MODELING OF ELECTROMAGNETIC WAVE
PENETRATION IN A HUMAN HEAD DUE TO
EMISSIONS FROM CELLULAR PHONE

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**MODELING OF ELECTROMAGNETIC WAVE PENETRATION
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FROM CELLULAR PHONE**

SESI PENGAJIAN : 2006/2007

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**MODELING OF ELECTROMAGNETIC WAVE PENETRATION IN A
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NURULHUDA BINTI ISMAIL

**A project report submitted in partial fulfillment of the requirements for the
award of Master of Electrical Engineering**

**Faculty of Electrical and Electronic Engineering
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MAY 2007

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*For my dearest father Hj. Ismail bin Kamari,
My lovely mother Hj. Saodah binti Nawawi & my family for their encouragement
and blessing*

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ABSTRACT

Nowadays, cellular phone becomes a necessity for human being due to its mobility, small size and useful applications provided in the chip. In a long term use, the user will be exposed to the high frequency EM radiation that possibly causes serious illnesses such as alzheimer and brain cancer. Increasing exposure from this radiation is a growing concern for the community to investigate the effects of the emissions to human health. While cellular phone is in used, the energy is transferred from the applied electric field to the human head in the form of kinetic energy of charged particles. The rate of change of the energy transferred is called the absorbed power or *Specific Absorption Rate* (SAR). SAR values are of key importance when validating possible health hazard and these values are compared with a safety limit set by International Commission on Non-Ionizing Radiation Protection, ICNIRP to ensure that the phone is safe to use. In this study, Finite Difference Frequency Domain (FDFD) technique was used to evaluate the electric field and SAR distribution in a human head due to the emissions from cellular phone that operates at 900 MHz. The numerical results were compared with the CST Microwave Studio software which is based on FDTD method. The results demonstrated that FDFD is not an efficient method to evaluate E field and SAR due to its limitation and imperfect boundary condition. On the other hand, the CST Microwave Studio results show that magnitude of EM field decreases exponentially with the penetration distance at a rate specified by the attenuation constant, α . Besides, the SAR is affected by operational frequency of the phone and the electrical properties of human head. Since FDFD technique can work only for 2D models, it is recommended that a fast and efficient numerical technique need to be studied for 3D human head model and an experimental technique on SAR distribution needs to be done to validate the results from simulation technique.

ABSTRAK

Dewasa ini, telefon selular merupakan keperluan dalam kehidupan seharian memandangkan kepada faktor mobilitinya, saiz yang kecil dan pelbagai aplikasi yang dimuatkan di dalam cipnya. Untuk penggunaan yang lama, pengguna telefon ini akan terdedah kepada radiasi elektromagnetik yang berfrekuensi tinggi dan berkemungkinan mengundang kepada penyakit serius seperti alzheimer dan barah otak. Peningkatan kepada pendedahan terhadap radiasi ini telah meningkatkan kesedaran di kalangan masyarakat untuk mengkaji kesan radiasi ini kepada kesihatan manusia. Semasa telefon selular sedang digunakan, sejumlah tenaga akan dipindahkan daripada medan elektrik ke dalam kepala manusia dalam bentuk tenaga kinetik yang terhasil daripada zarah-zarah bercas. Kadar perubahan terhadap tenaga yang dipindahkan ini dinamakan sebagai kuasa terserap atau Specific Absorption Rate (SAR). Nilai SAR begitu penting untuk mengesahkan simptom penyakit dan nilai ini kemudiannya akan dibandingkan dengan had keselamatan yang telah ditentukan oleh International Commission on Non-Ionizing Radiation Protection (ICNIRP) bagi memastikan bahawa telefon tersebut selamat digunakan. Dalam kajian ini, teknik Finite Difference Frequency Domain (FDFD) telah digunakan untuk menilai medan elektrik dan taburan SAR di dalam kepala manusia berdasarkan kepada pancaran telefon selular yang beroperasi pada frekuensi 900 MHz. Hasil daripada teknik ini akan dibandingkan pula dengan perisian CST Microwave Studio yang berasaskan kepada teknik Finite Difference Time Domain (FDTD). Keputusan yang terhasil menunjukkan bahawa kaedah FDFD tidak efisien untuk digunakan dalam kajian ini disebabkan oleh aplikasi yang agak terhad dan keadaan sempadan yang tidak tepat. Namun begitu, hasil daripada CST Microwave Studio menunjukkan bahawa magnitud medan elektromagnetik berkurangan secara eksponen melawan jarak penembusan pada kadar yang ditetapkan oleh pemalar pelemahan, α . Di samping itu, taburan SAR pula dipengaruhi oleh frekuensi kendalian telefon tersebut dan ciri-ciri elektrik kepala manusia. Oleh kerana teknik

FDFD hanya relevan untuk model 2 dimensi, kajian yang melibatkan model 3 dimensi dengan menggunakan teknik berangka yang lebih cepat dan efisien perlu dijalankan dan kaedah eksperimen tentang taburan SAR perlu dibuat bagi mengesahkan keputusan yang terhasil daripada kaedah simulasi.

