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Design and Verification of Noninvasive Wearable Continuous Blood Glucose Monitoring System for Smartwatches

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Abstract—In this paper, we propose a noninvasive blood glucose monitoring system that can be easily integrated into smartwatches. This system makes use of dielectric properties of blood-flow in human blood vessels as well as frequency dependency of blood glucose. To prove the proposed design principle, authors have verified the system working with vector network analyser and a directional coupler. The entire system design is explained in this paper. At the time of final system integration, the vector network analyser and directional coupler can be replaced with other on-chip sensors. Authors have also compared the obtained results with finger pricking based blood-glucose measurement. The results agree and have been tabulated. Clarke error grid was also used to evaluate the proposed system accuracy.

1. INTRODUCTION

Globally, 422 million people have diabetes, and the majority of them live in low- and middle-income nations. Diabetes is directly responsible for 1.5 million fatalities annually. Over the past few decades, there has been a consistent rise in both the number of cases and prevalence of diabetes [1].

The most common device for checking blood glucose levels (GLs) is glucometer, which is invasive. It is uncomfortable and painful to use this technique. Over the last ten years, researchers have looked into a variety of different methods for measuring blood glucose levels. They can be divided into two groups: minimally invasive and noninvasive [2]. The glucose-oxidase based electrochemical sensors are one example of a minimally invasive technique that is painful and uncomfortable, have delay artefacts, and place a significant socioeconomic load on the patient [3].

Some noninvasive techniques, like those that require samples of saliva [4], urine [5], tears [6], and breath [7], are not appropriate for continuous monitoring. In addition, researchers looked at other methods such reverse iontophoresis [8, 9], bio-impedance spectroscopy [10], infrared spectroscopy [11], and ultrasound [12]. But as of now, the alternatives to the glucometer have not been successful because they either lack the required accuracy and stability or have a significant time lag [13].

Electromagnetism (EM) is currently being studied as a key technique for noninvasive and continuous glucose monitoring (CGM) [14, 15]. In order to ascertain the GLs, the characteristics of the transmitted waves and reflected waves in terms of scattering parameters or S parameters are examined.

The World Economic Forum's most recent study on the top ten emerging technologies also confirms that the future of continuous glucose monitoring is confidently moving toward noninvasive wearable solutions that are painless and needle-free [16].

The focus of all current research and development must be on offering patients CGM options that do not require blood draw from the finger but rather use painless wireless techniques to monitor glucose fluctuations. In fact, research demonstrates that the community of diabetes people does not

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adhere to routine glucose monitoring because of traditional blood glucose monitoring methods that are uncomfortable, such as finger pricking [17, 18].

Through this paper, the authors propose a new system that can be integrated into smartwatches, and the user does not have to carry additional device. The paper has been arranged in a flow where system design goal and initial proposed concept are explained first. Authors then explain the necessity of specific human body model for this design and its design process. Next, the required antenna design is explained in detail, and its test results are discussed. Finally, lab testing of the proposed concept and its validation against existing methods are discussed. Finally, authors present the conclusion from this work.

2. SYSTEM DESIGN GOAL AND PROTOTYPE DESIGN APPROACH

Authors have started their research work with the goal of designing the truly noninvasive continuous blood glucose monitoring system. As discussed in the introduction section, most of the blood glucose measurement or monitoring systems are additional devices need to be carried by the user, whether diabetic or non-diabetic. Integrating these systems into smartwatches is difficult. Authors aimed to solve this problem through their proposed design. The proposed measurement principle is shown in Figure 1.

