iGLU 3.0: A Secure Noninvasive Glucometer and Automatic Insulin Delivery System in IoMT

Amit M. Joshi, *Senior Member, IEEE*; Prateek Jain, *Member, IEEE*; and Saraju P. Mohanty, *Senior Member, IEEE*

***Abstract*—The consumer technologies in healthcare has changed the human life with smart health management. The evaluation of Internet-of-Medical-Things (IoMT) has provided the closed loop control system for point of care mechanism. The hardware security of medical devices has drawn the attention where any security breach could have catastrophic impact. The paper discusses iGLU 3.0 which includes security model of glucose measurement device along with insulin pump of IoMT framework. The novel glucose-insulin model has been proposed for glucose control of diabetes patient. The physical unclonable function (PUF) based security solution is developed for non-invasive glucometer iGLU and insulin pump for safe insulin secretion. PUF based Hardware-Assisted Security (HAS) is helpful to mitigate challenges which are present in automatic insulin delivery with iGLU.**

***Index Terms*—Smart Healthcare, Continuous Glucose Measurement, Automatic Insulin Delivery, Physical Unclonable Function (PUF), Glucose-insulin modeling**

I. Introduction

Diabetes is a condition when the blood glucose is increased predominantly because of inadequate insulin of the body. There are around 470 million diabetic cases around the globe and is anticipated to be around 700 millions by 2045 [1]. The diabetes could also lead to other diseases such as blood pressure, cardiovascular disease, blindness, chronic kidney disease, alzheimer, hearing impairment etc. Therefore, the smart healthcare solution is required for better glycemic profile management to reduce the long term complication. The paper presents the insulin secretion for diabetic patients with integration of intelligent glucometer where insulin secretion occurs automatic as per current glucose value.

The healthcare sector has shifted its paradigm of traditional healthcare to smart healthcare using intelligent techniques. The smart healthcare has improved quality of care with aid of various components such as e-health, c-health, mobile-health and telemedicine [2]. The internet of medical things (IoMT) would provide the seamless integration of various physical systems with internet through Healthcare Cyber Physical systems (H-CPS). H-CPS would capture the vital pharmacological parameters through smart sensors and store them as electronic health record (EHR) for long term monitoring. It would allow to provide better personalised solution for better health management along with our daily life activities.

A. M. Joshi is with the Department of Electronics and Communications Engineering (ECE), Malaviya National Institute of Technology, Jaipur, E-mail: amjoshi.ece@mnit.ac.in.

Prateek Jain is with the School of Electronics Engineering (SENSE), VIT AP, Email: prtk.ieju@gmail.com.

S. P. Mohanty is with the Department of Computer Science and Engineering, University of North Texas, E-mail: saraju.mohanty@unt.edu.

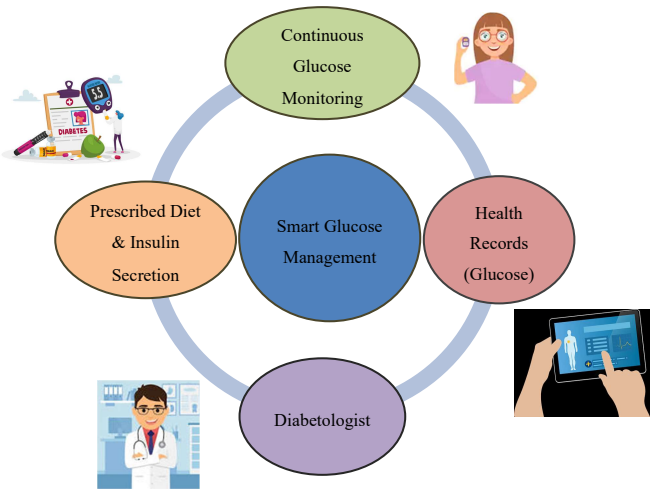


Fig. 1: Closed loop solution of Diabetes Care.

The integration of glucometer, diabetologist, patient and insulin drug delivery would allow to have point of care mechanism for better glucose control process. The intelligent glucose measurement device would provide recurrent glucose values which are stored at cloud as electronic health record. By observation, the diabetologist/dietician may provide the proper insulin/diet plan for diabetic person. The glucose-insulin balance is achieved with IoMT based closed loop control system (Fig. 1). The proposed glucose measurement is a IoMT integrated system which is useful for Continuous Glucose Monitoring (CGM) with automatic insulin delivery mechanism. It would provide easier way to interface with remotely located endocrinologist with diabetic person [3].

The flow of the paper is as follows: Section II provides the vision for secure glucose measurement with its control through IoMT. The main contribution and prior work is summarized in Section III. Proposed glucose-insulin model is covered in Section IV. The security model has been explained in Section V. The discussion about results are carried out in Section VI. Section VII concludes the work along with future directions.

II. Our Vision for Secure Glucose Monitoring and Control in IoMT Framework - iGLU 3.0

The diabetes can be managed very well through frequent glucose monitoring and its appropriate control mechanism [4]. The insulin secretion is necessary for diabetic patients with proper insulin dosage with real-time glucometer reading. The diabetologist would able to access the content from remote location and provide the necessary inputs for glucose

control. The data could be stored at cloud for better diabetes management.

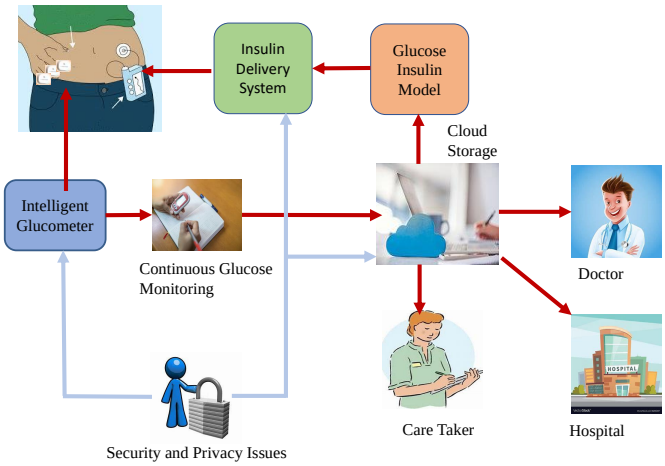


Fig. 2: Security Challenges in Insulin Delivery with CGM.

