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AN ELECTRICAL PARAMETRIC MODEL OF
HUMAN SKIN AND BLOOD GLUCOSE



SPECTROSCOPY
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By
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This thesis is submitted to the Department of Electronic &
Telecommunication Engineering
of the University of Moratuwa
in partial fulfillment of the requirements for
the degree of Master of Science in Full Time Research.

University of Moratuwa, Sri Lanka

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any University or institute of higher learning and to the best of my knowledge and belief. Furthermore, it does not contain any material previously published or written or orally communicated by another person except where the acknowledgement is made in the text and due reference is made in the text or in the figure captions or in the table captions.

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Thumeera R. Wansinghe

The above candidate has carried out research for the Masters thesis under my supervision and to the best of our knowledge the above particulars are true and accurate.

Dr. E. C. Kulasekere
Research Supervisor,
Head of the Department,
Electronic and Telecommunication Engineering.

To my parents, family, teachers and friends for giving me constant support and



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motivating me.

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ABSTRACT

An Electrical Parametric Model of Human Skin and Blood Glucose Spectroscopy

by

Thumeera Ruwansiri Wanasinghe

Submitted to the Department of Electronic and Telecommunication Engineering,
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Index Term: *Skin impedance model, non-invasive blood glucose measurement, dielectric spectroscopy, compact annular ring slot antenna*

Diabetes is well known as a leading cause of death all around the world. Mainly, invasive methods are used for blood glucose monitoring in the current context. The monitoring is done either as an inpatient procedures or using home based measuring devices. Invasive or minimally invasive methods make it difficult when it comes to frequent measurements required by diabetes patients. It also has other issues such as the associated pain, phobia, and the spread of diseases like AIDS. These issues are heightened in the case of home based monitoring devices. As a result many researchers have attempted to introduce non-invasive measuring techniques for home based glucose monitoring devices. However none of them have met the accuracy requirements for medical use.

Dielectric spectroscopy (DS) is one such methods which has been proposed for non-invasive glycaemia monitoring. In DS, the variation of skin impedance has been used to derive an index representing blood glucose fluctuation. As a result of the lack of knowledge of the impedance characteristics of the skin and the tissue underneath, and its relation to the level of blood glucose, the consistency and accuracy of the measurements are questionable. The ensuing research proposes a theoretical framework for skin impedance variations with the blood glucose level and also provides experimental verification of the same. This research also

proposes an electrical parametric (impedance) model for human skin and blood glucose spectroscopy which consists of human skin, electrode-electrolyte interface and coupling capacitance between transmitter and receiver. Such a mathematical model of the physiological system will enable us to further analyze the relationship the physiological parameters have with the fluctuation of the blood glucose levels for different individuals.

Moreover, the thesis analyzes the influence from bio-sensor to sensitivity measurements and proposes a concentric annular ring slot antenna (CARSA) as a possible sensor for non-invasive blood glucose measurement via DS. Compared to early research of Cadaff *et al.* [1], CARSA showed a 13 fold increment of the measurement sensitivity. Further, it could be seen that, this sensitivity increment was 40 fold when the effective length of CARSA decreases from 10 cm to 6.5 cm. The thesis further highlights the importance of careful design of this sensor and proposes a rigorous mathematical model of its derivation.



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ABBREVIATIONS

Following abbreviations or acronyms have been used in this thesis.

| Abbreviations/Acronyms | Meaning |
|------------------------|---------------------------------------|
| CARSA | Concentric Annular Ring Slot Antenna |
| CPE | Constant Phase Element |
| CVD | Cardiac Vascular Disease |
| DC | Direct Current |
| DS | Dielectric Spectroscopy |
| EM | Electromagnetic |
| FBS | Fasting Blood Sugar |
| FNS | Functional Neuromuscular Stimulation |
| IR | Infrared |
| IS | Impedance Spectroscopy |
| MIT | Massachusetts Institute of Technology |
| MMCX | Micro-Miniature Coaxial |
| MWS | Microwave Studio |
| NA | Network Analyzer |
| NIBGM | Non-Invasive Blood Glucose Monitoring |
| NIDAQ | National Instrument Data Acquisition |
| OGTT | Oral Glucose Tolerance Test |
| PTFE | Polytetrafluoroethylene |
| RF | Radio Frequency |
| SC | Stratum Corneum |
| TNC | Threaded Neill-Concelman |
| VCO | Voltage Controlled Oscillator |
| WHO | World Health Organization |



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NOMENCLATURE

Following symbols or notations have been used in this thesis.

Chapter 2

| | |
|-------------------|---|
| I_c | Ionic conduction current |
| I_d | Displacement current |
| j | $\sqrt{-1}$ |
| $\hat{\epsilon}$ | Complex relative permittivity |
| ϵ' | Real part of complex relative permittivity |
| ϵ'' | Imaginary part of complex relative permittivity |
| ϵ_r | Dielectric constant (Relative permittivity) |
| ϵ | Permittivity of the medium |
| ϵ_0 | Permittivity of free space |
| σ | Total ionic conductivity of the medium |
| ω | Frequency in rad/s |
| τ | Dispersion time constant |
| ϵ_∞ | Permittivity at $\omega\tau \gg 1$ |
| ϵ_s | Permittivity at $\omega\tau \ll 1$ |
| $\Delta\epsilon$ | Magnitude of the dispersion ($\epsilon_s - \epsilon_\infty$) |
| σ | Static ionic conductivity of tissue |
| α | Distribution Parameter (2.6); an exponent (2.19), (2.24) |
| R_s | Ohmic resistor for basic R-RC skin model |
| C_p | Polarization capacitance for basic R-RC skin model |
| C_p | Parallel resistor to polarization capacitor for basic R-RC skin model |