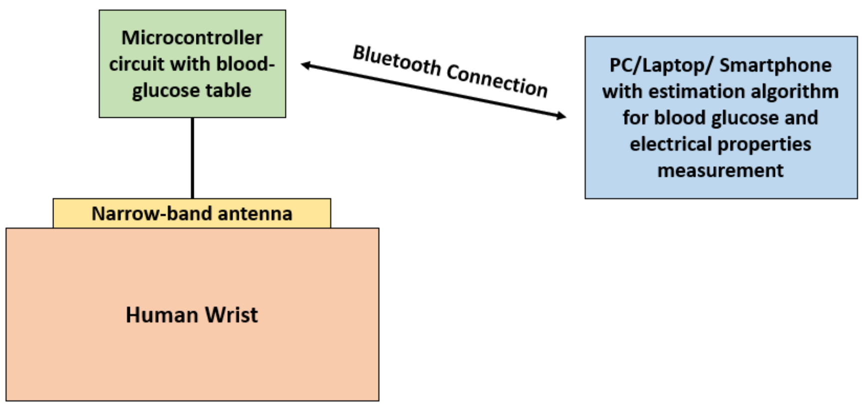

Figure 1. Initially proposed measurement principle. Conceptually, the narrow-band antenna and microcontroller circuit can be part of the smartwatch assembly.

To make this design work, authors had to establish the fact that changing concentration of blood glucose inside human body can change its dielectric properties. This change in dielectric properties can be used to detect the blood glucose value. The entire design flow and approach is shown in Figure 2.

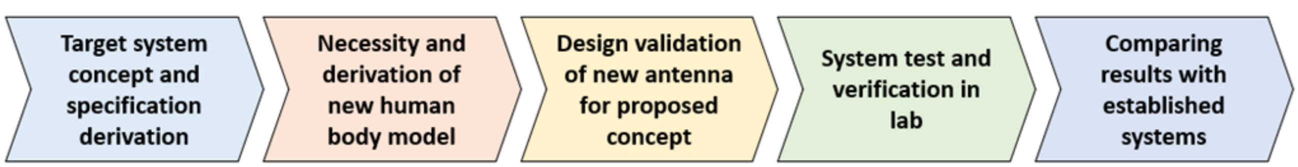

Figure 2. Complete system design flow followed for the system design and explained throughout this paper.

As already mentioned, authors wanted to integrate the proposed solution as part of the smartwatch, and the system requirements can be briefly specified as:

1. Final solution should be able to monitor blood glucose continuously. Hence, wearing and removing the system should be easy, and the user should be able to perform daily/routine tasks without

interference. Existing published systems need the user's finger, earlobe, or eye to be interfaced with the system, and in such cases, the user cannot do his/her routine tasks without getting distracted.

2. Antenna should work on 2.4 GHz band since most of the smartwatches have 2.4 GHz built-in antennas for other sensing and communication applications.
3. The system should accurately measure the blood-glucose using antenna, and these measurements should be comparable with other existing methods, for example, finger pricking.
4. Final solution should be easily integrated into a smartwatch.

2.1. Step 1: Human Body Model Derivation and Evaluation

As the first design step, authors conducted a survey of existing human body models so that they could simulate the system. Authors have found that there is no published human body model that can simulate the human blood flow inside arteries and veins so that its dielectric properties can be studied [19]. Hence, authors have developed their own human body model for this purpose, and the details can be found in [19]. This body model derivation steps are shown in Figure 3. The body model itself is shown in Figure 4. Both Figures 3 and 4 are reproduced from [19]. This human body model is used for further design and analysis.