Our vision for glucose control through IoMT framework has been illustrated in Fig. 2. The continuous glucose measurement has been provided through non-invasive intelligent glucometer called iGLU with optical detection mechanism [5]. *The current paper is extension of our earlier work iGLU1.0 and iGLU 2.0 with automatic insulin deliver and security model for insulin delivery in iGLU 3.0.* The glucose insulin model has been proposed with glucose consumption parameters to have balanced glycemic profile with insulin secretion mechanism through IoMT framework [6]. The secure insulin delivery system for better glucose management is presented in this paper. There are several challenges for development of secure insulin delivery system iGLU3.0 as follows: (1) The privacy of personalised electronics health records of diabetic patients at the cloud server. (2) the hardware security of the medical devices (insulin pump, glucometer) for proper insulin secretion mechanism. (3) The data integration of the medical records transfer from glucose measurement device to cloud and from cloud to insulin drug delivery system.

The glucose insulin model has been developed for glucose control for diabetes people using plasma insulin level, net glucose level and glucose excursion level. The proposed insulin delivery system would decide the amount of insulin secretion for insulin pump through glucose insulin model [7]. The model would calculate the precise insulin dosage as per plasma insulin level and various glucose consumption parameters. The insulin injection could be controlled under the supervision of remotely residing medical experts through IoMT network. The automation of insulin secretion could be done for better personalised treatment. The proper diet plan and prescribed treatment would be recommended from health experts for proper glucose insulin balance.

The authentication of the medical things in IoT is essential in order to have reliable insulin delivery mechanism [8]. Physical Unclonable Function (PUF) is the one of the powerful and cost-effective method for the authenticity of hardware. PUF uses the variability which is being present at the time of manufacturing of the hardware chips. PUF is one small digital circuit which carries challenge-response pair of each embedded chip which cannot be cloned. PUF is considered as a method where responses are stored as physical medium [9]. PUF is a simple and efficient approach and can be designed with small dedicated hardware. The small foot print of PUF is applied inside the glucometer and insulin pump to have hardware trust inside the closed loop glucose-insulin delivery system.

III. Prior Research Work and Novel Contribution

A. Related Work and Consumer Products

The smart healthcare is one of fastest growing sector with estimation of $176 billion by 2026. The integration of IoT in healthcare technologies has enabled affordable and effective solution for patient treatment. The smart healthcare solution of Neuro-Detect was proposed using EEG with machine learning model [10]. The automatic seizure detection system was designed with DWT and DNN methods using IoT framework. Similarly, Smart IoT-Edge gateway for wellness care was developed for heterogeneous medical devices [11]. Novel Structure of packet generation was devised to resolve the interoperability issues of healthcare sensors for consumers' medical ecosystems. The Smart-Yoga Pillow was developed to monitor the physiological parameters using IoT framework [12]. The stress managements was analysed and the stress level was predicted during sleeping time. For diabetes management, the CGM technology has allowed to observe the blood glucose concentration frequently throughout the day. The concept of artificial pancreas was defined with CGM for diabetes control with insulin secretion model [13].

Various insulin delivery system are available in the market such as Mediotronics MiniMed 640G with gaurdian sensor 3 CGM which requires atleast two times daily calibration. Another FDA approved Tandem Control-IQ system with Dexcom G6 CGM which does not have any fingertip calibration requirement [14] but uses invasive approach for blood glucose measurement. Aminas Vibe technology has better accuracy using Dexcom G4 CGM which corrects at midpoint of the target range of blood glucose. Similarly, OmniPod system can have wireless insulin management without multiple daily injections. To the best of knowledge, all the insulin delivery system either use invasive glucose measurement or require multiple calibration in a day. They are not supported with security measures and automatic insulin delivery mechanism.

B. Novel Contributions of the Current Paper

The "intelligent glucometer iGLU 1.0" was proposed as precise noninvasive edge device as low cost solution for CGM. It is IoMT integrated portable device with short NIR based reflectance and absorption spectroscopy [15]. The machine learning models were used for accurate glucose prediction. The iGLU 1.0 was calibrated and validated on diabetic, pre-diabetic and healthy real-world subjects.

Then, iGLU 2.0 was developed for precise serum glucose measurement with dual-NIR spectroscopy. It allows to have accurate blood glucose estimation with non-invasive approach. The polynomial regression models and deep neural network

(DNN) were proposed to have precise serum glucose estimation [16]. The iGLU 2.0 was capable to estimate serum glucose from 80 mg/dl to 420 mg/dl with all types of diabetic patients.

The current paper presents the concept of CGM with secure insulin delivery system iGLU 3.0 which provides IoMT integrated continuous glucose monitoring. It is novel secure glucose measurement solution for rapid diagnosis and glucose control using closed loop control system. The proposed paper has following significant contribution as follows:

- The cost-effective solution is designed with hardware security for closed loop insulin delivery system.
- The iGLU 3.0 provides area-efficient and low power security protocol suited for IoMT network.
- The novel glucose-insulin model is developed with continuous glucose monitoring.
- The various glucose consumption parameters are considered with glucose and plasma insulin variations for prescribed diet and insulin delivery mechanism.
- The closed loop insulin delivery system is developed by IoMT integrated for automatic insulin secretion with current serum glucose measurement.

IV. Proposed Glucose-Insulin Model for iGLU 3.0

The proposed glucose insulin model is integrated with iGLU with real-time glucose measurement and the insulin dosage is calculated as per current blood glucose level. The insulin delivery system has been developed to have proper insulin glucose control as shown in Fig. 3.