TABLE OF CONTENTS

CHAPTER	CONTENTS	PAGE
	THESIS STATUS CONFIRMATION	
	SUPERVISOR'S CONFIRMATION	
	TITLE	i
	TESTIMONY	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	viii
	LIST OF FIGURES	xi
	LIST OF TABLES	xiii
	LIST OF SYMBOLS / ABBREVIATIONS	xiv
CHAPTER 1	INTRODUCTION	1
	1.1 General	1
	1.2 Problem Statement	4
	1.3 Aim of the study	6
	1.4 Objectives of the study	6
	1.5 Research Scopes	7
	1.6 Report Outline	7

CHAPTER 2 REVIEW OF THE EM WAVE 9
PENETRATION DUE TO CELLULAR
PHONE

2.1	Cellular Phone and its Emission	10
2.2	Bioelectromagnetics	11
2.2.1	Biological Model	12
2.2.2	Macroscopic Model	12
2.2.3	Absorption in Biological Materials	15
2.3	Specific Absorption Rate (SAR)	16
2.4	ICNIRP Standard	18
2.5	Review of Important Research Works on Electromagnetic Absorption and SAR Distribution	20
2.6	Numerical Method used in this project	23

CHAPTER 3 METHODOLOGY 26

3.1	Research Flow	26
3.2	Derivation of Maxwell's Equations	28
3.3	Numerical analysis Using Finite Difference Frequency Domain (FDFD)	32
3.4	Electrical properties of a human head	37
3.5	2D Human Head Model	38
3.6	Commercial Software	39

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 PERPUSTAKAAN TUNKU TUN AMINAH

CHAPTER 4	RESULTS AND DISCUSSIONS	40
4.1	Numerical Analysis Results	41
4.2	Human Head Model	46
4.3	CST Results	47
CHAPTER 5	CONCLUSION AND FUTURE WORK	53
5.1	Conclusion	53
5.2	Future Work	54
REFERENCES		55
APPENDIX A	MATLAB SIMULATION RESULTS	57
APPENDIX B	CST RESULTS	66

PTTAUTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF FIGURES

FIGURE NUMBER	TITLE	PAGE
1.1	Electromagnetic wave propagation	2
1.2	Electromagnetic spectrum	3
1.3	The illustration of electromagnetic fields penetration in a human head	6
2.1	The variation of electrical properties of muscle and fat with frequency	15
3.1	Flowchart of research work	29
3.2	A biological body under EM radiation	30
3.3	2D rectangular region	35
3.4	A grid system	36
3.5	3D human head model in CST Microwave Studio	41
3.6	2D human head model in CST Microwave Studio	41
4.1	Six interior grid points	43
4.2	Contour of E-field intensity before iteration process	45
4.3	Contour of E-field intensity after iteration process	45
4.4	Electric field propagation in a lossless medium	46
4.5	Electric field propagation in a lossy medium	46
4.6	2D Human Head Model	48
4.7	FDTD model of human head (xy-plane)	49
4.8 & 4.9	Distribution of E-field in xz-plane	50
4.10 & 4.11	Distribution of H-field in xz-plane	50
4.12	Propagation of EM wave in a lossy medium	51

4.13	SAR (1g) at 900 MHz	52
4.14	SAR (10g) at 900MHz	52
4.15	SAR (1g) at 1800 MHz	52
4.16	SAR (10g) at 1800 MHz	52

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Current reference standards and limits (status January 2001)	19
2.2	ICNIRP Protection Guidelines	20
3.1	Densities and electrical properties of the simulated tissues	40
4.1	E-field at each unknown point	44
4.2	E-field at each unknown point before iteration	44
4.3	E-field at each unknown point after iteration	45
4.4	SAR _{max} for different averaging mass	53