Chapter 2 con't

| | |
|---------------------|---|
| V_{peak} | Peak voltage from Figure 2.8 |
| I_{peak} | Peak current from Figure 2.9 |
| I_{steady_state} | Steady-state current from Figure 2.9 |
| A | Cross sectional area of the conductor |
| R_o | Resistance at very low frequency |
| R_∞ | Resistance at very high frequency |
| ω | Angular frequency (rad/s) |
| τ_z | Characteristics time constant |
| R_m | Resistance of lipid-corneocyte matrix |
| C_m | Capacitance of lipid-corneocyte matrix |
| R_a | Resistance of appendages current path |
| C_a | Capacitance of appendages current path |
| φ_{CPE} | Phase angle of CPE |
| C_{CPE} | Capacitance of CPE |
| ΔG | Conductance of CPE, $R_o - R_\infty = 1/\Delta G$ |
| K | Real proportionality factor for the CPE admittance |
| m | exponent |
| R_{pol} | Polarization resistance at the electrode-electrolyte interface |
| C_{pol} | Polarization capacitance at the electrode-electrolyte interface |
| β | exponent |



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Chapter 3

| | |
|----------------------------------|--|
| w_1 | CARSA inner ring width |
| w_2 | CARSA outer ring width |
| r | Inner radial of inner ring of CARSA |
| s | Gap between two rings of CARSA |
| ϵ_r | Relative dielectric constant of substrate |
| R_{ref} | Resistance of reference resistor Figure 3.9 |
| V_{ref} | Voltage just before the R_{ref} Figure 3.9 |
| V_{sens} | Voltage just after the R_{ref} Figure 3.9 |
| ρ | Resistivity of the tissue |
| ℓ | Thickness of the tissue layer |
| A | Effective area under measurement |
| ϵ | Permittivity of the tissue |
| ω | Radial frequency (rad/s) |
| $S_{11}, S_{12}, S_{21}, S_{22}$ | Full 2-port scattering parameters |
| A, B, C, D | Full 2-port ABCD parameters |
| Z_l | Load impedance |
| Z_s | Source impedance |
| Z_o | Reference impedance |
| Z_s^* | Complex conjugate of the source impedance |
| $H(s)$ | System transfer function |

Chapter 4

| | |
|--------------|-------------------------------------|
| $OGTT_{imp}$ | OGTT impedance at a given frequency |
| FBS_{imp} | FBS impedance at the same frequency |
| I_{av} | Average impedance shift |
| $OGTT_{glu}$ | OGTT value from invasive method |
| FBS_{glu} | FBS value from invasive method |

Chapter 5

| | |
|-------------------------|---|
| ε | Permittivity of the dielectric material |
| ε_0 | Permittivity of the free space |
| ε_r | Relative dielectric constant of the dielectric material |
| μ | Permeability of the dielectric material |
| μ_0 | Permeability of the free space |
| μ_r | Relative Permeability of the dielectric material |
| D | Inner diameter of the shield (co-axial cable) |
| d | Outer diameter of the inner conductor (co-axial cable) |
| w_1 | CARSA inner ring width |
| w_2 | CARSA outer ring width |
| r | Inner radial of inner ring of CARSA |
| s | Gap between two rings of CARSA |
| C_{cup_air} | Coupling capacitance through air |
| $C_{cup_substrate}$ | Coupling capacitance through substrate |
| h | Thickness of the substrate |
| $K(k)$ | Elliptical integral of first kind |
| $K(k')$ | Complementary elliptical integral of second kind |
| C_{gap_cup} | Gap couple capacitance |
| Z_{11} | Driven point impedance |
| Z_0 | Reference impedance |
| R_m | Resistance of ionic channel |
| g_n | Conductance of the ionic channel |
| α, β, γ | Constants |
| τ_φ | Activation time constant |
| τ_χ | Inactivation time constant |
| φ_0 | Initial value for activation |
| χ_0 | Initial value for inactivation |
| φ_∞ | Steady state value for activation |
| χ_∞ | Steady state value for inactivation |

Chapter 5 con't

| | |
|---|--|
| $\sigma, \omega, \varepsilon_o, \hat{\varepsilon}, \omega,$ | As same as Chapter 2 |
| A, d | |
| d_o | The tissue layer thickness when the sensor is at the proximity |
| d_f | The tissue layer thickness when F N force is applied on a skin (sensor) |
| F | Force on a sensor |
| α_f | The force coefficient |
| β_f | The force exponent |
| R_{m0} | The ionic channel resistance at zero temperature |
| $R_{m\theta}$ | The ionic channel resistance at θ C° temperature |
| θ | Temperature |
| α_t | The temperature coefficient |
| β_t | The temperature exponent |
| C_m | Capacitance of lipid bilayer |
| R_i | Resistance of the intracellular medium |
| R_e | Resistance of the extracellular medium |
| V | Applied voltage across anode and cathod |
| I_{C_m} | Dielectric current through lipid bilayer capacitor |
| I_{R_m} | Ohmic current through ionic channel |
| C_{cup_skin} | Coupling capacitance through skin |
| $C_i(t, \omega, c, f)$ | Capacitance across the dielectric layer (tissue layer) of thickness h_i |
| h_i | Thickness of the i^{th} tissue layer |
| $(\varepsilon_{ri} - \varepsilon_{r(i+1)})$ | Relative dielectric constant between i^{th} and $(i - 1)^{th}$ tissue layers |