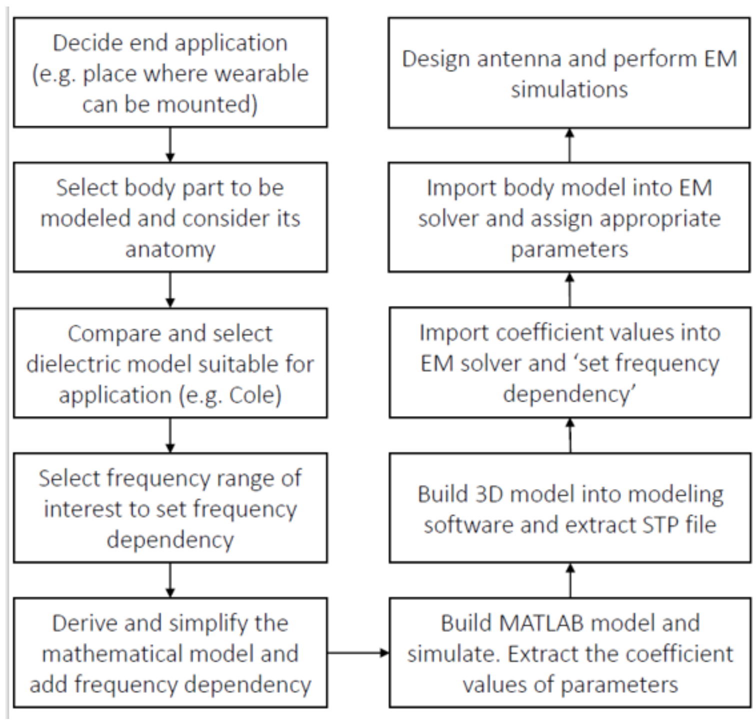

Figure 3. Human body model derivation steps. Figure reproduced from [19]. These steps ensure that any change of blood glucose concentration inside human body changes dielectric properties and can be estimated with an antenna.

Through this human body model, the authors successfully established the fact that changes in blood glucose concentrations change the dielectric properties of human blood. This in turn can affect antenna performance. This performance can be measured and translated into corresponding blood glucose value.

2.2. Step 2: Antenna Design that Suits the Design Requirements

The major challenge in designing the antenna was that the antenna performance varied based on the user's body type, age, and other physical parameters. If these factors and initial blood glucose

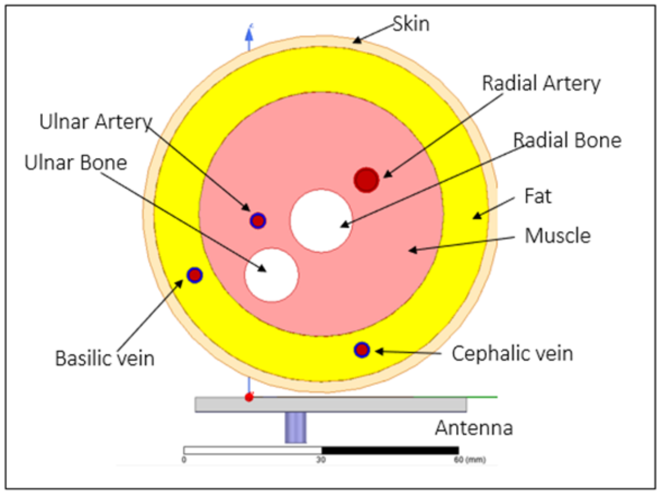

Figure 4. Derived human body model and mounted antenna position. Antenna has been mounted approximately near Cephalic vein for better detection. Antenna radiation direction kept towards the wrist.

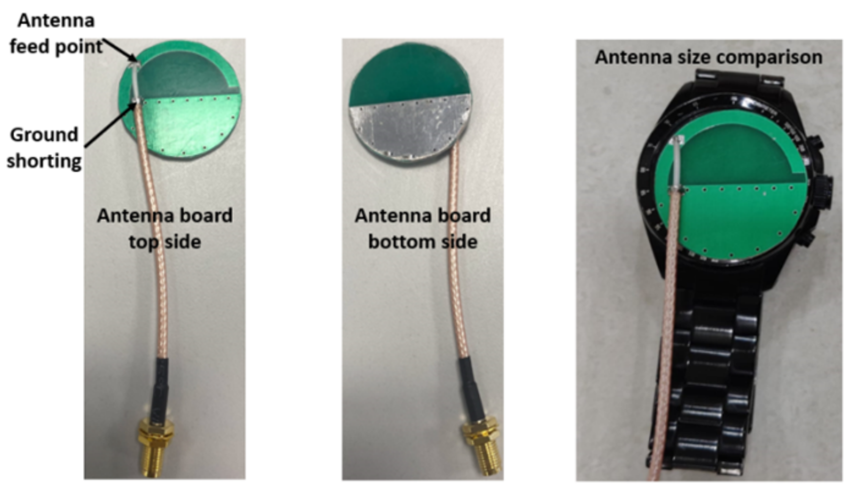

Figure 5. Fabricated antenna and size comparison. More details about this design can be found in [20].

concentration were not considered, then it can produce error in the measurement. The antenna was designed at 2.4 GHz and tested with a vector network analyser. The design flow and process are explained in [20]. The fabricated antenna is shown in Figure 5. Its test results are also shown in Figure 6.

