiment computations were ended when one of the following conditions were fulfilled:

- Exceeded number of generations: 100,
- Stall time limit: 2000,
- Function tolerance: 1e-06.

In each turn meal classification (which product should be served in which meal), order of service and amount for each product may change, triggering changes in total GI of the meals, and therefore changes is simulated blood glucose curves. Best solution represents optimal combination of products with suggested amounts. Amounts can be bounded by user before planning starts so only logical solutions are produced.

VII. Results

The use of this system has been limited to educational purposes, because model takes into account only a confined number of the factors associated with glucose metabolism, and model parameters are not easily individualized to accurately simulate metabolic processes for all specific diabetes individuals.

Optimal meal planning with GA gave highly satisfactory results – blood glucose curves predicted by model with conjunction with GA component were fitting experimentally found data with ignorable error (assuming educational purposes of the system), except some rare cases of severe hypoglycemia presented in the output.

Short-term prediction of glucose levels based on information about patient's glucose levels and diet proposed by Meal Plannerwere visualized, allowing patients to practice, and gain experience with diet planning however at the stage of system development each result (output signal proposed by cooperating GA optimizer and model component) should be examined by qualified consultant to ensure reasonable visualization and medical interpretation of the obtained signal.

The system was tested on non-diabetes group (10 healthy students age 20-25) as well as on diabetes patients in clinical tests made in Krakow's Hospital (11 women, age 65-78, all treated with insulin). Results of the simulation were satisfactory and educational goal was reached. All subjects show high interest on presented visualization, many of them wished to carry simulation on their own.

The value of computer aided therapy management is undisputed but the challenge is not only to develop innovative, validated algorithms and tools to aid patient decision-making and optimize glycemic control but also to assure high usability, accessibility and compliance with patients' requirements. This is why we are trying to develop additional tools available on GIGISim website, which may help in optimal meal planning. Further suggestions of patients will be discussed as well in future papers.

VIII. CONCLUSION

The main advantage of the GIGISim simulation is that the personal variations in physiological parameters are taken into account, which has the good psychological effect and educational impact. GIGISim is a tool designed for educational purposes only, and similarly to other popular GlucoSim [13] simulator warns possible users against making medical decisions basing on presented plots.

One of the weaknesses of the methodology implemented in GIGISim includes the high variability of output responses which occurred in real-life situations when patients were trying to perform adaptation of GIGISim. Another interesting problem occurred while testing GA based Meal Planner. Algorithms suggest adding certain amounts of fats to each meal which has clear justifications as fats slow down digestion process and therefore lower the GI of the meal, cardiovascular disease should be however taken into account and vegetable fats suggested in diet plans instead of saturated ones.

One of the intermediate goals of our present work is to introduce modifications to the existing simulation framework, in order to enable GIGISim implementation on mobile devices.

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