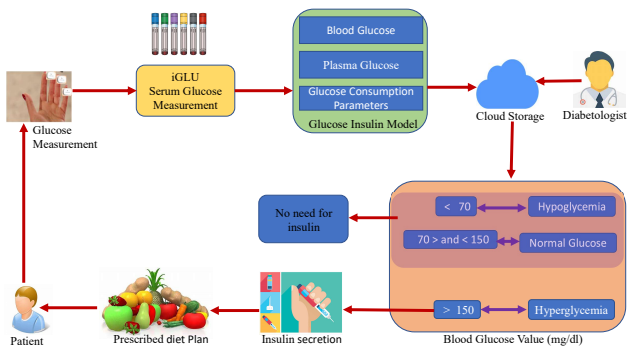


Fig. 3: Insulin Delivery System with IoMT framework

A. Closed Loop Insulin Delivery System

The person glucose would be measured continuously using intelligent glucometer iGLU. The consumption of food would result in the glycemic profile variation inside the body. In human, the islets of pancreases is responsible to generate the specific hormones inside the body. The alpha and beta cell have main role for glucose insulin balance inside the body. The beta cell would generate insulin which leads to lower the blood glucose value. This would help to maintain blood glucose in normal range. However, the alpha cell is responsible to produce glucagon where blood glucose value tends to increase which is considered as hyperglycemia known as diabetes. In such case, the blood glucose could be controlled through insulin secretion for diabetic person or it is managed with routine exercise and proper diet plan. The blood glucose of normal range varies from 70 mg/dl to 150 mg/dl for fasting as well as in prandial modes. The proper balance of glucose and insulin would help to keep the blood glucose within the normal range. However, if the blood glucose concentration remains high for prolong period then there is a requirement of insulin secretion inside the body.

B. Proposed Glucose Insulin Model

The current paper presents novel glucose insulin model which has considered plasma and glucose variation parameters. The model includes hepatic glucose, renal threshold glucose, hepatic glucose balance, intestinal absorption, plasma and glucose level. The differential equations for plasma insulin I_P is defined by the following expression:

$$\frac{dI_P}{dt} = \left(\frac{I_{absorb}}{V_{oi}}\right) - P_{ie} \times I_P \tag{1}$$

whereas, I_{absorb} denotes the absorbance rate of the insulin, V_{oi} defines the insulin distribution volume and P_{ie} is rate constant of insulin elimination. The active insulin rate change with first order kinetics is defined as the following:

$$\frac{dI_{Act}}{dt} = (P_1 \times I_P) - (P_2 \times I_{Act}) \tag{2}$$

In the above expression, the rate constants of insulin action delay is represented as P_1 and P_2. The rate of absorption of insulin is expressed as:

$$I_{absorb}(t) = \left(\frac{I_{type} \times t \times T_{D50}^5 \times D}{t[T_{D50}^5 + t^5]^2}\right) \tag{3}$$

As shown in above eqn.(3), the time for insulin secretion is denoted as t. t_{D50} denotes the time taken to consume around 50% of total insulin dose D and I_{type} is type of insulin dosage among short, intermediate and long-acting type. The insulin dosage for t_{D50} is defined by eqn.(4):

$$t_{D50}^5 = p \times D + q \tag{4}$$

In this case, the parameters p and q relates insulin dose and time taken for 50% insulin dosage. Therefore, $I_{absorb}(t)$ is denoted by the following expression:

$$I_{absorb}(t) = \left(\frac{I_{type} \times t(p \times D + q) \times D}{t[p \times D + q + t^5]^2}\right) \tag{5}$$

If multiple insulin dosages are required then the total absorbed insulin I_{absorb} is the sum of each insulin absorption from injections. The insulin of steady-state is cumulative summation of insulin over the period of three days and is represent as follows:

$$I_{steady}(t) = I(t) + I(t+12) + I(t+24) + I(t+48) \tag{6}$$

The eqn. (6) is not valid for short-acting insulin. The absorbed insulin of steady state is defined by the following expression:

$$I_{Act,steady}(t) = I_{Act}(t) + I_{Act}(t+12) + I_{Act}(t+24) + I_{Act}(t+48) \tag{7}$$

The equilibrium insulin is expressed using steady state insulin as follows:

$$I_{equil}(t) = P_2 \left(\frac{I_{Act,steady}(t)}{P_1} \right). \tag{8}$$

The following expression would be useful for the calculation of net hepatic glucose balance (NHGB) and glucose uptake for peripheral:

$$I_{equil}(t) = P_2 \left(\frac{I_{Act}(t) + I_{Act}(t+12) + ... + I_{Act}(t+48)}{P_1} \right) \tag{9}$$

Subsequently, the change of glucose value with time is represented as by differential Eqn.(10):

$$\frac{dG_{plasma}}{dt} = G_{tot} + G_{rc} \tag{10}$$

Here, G_{tot} represents total body glucose without consumption and is expressed as:

$$G_{tot} = \frac{[NHGB(t) + G_{abgut}(t)]}{V_g} \tag{11}$$

In the above expression, the absorbed glucose from the gut is represented as $G_{abgut}(t)$.

Similarly, In eq.(10), G_{rc} denotes renal and consumed excreted glucose and it is expressed as:

$$G_{rc} = \frac{[G_{aiu}(t) + G_{ren}(t)]}{V_g} \tag{12}$$

the peripheral consumption and insulin glucose is denoted as $G_{aiu}(t)$. The renal excretion of glucose is $G_{ren}(t)$. The distribution volume of glucose is defined as V_g.

