# Skin Variations Impact on Non-Invasive Measurement of Blood Glucose with Interdigital Electrodes

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**Abstract:** This work investigates the effects of variations in skin-topology on the non-invasive measurement of blood glucose levels using an interdigital electrode. Several models of varying skin topologies were built and analysed within the COMSOL Multiphysics® 4.3 software environment. The deviations in blood glucose readings for the varying skin topologies were quantised. Finally the authors propose and model an alternative interdigital electrode structures. Variations in skin-topology can occur due to movement of the patient during readings and common variations in the skin surface from one person to the next or even different locations on the same person. Non-invasive measurement methods offer improved patient quality of care by reducing the pain and risk associated with testing.

**Keywords:** Blood glucose, interdigital electrode

## 1. Introduction

Diabetes is a major health issue which currently affects more than 300 million persons worldwide [1]. Furthermore, the World Health Organisation (WHO) expects that by 2030 diabetes will become the seventh leading cause of death in the world [2]. One key activity for the proper management of the disease is the regular monitoring of blood glucose levels in order to establish the needed dosage of insulin [3]. Currently the majority of blood glucose monitors require a blood sample for each test which results in significant discomfort to the patient particularly children and the elderly [4]. Several methods of non-invasive blood glucose measurement exist. One measurement method utilises interdigital electrodes to monitor the changes in conductivity and permittivity based on the variations in glucose levels [4]. The functionality of the interdigital sensor when used in bio sensing applications is affected by several factors including the size of the sensing area, variations in the dimensional cross-section and material consistency of the electrodes & substrate, and the flexibility and robustness of the interdigital structure [7]. Previous work has been conducted to establish the viability of the measurement method using simulation models and testing. Studies have examined various aspects of the sensor's performance including the linearity of the sensor response and sensitivity to changes in glucose concentrations to name a few [4,6]. The technology has also been offer commercially as Pendra® from Pendragon Medical Ltd. but was discontinued in 2005 due, in part, to the inability to accommodate different skin types and skin conditions [4]. To the best of the authors' knowledge, little work has been conducted on examining the effect of the measurement-site skin-topology (skin roughness, scarring, etc.) on the sensor performance. Furthermore existing studies have been limited to planar structures [5-7].

This work aims to investigate the behaviour of a simple interdigital sensor in response to distortions in the skin-topology and differences in skin undulation during use. The study then extends to consider a flexible sensor structure which is better able to contour to the skin variations. The paper is structured as follows. A brief literature review is presented along with the motivation behind the work. This is followed by the methodology and a description of the modelling work. Finally, the simulated results are presented and discussed.

## 2. Background & Motivation

The utilisation of the interdigital sensor for bio-impedance measurement of body tissue involves tracking the changes in the resistance of the electric current flowing through the target area in response to the changes in the underlying tissue. For the specific monitoring of blood glucose, the variations in glucose levels have been shown to cause variations in the levels of sodium and potassium ion concentrations within the red blood cell [8]. The changes in ion concentration in turn produce a measurable change in the permittivity and conductivity of the cell membranes [9].

Researchers have dedicated considerable effort into the application of systems to the monitoring of the electrical properties of blood due to the changes in blood glucose levels. This research has resulted in the development of several commercial initiatives including the Pendra system in 2003 and Glucoband system in 2005. Currently there are several company initiative including Glucosense of Boston, Biovotion of Switzerland, Biopeak of Canada, Integrity Applications and Bio-Impedance General Ltd. of Israel [10-11].

There are several challenges in monitoring the electrical phenomena. Specifically, the measurement system signal must be able to penetrate through the intervening bio materials to the blood vessel level. Another challenge would be the ability to differentiate between the glucose related changes from other constituents (e.g. water). The sensors have also been shown to produce variations in readings due to differences in tissue characteristics (e.g. skin dielectric properties) [12]. The bio-impedance measurement process is also complicated because of changes in the electrical properties of body tissue due to temperature, sweat and the movement of the patient (which affects the microvascular blood flow). Previous studies conducted by Caduff et al have examined the effect of motion-induced microvascular blood flow [12] but little work has been conducted on the impact of the skin-topology of the measurement-site on the performance of the impedance sensor. The non-invasive measurement of blood glucose involves the placement of the interdigital sensor on the most superficial layer of the skin surface i.e. the epidermis. Variations in skin-topology involve changes in the epidermis which can manifest in a broad variety of phenomena including scarring, blistering, inflammation, undulations etc. these factors can potentially affect the blood glucose measurement accuracy.