3. MEASUREMENT SETUP EXPLAINED

Though the final system integration can include microcontroller and memory unit, we have used a vector network analyser and direction coupler to evaluate the designed prototype. For any resonant frequency, we can measure the changes in antenna return loss (S_{11}) due to blood glucose variation using this setup. The measurement setup requires continuous wave (CW) signal source, directional coupler, and vector network analyzer (VNA). Figure 7 shows the basic measurement setup for this connection. At the time of final integration with smartwatch, surface mounted or chip-based directional coupler can be used.

Directional coupler plays an important role in the measurement, and hence, it will also be used in the final system integration. Directional coupler working is explained in Figure 8 for the intended

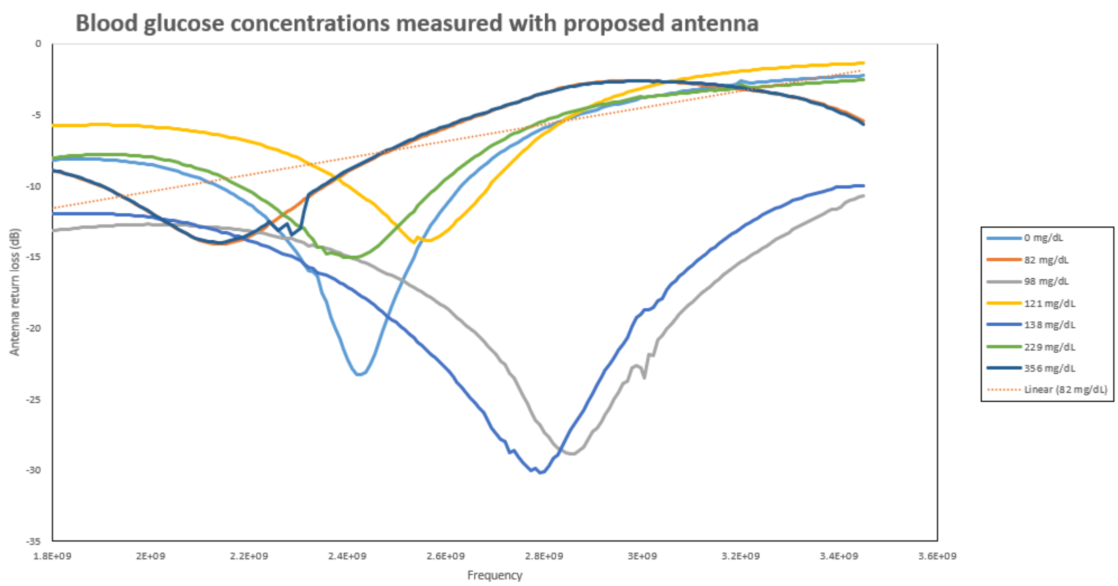

Figure 6. Plotted return loss variations for varying range of glucose values for the aqueous solutio; measured using the fabricated antenna [20]. The linear line shows the trend of glucose concentrations with respect to the glucose level of an average healthy person with no diabetes.

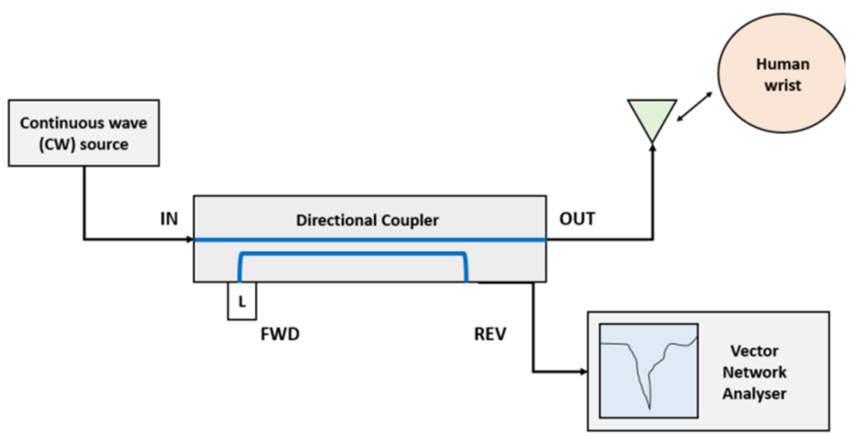

Figure 7. Basic measurement setup for the lab.