As per Michaelis-Menten theorem, the plasma glucose is defined by the various glucose consumption parameters with insulin concentration reflection:

$$G_{aiu}(t) = \left(\frac{G_{plasma}[(c.I_{eff} + G_{ii})(k + G_{ref})]}{G_{ref}(k + G_{plasma})} \right) \tag{13}$$

In the above expression, c represents the slop between glucose in peripheral and insulin, G_{ii} defines utilization of the glucose without insulin consideration, the reference glucose consumption is G_{ref}. I_{eff} defines the effective level of the insulin and it is the following:

$$I_{eff} = [S_p \times I_{equil}] \tag{14}$$

The gut has the glucose as mean of the carbohydrates as calculated by the following expression:

$$\Delta G_{gut} = G_{Emp} - G_{cons} \tag{15}$$

where the glucose concentration in gut is G_{gut}, the empty gestric is G_{Emp}. G_{cons} represents the consumption of glucose with systematic circulation and is denoted as

$$G_{cons} = K_{gabsorb} \times G_{gut} \tag{16}$$

The insulin delivery model has been developed which suggests the relationship of steady-state active insulin concentration and glucose consumption. The relationship describes insulin delivery mechanism and the different model parameters as in Table I.

TABLE I: Model Parameters of Glucose Insulin Control

Parameter	Notation	Value
Insulin Elimination Rate Constant	P_{ie}	5.4 l/hr
Insulin Delay Rate Constant	P_1	0.025 l/hr
Michaelis constant	k	10 mmol/l
Glucose usage without Insulin	G_{ii}	0.54 mmol/hr/kg
Reference Glucose consumption	G_{ref}	5.3 mmol/l
Glucose Insulin Peripheral slope	c	0.015 mmol/hr/kg/mU*l
Glucose absorption Gut Constant	$k_{gabsorb}$	1/hr
volume for Insulin Distribution	V_{oi}	0.142 l/kg

V. Our Proposed Secure iGLU 3.0

The traditional cryptography approaches are not suited for medical devices as they have low power and less area requirement. The hardware security of insulin delivery system is required where the glucose measurement device and insulin pump are operated in open insecure environment where the adversary can have the control of the devices. PUF is a useful hardware security primitive where unique fingerprint is extracted as a secret key from medical device. Moreever, it is not possible to clone similar key from other medical device. The hardware assisted security using PUF for iGLU 3.0 is shown in Fig. 4 which includes insulin pump, iGLU device, central server and controller node. PUF is useful to identify the trusted hardware for our proposed automatic insulin delivery system. PUF concept is based on the pair of Challenge-Responses which are stored at Edge-Datacenter (EDC) and connected to devices through IoMT. The Challenge-Response Pair (CRP) would play an vital role to identify the each hardware using authentication protocol.

PUF concept exploits the physical disorder of the hardware through external stimuli of challenges to have corresponding responses [17]. PUF depends on nano-scale disorders introduced during the manufacturing which cannot be reproduced by the same manufactures again. It is almost impossible to clone the same hardware with a similar disorder as it introduces a unique random key from each chip which is to be considered as a hardware-specific fingerprint. PUF provides a potential solution for secret key storage as well as authentication without much storage [18]. Hence, PUF could be a promising candidate to provide hardware security of glucometer and insulin pump.

A. Secure-iGLU Architecture

Silicon PUF is a useful to generate a unique response from the device by extracting the manufacturing variation. It is implemented on FPGA based reconfigurable hardware to extract the process variation of hardware chips. Arbiter PUF (APUF) is considered in the proposed system where two identical path are configured by activating the signal as shown in Fig. 5. The APUF consists of two main components known as arbiter and Muxes. The path difference is created with various challenges where the difference is observed with

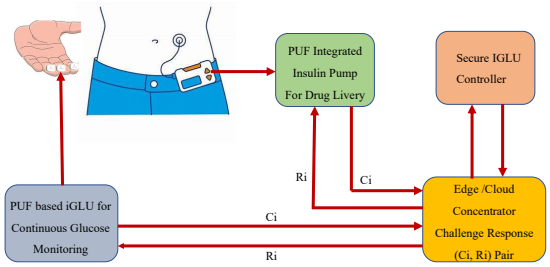


Fig. 4: PUF based Hardware-Assisted Security on iGLU 3.0.

an edge trigger D FF know as arbiter. The response bit is generated as 1 if first path is faster than second otherwise it is 0. The increase of response bits could be n times by duplication of the same hardware with n times.

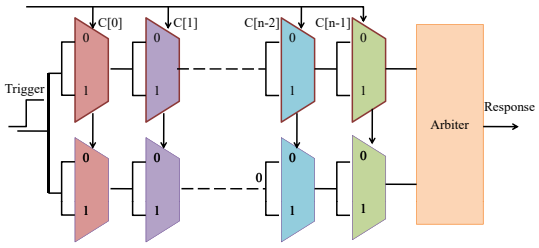


Fig. 5: Arbiter PUF Topology.

B. PUF based iGLU Device Security

The hardware security is developed using PUF based lightweight authentication protocol. The proposed low-cost solution is useful to find the trusted hardware (iGLU, insulin pump) in the IoMT network. The proposed security mechanism comprises of two phases: (i) Enrollment Phase and (ii) Authentication Phase

1) PUF based Enrollment in iGLU 3.0: The enrollment phase is conducted by manufacturer of the device at design house with secure and safe environment at 25°C. The CRPs have been collected for each device after the fabrication process. It is assumed that CRPs of every devices are stored at Edge-Data-center (EDC) after the successfully customer authentication process. The steps for enrollment has been explain in Algorithm 1.

Algorithm 1 Enrollment Phase for the devices

Input : X total number of input devices
Output : Challenge Response Pairs for X devices
  for k **do** $\leftarrow$ 0 to X do
  Assign ID_k for the device k
  Generate PRNG with unique polynomial
  N_0, N_1,....., N_t $\leftarrow$ TRNG
    for i **do** $\leftarrow$ 0 to t do
  C_i $\leftarrow$ PRNG (N_i)
  Send C_i $\rightarrow$ Device to be identified
  R_i $\leftarrow$ PUF (C_i)
    end for
  end for

2) PUF based Authentication for iGLU 3.0: The hardware authentication is done through the verification of store CRPs in the database. Every medical device of IoMT has its unique ID which are used for initialization for the authentication phase. The authentication phase is explained as Algorithm 2. The challenges are applied to the devices which generate responses correspondingly. At authentication phase, the response bits are compared with available responses at CRPs for the specific challenge at data-concentrator unit to identify the trusted device. Every medical device has been assigned with unique ID in the IoMT network.