The ideal sensor should be able to demonstrate good sensitivity to glucose level changes and provide repeatability in the sensor response while minimising the effects of the measurement-site. The goal of this study is to examine the impact of the measurement-site topology on the impedance readings for a specific interdigital sensor structure. The measurement-site phenomena which were examined were the application specific issue of sensor depth and measurement-site undulation due to the presence of a blood vessel.

## 3. Use of COMSOL Multiphysics®

The interdigital sensor structure can be examined using simple circuit analysis concepts which leverage the planar and repetitive nature of the capacitive structure. However application of such paper analysis becomes difficult when considering more irregular/distorted structures. Based on the complexity of the interdigital sensor structure it was necessary to construct a 3D model of the sensor. The AC/DC module of the COMSOL Multiphysics® was used to simulate the capacitance values of the interdigital sensor structure. The specific physics used was Electric Currents and the study was a Frequency Domain study. It was possible to use the AC/DC module for the analysis since the wavelength of the sensor signals used for the model simulation were sufficiently (a factor of 100) larger than the dimensions of the various geometries contained within the 3D model. For the model, the electrode structures were considered to be highly conductive and it was assumed that any magnetically induced currents within the electrode structures were negligible. As such the field within the electrode structure was not examined.

## 4. Methodology

Two distinct sensor structures were created and simulated in two sets considering varying levels of skin undulation and skin-topology distortion respectively. The sensor operating principles, underlying modelling assumptions and model setup are stated in the following sections.

### 4.1 Sensor operating principle

A simple interdigital sensor is created through the deposition of a repeated interwoven electrode pattern onto an underlying substrate. For the purpose of this work the sensor is considered to be the combined electrode pattern and substrate. The capacitance of the structure and the penetration depth of the electric field are dependent on the dimensions of the electrode pattern, the materials of the sensor and the material under test (MUT). The relevant dimensional information is presented in Figure 1.

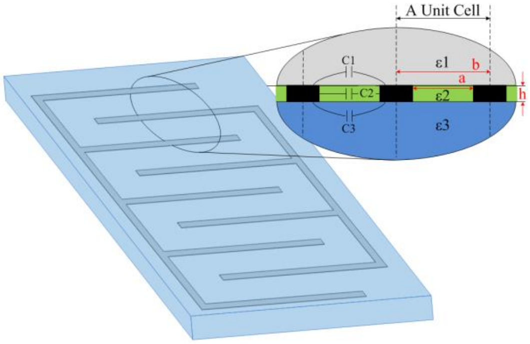


**Figure 1.** Relevant dimensions of the interdigital structure

The capacitance of the simple interdigital sensor can be calculated by utilising the planar nature and repeated electrode pattern. Consider a pair of positive and negative electrodes as a single entity, the sensor capacitance C would be given by [13]:

$$C = C_{UC}(N\text{-}1)L\,, \qquad (1)$$

where $N$ represents the number of unit cells and $L$ the length of the electrode. The unit cell capacitance $C_{UC}$ represents the collective capacitance effects between the electrodes (where $C_1$ to $C_3$ represents the capacitance effects between matching electrode face pairs as shown in Figure 1) such that:

$$C_1 + C_3 = \varepsilon_0 \left(\frac{\varepsilon_1 + \varepsilon_3}{2}\right) \frac{K\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{K\left(\frac{a}{b}\right)}\,, \qquad (2)$$

$$C_2 = \varepsilon_0 \varepsilon_2 \frac{h}{a}\,, \qquad (3)$$

where $\varepsilon_0 = 8.854\,x\,10^{-12}$ F/m, and $K[x]$ is a complete elliptic integral of the first kind.

In calculating the sensor capacitance the relative permittivity of the surrounding medium are considered (ε1 – ε3). In practice these media are complex compositions which vary based on the underlying tissue, patient skin conditions and the general test environment. The use of modelling software such as COMSOL Multiphysics® greatly assists in studying these complex phenomena.

### 4.2 Model details

The model used for the study is shown in Figure 2. The dimensional and material details which were used in building the model are captured in Table 1 [14].