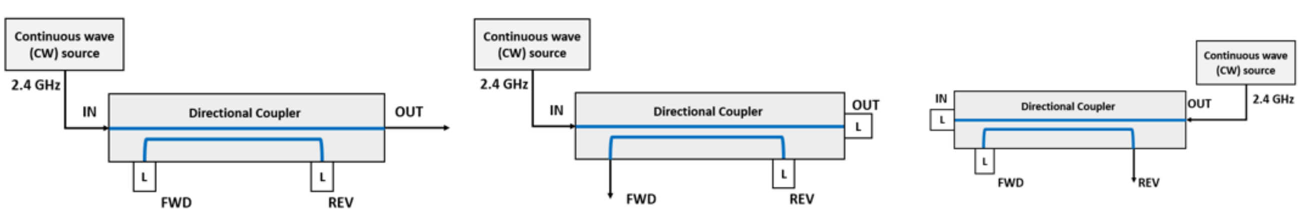

Figure 8. Directional coupler basic working and connection diagram. Actual use and calculations given in subsequent sections.

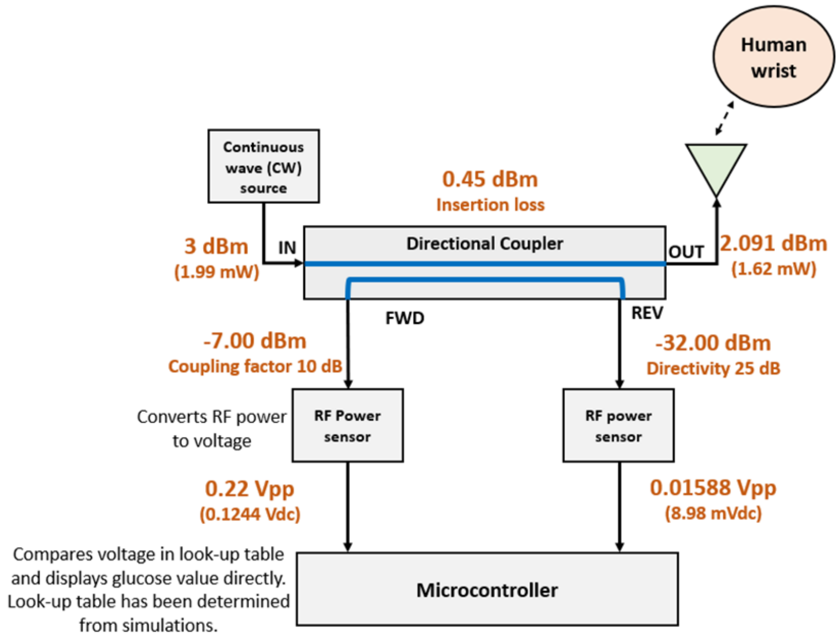

Figure 9. Sample calculation about how return loss variation translates into blood glucose value.

measurement. Authors have used a 10 dB directional coupler with directivity 25 dB and insertion loss of 0.45 dB.

Antenna S_{11} variation due to blood glucose change will not be significant, and the power variation could be in mW or micro-W, but it depends on power being fed into antenna ports. For measurement purposes, authors have fed 3 dBm input power through directional coupler to antenna inputs to obtain detected voltage change in mV range. Figure 9 shows example calculation at mW calculation changes. Using directional coupler improves the system accuracy. Using the setup in Figures 7 and 9, authors have calculated blood glucose values from aqueous solution as well volunteers. This measurement was carried out initially, and the obtained values are listed in Table 1 [20]. Details about preparation of aqueous solution and measurement are also explained in [20].

Table 1. Blood glucose values measured from aqueous solution.