Algorithm 2 Authentication Phase for Device Identification

  for i= 1 to M **do**
  EDC generates Pseudo Random Number Generator P.
  EDC has access of Device ID for each hardware which is unique
    $A \leftarrow R$ xor ID
  Device would receive A and extract R with ID.
  From EDC, Send
    $A^{'} \leftarrow R$ xor C_i,here C_i= Challenges
  Device receives $A^{'}$, subsequently extract C_i with the help of R.
  Further, device produces the response $R_i^{'}$, again it sends
    $A^{''} \leftarrow R$ xor $R_i^{'}$
  Now, EDC extracts $R_i^{'}$ from $E^{''}$ with help of R.
  At EDC side,
    if $R_i^{'}$ = R_i **then**
  then, Next challenges applied for further authentication
  else
  Unauthenticated Device and process terminates
    end if
  end for

In order to have device authentication, large number of challenges are applied where response bits are observed. Every time, the received response bits are compared with responses of the database then process of authentication continue otherwise the device is considered as unauthenticated.

3) Threat Analysis of PUF for iGLU 3.0: In PUF, the secret information is derived from the physical properties of the hardware. Therefore, it would be difficult to execute invasive attacks for changes in physical characteristics which replicate the same hardware properties. At the same time, the physical attack requires power on for a substantial time of the hardware to derive the physical characteristics that can help to predict the PUF performance [19]. There are several machine learning-based modeling attacks and side-channel attacks have been explored to verify the robustness of PUF. However, such ML algorithms require some parameter tuning in order to work effectively [20]. The paper has arbiter PUF which is considered as one of the strongest PUF with a large Challenge-Response Pairs (CRPs). The adversary would find it hard to enumerate all possible CRPs in a fixed time computationally even by using intensive ML algorithms.

VI. Experimental Results

A. Validation of Drug Delivery in iGLU 3.0

The proposed glucose insulin model has been validated on four real-time subjects as per medical protocols under the observation of endocrinologist. The analysis of diet schedule, diabetes level, physiological parameters, insulin secretion and

frequent blood glucose reading have been carried out. The glucose is monitored closely for each individual case by following prescribed diet plan for diabetes control. The simulation is carried out with necessary functional parameters to observe the blood glucose level. The proposed model has been investigated under various condition for proper diabetes management. The details of the subject is defined in Table II.

TABLE II: Details of subject for glucose insulin model validation

Case	Age (yrs)	Weight (kg)	Gender	Observation
1	32	70	Female	Three injection of short-acting insulin daily, She is pregnant and usually higher blood glucose at morning.
2	45	68	Male	Short or intermediate insulin dosage four times a day. He used to have low glucose at day & high glucose at night.
3	58	98	Female	Smoking habit with heart attack. Frequent hungriness due to insulin secretion and adjust carbohydrate using diet.
4	18	70	Male	Improper diet due to hostel life,low glucose at starting of day. Monitoring of the plasma insulin level is done recurrently, Use prescribed insulin dosage.

The plasma level of insulin and glucose consumption parameter is observed in Fig. 6. The transient response is also shown for proper diet plan and insulin delivery system. The diet plan is considered as breakfast, pre-lunch snack, lunch, evening snack and dinner with carbohydrates with multiple cases. The long and short insulin dosage is scheduled for all cases. The glucose insulin model is applied for glucose profile control and the observation is defined in Fig. 6 for all cases.

The proposed glucose-insulin model is compared with similar state of art work in Table III. Most of previous work was based on UVA/Padova simulator with virtual subjects for validation purpose. However, our model is validated with real subjects for glucose control. The proposed system has only considered the hardware security for safe automatic insulin delivery mechanism.

B. Validation of Security in iGLU 3.0

The security of iGLU 3.0 has been obtained through PUF and the performance has been verified with various qualitative parameters such as Reliability, Uniformity and Uniqueness which are shown in Table IV. The validation has been carried out on forty FPGA boards. The challenges-responses pairs for each boards have been stored at Block RAM. The set-up is prepared using hardware-software interface and experiments results are obtained at room temperature at 25°C.

The responses from Arbiter PUF are collected using Logic Analyzer. The reliability with varying temperature values using temperature chamber (Table V). It is being computed with intra-chip hamming distance which defines the number of response bits flipped because of temperature variation.

The proposed work has been compared with previous work for Secure IoMT framework as shown in Table VI. There have been various level of security mechanisms developed for different applications hence it is difficult to have the fair comparison. The results show that iGLU 3.0 focuses on hardware security of glucometer and insulin pump for safe insulin delivery system.

VII. Conclusions and Future Research

The paper covers iGLU 3.0 concept which has glucose insulin model integrated with non-invasive glucose measurement device and also has hardware security model. iGLU 3.0 comprises automatic insulin drug delivery mechanism for better glucose control with secretion of insulin amount as per present glucose value. It is also integrated with IoMT framework with recurrent glucose measurement where values are stored at cloud for long term observation. The proposed iGLU 3.0 incorporates efficient glucose-insulin model where simulation are carried out on real-subjects with prescribed insulin secretion and diet plan. The model is developed with plasma and glucose variation for diabetes control. The paper also covers PUF based efficient hardware security module for insulin pump and iGLU device. The security measurement is validated with implementation of Arbiter PUF on two FPGA family of 28 nm technology. The results show the suitability of proposed security protocol for hardware security in iGLU 3.0.

In future, the issue of the data integrity could be solved for iGLU 3.0 framework. The secure robust system level solution could be designed for tolerance against various channel attacks. The error control codes could be integrated to improve the reliability against various environmental variation. The glucose-insulin model could be further improved with more parameters for better glucose management. The model could be validated on more real-subjects with hypoglycemia and hyperglycemia cases.

