UNIVERSITY OF MORATUWA

AN ELECTRICAL PARAMETRIC MODEL OF HUMAN SKIN AND BLOOD GLUCOSE SPECTROSCOPY

By

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Telecommunication Engineering
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DECLARATION

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

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ABSTRACT

An Electrical Parametric Model of Human Skin and Blood Glucose Spectroscopy

by

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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 then 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

NOMENCLATURE

Following symbols or notations have been used in this thesis.

Chapter 2

I_c	Ionic conduction current
I_d	Displacement current
j	$\sqrt{-1}$
$\hat{\varepsilon}$	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
$\varepsilon_\circ$	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 $\omega\tau \ll 1$
$\Delta\varepsilon$	Magnitude of the dispersion $(\varepsilon_s - \varepsilon_\infty)$
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
$R_{\circ}$	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 , $R_{\circ} - R_{\infty} = 1/\Delta G$
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

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
$Z_\circ$	Reference impedance
$Z_s^\star$	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_{aiv}	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
$\varepsilon_\circ$	Permittivity of the free space
ε_r	Relative dielectric constant of the dielectric material
μ	Permeability of the dielectric material
$\mu_\circ$	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
$Z_\circ$	Reference impedance
R_m	Resistance of ionic channel
g_n	Conductance of the ionic channel
$\alpha,\ \beta,\ \gamma$	Constants
τ_φ	Activation time constant
τ_χ	Inactivation time constant
$\varphi_\circ$	Initial value for activation
$\chi_\circ$	Initial value for inactivation
φ_∞	Steady state value for activation
χ_∞	Steady state value for inactivation

Chapter 5 con't

σ, ω, $\varepsilon_\circ$, $\hat{\varepsilon}$, ω, A, d	As same as Chapter 2
$d_\circ$	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
$R_{m\circ}$	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