Sr. no.	Aqueous solution concentration (mg/dL)	Estimated concentration with setup of Figure 9 (mg/dL)
1	72	78
2	86	94
3	99	108
4	137	141
5	257	262

It is observed from Table 1 that results are fairly accurate; however, authors wanted to verify the results with finger pricking method. For this purpose, authors collaborated with a diagnostic lab and conducted a blood glucose measurement drive at the lab. Authors collected blood glucose samples from seventeen volunteers using conventional finger pricking measurement and using measurement setup explained in Figures 7 and 9, simultaneously. The results of measurement are listed in Table 2. A measurement photograph is shown in Figure 10, and the fabricated prototype is shown in Figure 11.

It can be observed from Table 2 that at the lower end of blood glucose concentration, estimation is fairly accurate with the difference of 2–5 mg/dL. However, at the higher end of blood glucose

Table 2. Proposed system measurement results vs finger pricking measurement.

Volunteer number	Gender	Age (years)	Finger pricking based blood-glucose (mg/dL)	Proposed system-based blood-glucose (mg/dL)	Return Loss in dB	Equivalent DC Voltage (in mV)
1	Female	38	73.28	71	−19.45	318
2	Male	66	80.5	76	−19.12	318
3	Female	40	84.54	81	−18.75	356
4	Female	65	84.54	82	−18.61	356
5	Male	17	87.86	85	−18.47	356
6	Female	49	91.46	88	−18.26	356
7	Female	30	96.48	92	−17.89	400
8	Male	57	97.96	93	−17.83	400
9	Male	66	102.9	97	−17.15	400
10	Female	74	104.02	110	−16.68	450
11	Male	30	112.06	119	−16.44	45
12	Male	66	119.34	124	−16.25	450
13	Female	50	121.39	127	−16.21	450
14	Male	56	126.09	130	−16.08	450
15	Female	63	156.24	162	−15.78	510
16	Male	65	156.98	163	−15.64	510
17	Male	67	289.3	295	−15.06	560

Figure 10. A representative measurement photograph corresponding to Table 2.

concentration the difference between finger pricking based detection and proposed system-based detection is high ranging between 7 and 15 mg/dL. Authors have also plotted Clarke error grid to evaluate the proposed system performance, as shown in Figure 12.

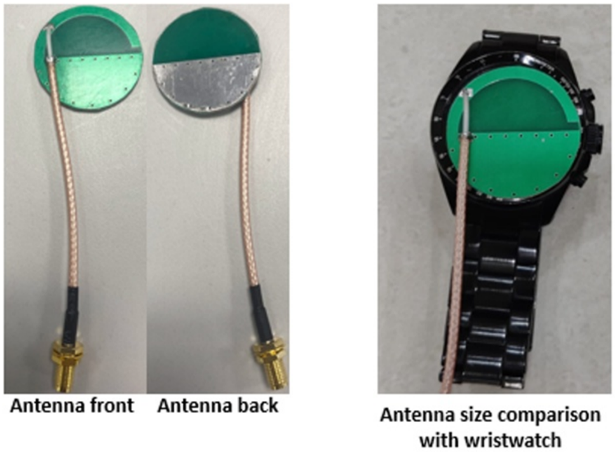

Figure 11. Antenna fabricated prototype; figure reproduced from [20].

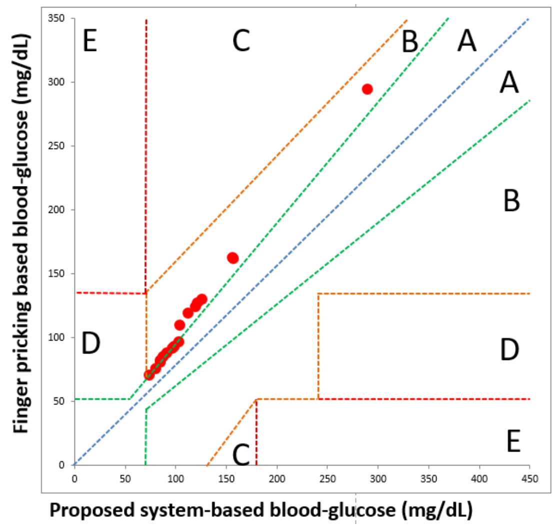

Figure 12. Blood glucose concentrations tabulated in Table 2 are plotted on Clarke error grid.