References

[1] A. M. Joshi, P. Jain, and S. P. Mohanty, "Everything you wanted to know about continuous glucose monitoring," *IEEE Consum. Electron. Mag.*, vol. 10, no. 6, pp. 61–66, Nov 2021.

[2] P. Sundaravadivel, E. Kougianos, S. P. Mohanty, and M. K. Ganapathiraju, "Everything you wanted to know about smart health care: Evaluating the different technologies and components of the internet of things for better health," *IEEE Consum. Electron. Mag.*, vol. 7, no. 1, pp. 18–28, Jan 2017.

[3] J. Yang, L. Li, Y. Shi, and X. Xie, "An ARIMA model with adaptive orders for predicting blood glucose concentrations and hypoglycemia," *IEEE J. Biomed. Health Inform.*, vol. 23, no. 3, pp. 1251–1260, 2018.

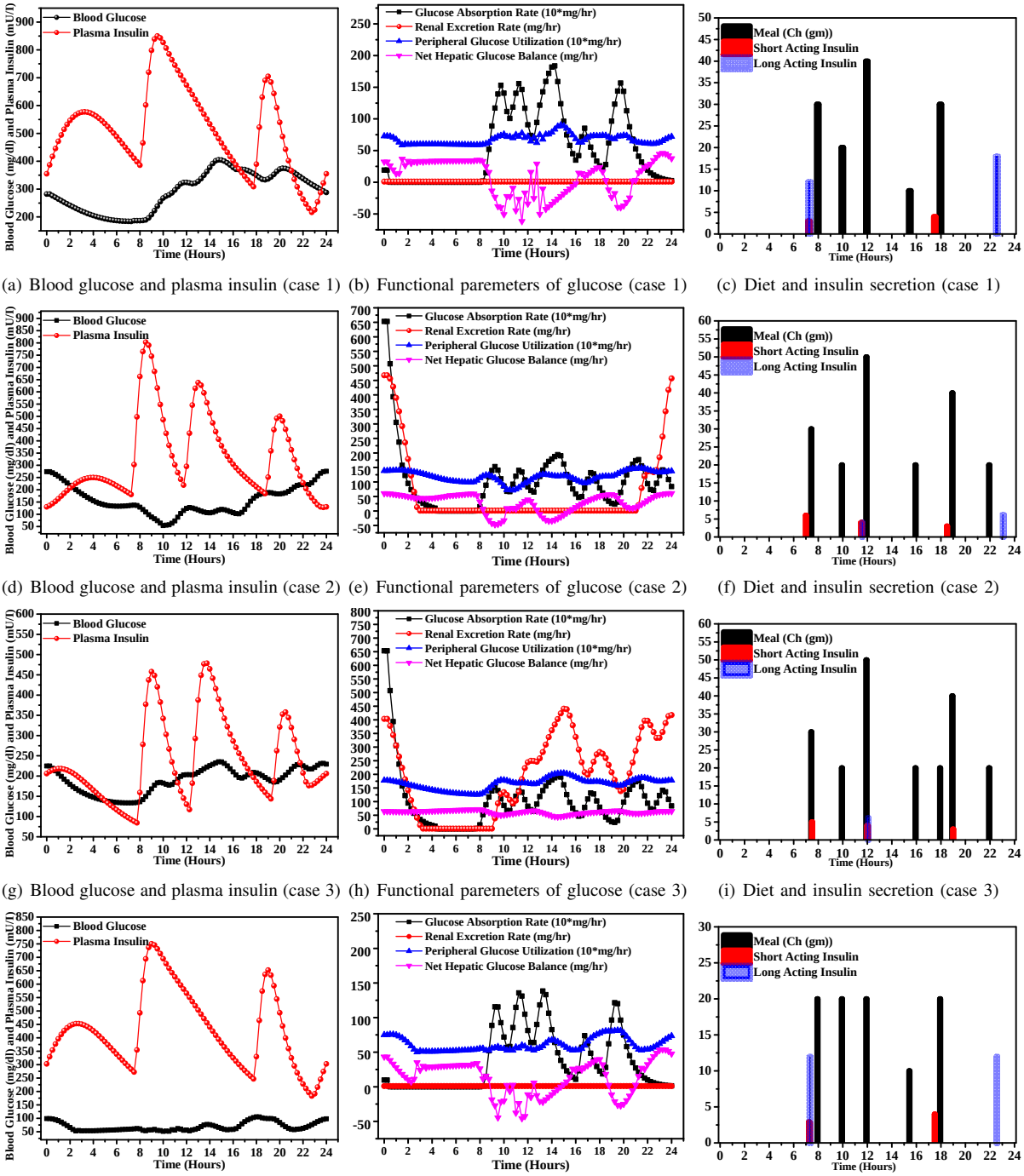
[4] K. Li, J. Daniels, C. Liu, P. Herrero, and P. Georgiou, "Convolutional recurrent neural networks for glucose prediction," *IEEE J. Biomed. Health Inform.*, vol. 24, no. 2, pp. 603–613, 2019.

[5] P. Jain, A. M. Joshi, and S. P. Mohanty, "iGLU: an intelligent device for accurate noninvasive blood glucose-level monitoring in smart healthcare," *IEEE Consum. Electron. Mag.*, vol. 9, no. 1, pp. 35–42, 2019.

[6] P. Jain, S. Pancholi, and A. M. Joshi, "An IoMT based non-invasive precise blood glucose measurement system," in *Proc. IEEE Int. Sympo. Smart Elect. Sys.*, 2019, pp. 111–116.

[7] C. Toffanin, L. Magni, and C. Cobelli, "Artificial pancreas: In silico study shows no need of meal announcement and improved time in range of glucose with intraperitoneal vs subcutaneous insulin delivery," *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 2, pp. 306–314, 2021.

[8] A. M. Joshi, P. Jain, and S. P. Mohanty, "Secure-iGLU: A secure device for noninvasive glucose measurement and automatic insulin delivery in iomt framework," in *Proc. IEEE-CS Annu. Symp. VLSI,*, 2020, pp. 440–445.