**Table 1:** Dimensional and material details used in the model

| Item | Dimensions | Electrical Parameters |
|---|---|---|
| Copper comb | Trace width: (20mil) 0.51mm;<br>h: (1oz) 0.035mm;<br>b: 2.5mm;<br>a: 2.0mm | σ = 5.998e7[S/m] |
| Substrate (FR4) | 26.0mm, 18.2mm, 1.6mm | σ = 0.004[S/m]<br>$\varepsilon_r$ = 4.5 |
| Skin | 36.0mm, 28.2mm, 1.5mm | σ = 2e-4 - 5e-5[S/m]<br>$\varepsilon_r$ = 1133 – 1119 |
| Tissue | 36.0mm, 28.2mm, 20.0mm | σ = 2e-2[S/m]<br>$\varepsilon_r$ = 1085 – 93 |
| Air | 36.0mm, 28.2mm, 20.0mm | |
| Blood Vessel | 36mm, dia. 3.2mm | σ = 0.7[ S/m]<br>$\varepsilon_r$ = 5248 – 5120 |

Frequency band: 10k – 1MHz

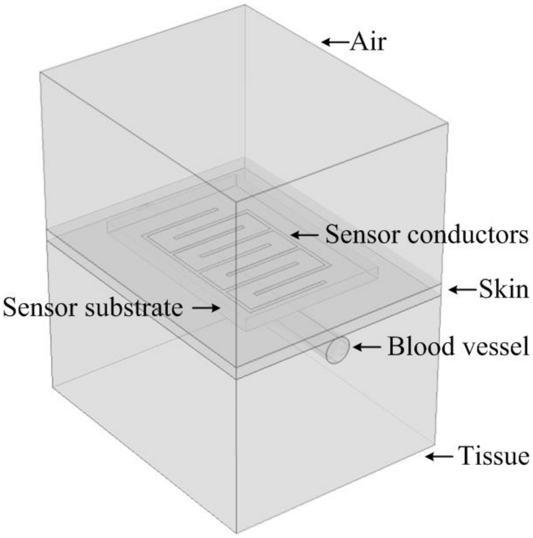


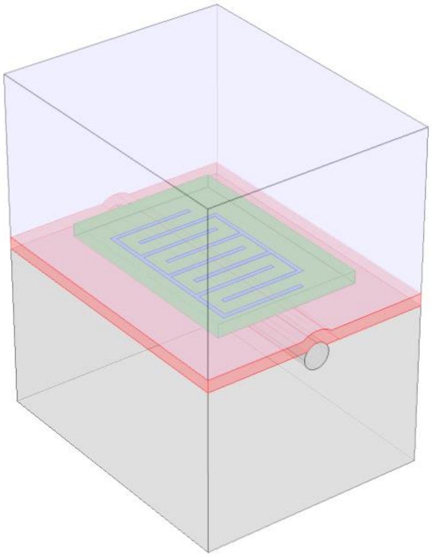
**Figure 2.** Interdigital sensor model used for monitoring blood glucose levels

Interdigital transducers which are used for impedance analysis typically operate in the range 100Hz – 10MHz [7]. For the purposes of this study the frequency range of 10kHz – 1MHz was used. The interdigital sensor structure which was created for the modelling work represents an etched copper pattern composed of eight (8) unit cells. The electrodes are 1oz copper laminate and the underlying substrate is rigid FR4. The test location as represented in the model seeks to emulate a blood vessel which is located just under the skin layer and is embedded in fatty tissue (for example the posterior surface of the forearm).

### 4.3 Test Cases

Test cases were developed in order to consider the effects of skin distortion during use of the interdigital sensor and effects of skin undulations on sensor performance. For the examination of *skin distortion* three (3) scenarios were considered:

1. Sensor directly against the skin
2. Electrodes embedded within the skin
3. Sensor embedded 0.4mm within the skin


(a)

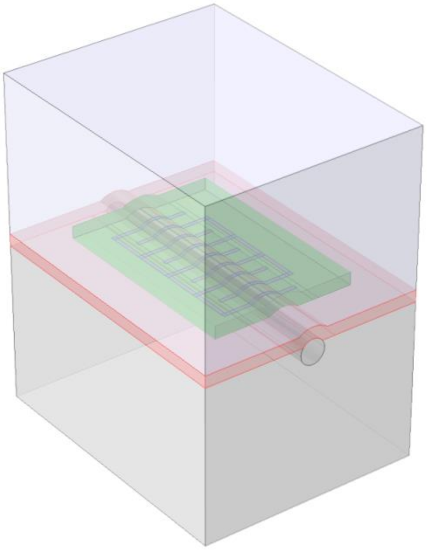
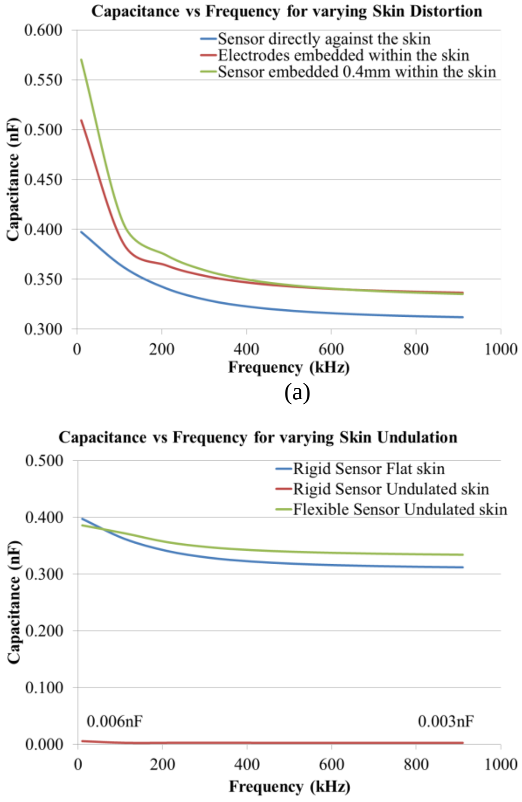