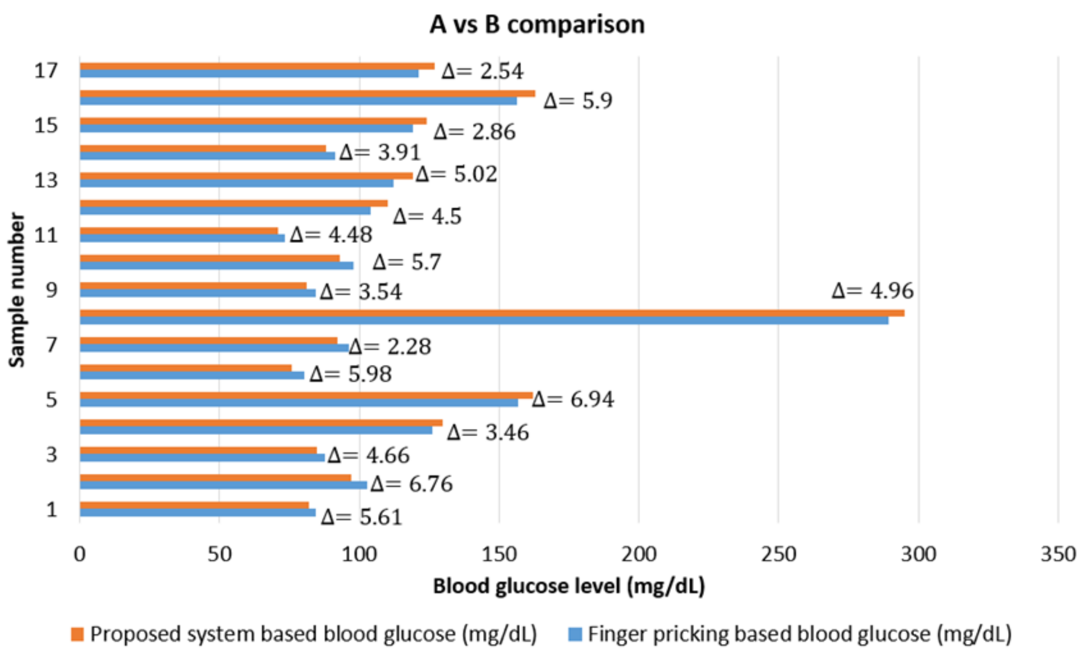

Figure 13. Absolute difference and A vs B comparison of traditional method vs proposed system for blood glucose measurement.

It can be seen from Clarke error grid model that the proposed system can accurately estimate the real-time blood glucose value. The absolute difference points between traditional and proposed system methods of real time blood glucose measurements are also seen in Figure 13. This gives a fair idea of accuracy of the system proposed in this paper. Further enhancements can be done by coupling the proposed system with the relevant algorithm commented as part of future scope in the next section.

4. CONCLUSION AND FUTURE SCOPE

Authors started the work with an aim of designing a truly noninvasive continuous blood glucose monitoring technique. Authors have successfully established the fact that the change in blood glucose concentrations changes dielectric properties of blood. This change can be estimated with an antenna. Authors have also made measurement on antenna return loss for varying glucose concentrations. These measurements were initially done with aqueous solution and later with volunteers. It was found that glucose concentrations estimated with antennas agreed with simulation results as well as the finger pricking based results. It was also noted that on lower values of blood glucose (below 80 mg/dL), the proposed system has tolerance of 2–5 mg/dL irrespective of gender. However, for higher values of blood glucose (above 100 mg/dL) the proposed system has tolerance of 7–15 mg/dL. As a future scope, the estimation can be greatly improved if the microcontroller circuit with adaptive algorithms are used. Hence, authors have successfully developed ready-to-integrate into smartwatch prototype of noninvasive continuous blood glucose measurement method.

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