(a) Blood glucose and plasma insulin (case 1) (b) Functional paremeters of glucose (case 1) (c) Diet and insulin secretion (case 1)

(d) Blood glucose and plasma insulin (case 2) (e) Functional paremeters of glucose (case 2) (f) Diet and insulin secretion (case 2)

(g) Blood glucose and plasma insulin (case 3) (h) Functional paremeters of glucose (case 3) (i) Diet and insulin secretion (case 3)

(j) Blood glucose and plasma insulin (case 4) (k) Functional paremeters of glucose (case 4) (l) Diet and insulin secretion (case 4)

Fig. 6: Simulated functional parameters with glucose-insulin levels and schedules for All cases.

TABLE III: Comparison with State of the Art Works on Glucose Delivery.

Research Works	Method	Type of Subjects	Total Patients	Automatic Insulin	Security
Turksoy, et al. [21]	Minimal Model & Kalman Filter	Virtual	9	No	No
Xie, et al. [22]	Variable State Dimension & Kalman Filter	Virtual	30	No	No
MohammadRidha, et al. [23]	Intelligent proportional-integral-derivative	Virtual	15	Yes	No
Ramkissoon, et al. [24]	Minimal Model & Unscented Kalman Filter	Virtual	10	No	No
Meneghetti, et al. [25]	Unsupervised	Virtual	100	Yes	No
Meneghetti, et al. [26]	Autoregressive Moving Average Model	Virtual	50	Yes	No
Current Paper (iGLU 3.0)	Glucose Insulin Model	Real	4	Yes	Yes

TABLE IV: Experimental Analysis of iGLU3.0.

Parameters	3-Stages	5-Stages	7-Stages
Uniqueness (%)	40.7	41.5	42.3
Uniformity (%)	61.0	60.0	58.0
Reliability (25°C) (%)	96.0	97.5	95.5

TABLE V: Reliability of Arbiter-PUF in iGLU 3.0.

Temperature	Intra HD	Reliability
15°C	0.43	94.3
20°C	0.44	95.8
25°C	0.46	97.5
30°C	0.45	96.2

[9] J. Delvaux, D. Gu, D. Schellekens, and I. Verbauwhede, "Helper data algorithms for PUF-based key generation: Overview and analysis," *IEEE Trans. Comput.-Aided Design Integr. Circuits Syst.*, vol. 34, no. 6, pp. 889–902, 2014.

[10] M. A. Sayeed, S. P. Mohanty, E. Kougianos, and H. P. Zaveri, "Neuro-Detect: a machine learning-based fast and accurate seizure detection system in the IoMT," *IEEE Trans. Consum. Electron*, vol. 65, no. 3, pp. 359–368, 2019.

[11] P. P. Ray, N. Thapa, and D. Dash, "Implementation and performance analysis of interoperable and heterogeneous IoT-edge gateway for pervasive wellness care," *IEEE Trans. Consum. Electron*, vol. 65, no. 4, pp. 464–473, 2019.

[12] L. Rachakonda, A. K. Bapatla, S. P. Mohanty, and E. Kougianos, "SaYoPillow: Blockchain-integrated privacy-assured iomt framework for stress management considering sleeping habits," *IEEE Trans. Consum. Electron*, vol. 67, no. 1, pp. 20–29, Feb 2021.

[13] P. Jain, A. M. Joshi, and S. P. Mohanty, "iGLU 1.1: Towards a glucose-insulin model based closed loop iomt framework for automatic insulin control of diabetic patients," in *Proc. IEEE 6th World Forum Internet Things (WF-IoT)*, 2020, pp. 1–6.

[14] C. Berget, S. Lange, L. Messer, and G. P. Forlenza, "A clinical review of the t:slim X2 insulin pump," *Expert Opin. Drug Deliv.*, vol. 17, no. 12, pp. 1675–1687, 2020.

[15] P. Jain, R. Maddila, and A. M. Joshi, "A precise non-invasive blood glucose measurement system using nir spectroscopy and huber's regression model," *Opt. Quantum Electron.*, vol. 51, no. 2, p. 51, 2019.

[16] A. M. Joshi, P. Jain, S. P. Mohanty, and N. Agrawal, "iGLU 2.0: A new wearable for accurate non-invasive continuous serum glucose measurement in iomt framework," *IEEE Trans. Consum. Electron*, vol. 66, no. 4, pp. 327–335, Nov 2020.

[17] Y. Xu, Y. Lao, W. Liu, Z. Zhang, X. You, and C. Zhang, "Mathematical modeling analysis of strong physical unclonable functions," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 39, no. 12, pp. 4426–4438, 2020.

[18] S. Kalanadhabhatta, D. Kumar, K. K. Anumandla, S. A. Reddy, and A. Acharyya, "Puf-based secure chaotic random number generator design methodology," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 28, no. 7, pp. 1740–1744, 2020.

[19] U. Ruhrmair and J. Solter, "PUF modeling attacks: An introduction and overview," in *Proc. Design, Automation & Test in Europe Conference & Exhibition (DATE)*, 2014, pp. 1–6.

[20] Y. Liu, S. Arunachalam, and K. Temme, "A rigorous and robust quantum speed-up in supervised machine learning," *Nature Physics*, vol. 17, no. 9, pp. 1013–1017, 2021.

[21] K. Turksoy, S. Samadi, J. Feng, E. Littlejohn, L. Quinn, and A. Cinar, "Meal detection in patients with type 1 diabetes: a new module for the multivariable adaptive artificial pancreas control system," *IEEE J. Biomed. Health Inform.*, vol. 20, no. 1, pp. 47–54, 2015.

[22] J. Xie and Q. Wang, "A variable state dimension approach to meal detection and meal size estimation: in silico evaluation through basal-bolus insulin therapy for type 1 diabetes," *IEEE Trans. Biomed. Eng.*, vol. 64, no. 6, pp. 1249–1260, 2016.