(b)

**Figure 3**. Comsol model showing (a) rigid sensor (b) flexible sensor, on the undulated skin surface

For the consideration of *skin undulation*, the specific scenario of skin surface undulation due to the presence of a blood vessel was contrasted with the planar sensor directly against the skin surface. Finally, a non-planar sensor structure which contours to the deformed skin surface was considered (as shown in Figure 3). In all cases, the model capacitance was calculated for the frequency range of 10kHz – 1MHz in 10kHz steps.

## 5. Results

Figure 4 shows the plots of capacitance vs frequency for the *skin distortion* scenarios and *skin undulation* scenarios respectively. For all scenarios the measured capacitance was seen to decrease as the signal frequency increases. For the skin distortion scenarios, the measured capacitance was seen to increase the further that the sensor structure was positioned into the skins surface. It was also noted that the difference in the measured capacitance readings decreased as the frequency increased. For the skin undulation scenarios, the measured capacitance was seen to be significantly smaller for the case of the rigid sensor on the deformed skin's surface compared to the ideal case (rigid sensor and perfectly flat skin surface). However the flexible sensor was seen to closely match the capacitance values of the ideal case.



(a)

(b)

**Figure 4**. Plots of capacitance vs frequency for (a) skin distortion (b) skin undulation, for the various models

## 6. Analysis

From the results observed for the different skin-topology variation scenarios, the skin distortion measurements indicated that the method of application of the sensor to the skin surface (e.g. with/without pressing force) results in signification variation of the measured capacitance. The extent of the variation tended to diminish for the higher frequencies within the range of interest (10kHz – 1MHz). For the two scenarios which involved the application of a pressing force to the sensor (thus embedding it to different extends in the skin layer) it was observed that the capacitance readings converged at approximately 600kHz. The scenario where the sensor is made to rest against the skin without an applied force is not seen to converge. This observation implies that a force should be applied to the sensor to ensure that it is pressed into the skins surface when measurements are being taken.

For the skin undulation readings, significant deviation from the ideal testing scenario (perfectly flat skin surface and rigid sensor) was observed when the rigid sensor was used on the undulated skin surface, the observed capacitance readings were a factor of 100 smaller than the ideal case. This result implies that the sensor readings can be significantly affected by the presence of skin undulations which impact the integrity of the sensor’s contact to the skin surface. The proposed flexible sensor whose structure folds to conform to the undulated skin surface was shown to perform comparably to the ideal sensor scenario. This would suggest that a flexible sensor structure would be the recommended sensing solution for use on real skin surfaces which exhibit undulations due to subsurface blood vessels, scars etc.

The preliminary results which were obtained from this work suggest that it would be fruitful to conduct further investigations into the performance of the flexible structures as applied to additional examples of localised skin undulation phenomena. We would also wish to further substantia the results through the manufacture and testing of suitable flexible sensors both in the frequency range of 10kHz – 1MHz.

## 7. Conclusions

Simulation models were created which allowed for the investigation of the performance of an interdigital structure for monitoring blood glucose levels under varying conditions of skin distortion and skin undulation. It was shown that skin distortion due to, for e.g. pressing the sensor into the skins surface, results in a significant variation in sensor reading compared to the ideal scenario. The capacitance values were seen to converge at a testing frequency of approximately 600kHz. For the instances of skin-topology undulation it was observed that significant variations in readings were obtained when the sensor was displaced from the surface. A flexible sensor was shown to provide a significantly improved performance which can potentially allow for the compensation of undulations in the skin-topology. Further work is proposed to investigate the performance of the flexible sensors on a broader range of skin topologies. This work would be conducted through further simulations as well as the building and testing of prototype sensor structures.

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