[23] T. MohammadRidha, M. Aït-Ahmed, L. Chaillous, M. Krempf, I. Guilhem, J.-Y. Poirier, and C. H. Moog, "Model free iPID control for glycemia regulation of type-1 diabetes," *IEEE Trans. Biomed. Eng.*, vol. 65, no. 1, pp. 199–206, 2017.

[24] C. M. Ramkissoon, P. Herrero, J. Bondia, and J. Vehi, "Unannounced meals in the artificial pancreas: detection using continuous glucose monitoring," *Sensors*, vol. 18, no. 3, p. 884, 2018.

[25] L. Meneghetti, M. Terzi, S. Del Favero, G. A. Susto, and C. Cobelli, "Data-driven anomaly recognition for unsupervised model-free fault detection in artificial pancreas," *IEEE Trans. Control Syst. Technol.*, vol. 28, no. 1, pp. 33–47, 2018.

[26] L. Meneghetti, A. Facchinetti, and S. Del Favero, "Model-based detection and classification of insulin pump faults and missed meal announcements in artificial pancreas systems for type 1 diabetes therapy," *IEEE Trans. Biomed. Eng.*, vol. 68, no. 1, pp. 170–180, 2020.

[27] J.-X. Hu, C.-L. Chen, C.-L. Fan, and K.-h. Wang, "An intelligent and secure health monitoring scheme using iot sensor based on cloud computing," *J. Sens.*, vol. 2017, 2017.

[28] M. Wazid, A. K. Das, N. Kumar, M. Conti, and A. V. Vasilakos, "A novel authentication and key agreement scheme for implantable medical devices deployment," *IEEE J. Biomed. Health Inform.*, vol. 22, no. 4, pp. 1299–1309, 2017.

[29] H. Tao, M. Z. A. Bhuiyan, A. N. Abdalla, M. M. Hassan, J. M. Zain, and T. Hayajneh, "Secured data collection with hardware-based ciphers for IoT-based healthcare," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 410–420, 2018.

[30] V. P. Yanambaka, S. P. Mohanty, E. Kougianos, and D. Puthal, "PMsec: Physical unclonable function-based robust and lightweight authentication in the internet of medical things," *IEEE Trans. Consum. Electron*, vol. 65, no. 3, pp. 388–397, 2019.

[31] B. Deebak and F. Al-Turjman, "Smart mutual authentication protocol for cloud based medical healthcare systems using internet of medical things," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 2, pp. 346–360, 2020.

TABLE VI: Comparison with works on Cybersecurity of Internet of Medical Things (IoMT).

Previous Work	security	Application	Features
Hu, et al. [27]	Cryptography and cloud computing	Continuous Monitoring of Elderly People	Confidential information uploaded to cloud through authentication
Wazid, et al. [28]	Lightweight three-factor remote user authentication scheme	Secure authentication scheme for Implantable Medical Devices	Formal security verification with AVISPA tool to verify the security against the man-in-the middle attacks and reply attacks.
Tao, et al. [29]	KATAN secret cipher algorithm	Privacy and Security of patient personalised healthcare data	SecureData based scheme for energy cost, frequency, and overall computation cost against attacks.
Yanambaka, et al. [30]	Lightweight authentication with PUF	Hardware Security of medical devices in IoT network	Low power Hybrid Oscillator Arbiter PUF for medical device authentication in IoT network
Deebak & Al-Turjman [31]	Enhanced mutual authentication protocol	Remote Health Monitoring System	Smart service authentication (SSA) framework for better data security in Telecare Medical Information System (TMIS)
Current Paper (iGLU 3.0)	Device Authentication using PUF	Secure Automatic Insulin Delivery System	Hardware security of iGLU with insulin pump for safe drug delivery mechanism

Amit M. Joshi (Senior Member, IEEE) received the Ph.D. degree from the NIT, Surat, India. He is currently an Assistant Professor in Department of ECE, MNIT, Jaipur. He is an author of 70+ peer-reviewed publications. His current research interests include biomedical signal processing, smart healthcare, VLSI DSP systems, and embedded system design. He received the UGC Travel Fellowship, the SERB DST Travel Grant, and the CSIR Travel Fellowship to attend IEEE Conferences in VLSI and Embedded System. He is a regular reviewer of 15+ journals and 40+ conferences. He has advised 09 Ph.D. and 18 Masters thesis.

Prateek Jain (Member, IEEE) received PhD degree from MNIT Jaipur, India. He is currently an Assistant professor with School of electronics engineering (SENSE), VIT AP University, Amaravati (AP), India. He is author of more than 15 peer reviewed publications. He is regular reviewer of many reputed journals and conferences. His current research interest include Embedded system design, Biomedical system and VLSI design.

Saraju P. Mohanty (Senior Member, IEEE) received the bachelor's degree (Honors) in electrical engineering from the Orissa University of Agriculture and Technology, Bhubaneswar, in 1995, the master's degree in Systems Science and Automation from the Indian Institute of Science, Bengaluru, in 1999, and the Ph.D. degree in Computer Science and Engineering from the University of South Florida, Tampa, in 2003. He is a Professor with the University of North Texas. His research is in "Smart Electronic Systems" which has been funded by National Science Foundations (NSF), Semiconductor Research Corporation (SRC), U.S. Air Force, IUSSTF, and Mission Innovation. He has authored 400 research articles, 4 books, and invented 7 granted/pending patents. His Google Scholar h-index is 45 and i10-index is 180 with 8500 citations. He is a recipient of 13 best paper awards, Fulbright Specialist Award in 2020, IEEE Consumer Electronics Society Outstanding Service Award in 2020, the IEEE-CS-TCVLSI Distinguished Leadership Award in 2018, and the PROSE Award for Best Textbook in Physical Sciences and Mathematics category in 2016. He has delivered 15 keynotes and served on 13 panels at various International Conferences. He has been the Editor-in-Chief of the IEEE Consumer Electronics Magazine during 2016–2021 and serves on the editorial board of multiple journals/transactions.