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF SYMBOLS/ ABBREVIATIONS

E	-	Electric Field Intensity (V/m)
H	-	Magnetic Field Intensity (A/m)
f	-	Frequency (Hz)
α	-	Attenuation Constant (Np/m)
β	-	Phase Constant (rad/m)
γ	-	Propagation Constant (m^{-1})
δ	-	Skin Depth (m)
D_p	-	Depth of Penetration (m)
ϵ	-	Relative Permittivity (F/m)
ϵ_o	-	Relative Permittivity of Free Space ($\epsilon_o = 8.854 \times 10^{-12} F/m$)
ϵ_r	-	Relative Permittivity of Material (dimensionless)
μ	-	Relative Permeability (H/m)
μ_o	-	Relative Permeability of Free Space ($\mu_o = 4\pi \times 10^{-7} H/m$)
μ_r	-	Relative Permeability of Material (dimensionless)
σ	-	Conductivity (S/m)
η	-	Intrinsic Impedance (Ω)
η_o	-	Impedance of Free Space ($\eta_o = 377\Omega$)
λ	-	Wavelength (m)
v	-	Velocity (m/s)
ω	-	Angle Frequency (rad/s)
c	-	Speed of Light in Free Space ($2.998 \times 10^8 m/s$)
h	-	Step size
EM	-	Electromagnetic
FDTD	-	Finite Difference Time Domain

FDFD	-	Finite Difference Frequency Domain
FEM	-	Finite Element Method
SAR	-	Specific Absorption Rate
RFR	-	Radio Frequency Radiation
ICNIRP	-	International Commission on Non-Ionizing Radiation Protection
ANSI	-	American National Standards Institute
IEEE	-	Electrical and Electronic Engineer
FCC	-	Federal Communication Commission
ACGIH	-	American Conference of Governmental Industrial Hygienists

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CHAPTER 1

INTRODUCTION

1.1 General

Electromagnetic wave consists of electric and magnetic field that are perpendicular to each other as illustrated in Figure 1.1. Electric fields are created by differences in voltage: the higher the voltage, the stronger will be the resultant field. Magnetic fields are created when electric current flows: the greater the current, the stronger the magnetic field. An electric field will exist even when there is no current flowing. If current does flow, the strength of the magnetic field will vary with power consumption but the electric field strength will be constant.

Figure 1.1: Electromagnetic wave propagation

Besides that, electric field, E and magnetic field, H are coupled for time-varying, but they become independent in the limit of unchanging fields [1]. Practically, from 20-30 kHz and above, E and H cannot be seen separately; they merge to form EM waves. EM waves at low frequencies are referred to as EM fields and at very high frequencies are called EM radiation. As the frequency goes up, the wavelength becomes shorter, and more energy is transferred to objects similar in size to the wavelength. The term EM radiation applies to the dispersal of EM energy. Once generated, EM fields radiate in all directions, depending on how they have been converged. As the field opens, the power spreads, and the energy could be reflected, transmitted, or absorbed as it comes into contact with different types of material.

Moreover, the evolution of the electromagnetic frequency spectrum as shown in Figure 1.2 started from the discoveries of Maxwell, Hertz, and Marconi. The EM spectrum under which devices and systems are working extended from extremely low-frequency (ELF) fields and very low-frequency (VLF) fields to radio frequency radiation (RFR), infrared (IR) radiation, visible light, ultraviolet (UV), X-rays and gamma-ray frequencies exceeding 10^{24} Hz.

Radio frequency radiation (RFR) is a general term applying to the use of EM waves for radio and television, radar, and other RF/microwave communication applications. RFR is composed of moving waves, which lie in the frequency range of 3 kHz to 300 GHz. Interesting bands of frequency with wide applications especially in wireless, mobile, cellular, and satellite communications are the VHF and UHF (30 MHz-3 GHz). Propagation above 30 MHz is basically a straight line (line of sight) with probability of scattering. Frequencies of special interest for cellular communications are in the range of 800-900 MHz, while personal communications band extends from 1700-2200 MHz.

Figure 1.2: Electromagnetic spectrum [1]

Therefore, the interest of this research work presented in this report is to model the EM wave penetration in a human head due to cellular phone.

1.2 Problem statement

The revolution in communication technology in recent years has seen widespread use of cellular phone. It becomes a necessity for human being due to its mobility, small size and useful applications provided in the chip. Widespread use of cell phone and other types of hand-held transceivers has led to increased concerns about possible health hazards, particularly concerns about brain cancer, as the antennas for these phones lie along the head during use [2].

Frequently reported symptoms to physicians and cellular phone manufacturers include headaches, vision and hearing difficulties, increased ear and facial temperatures, nausea, dizziness, tingling sensations on the skin, and numbness or irritation to the face and neck. Some studies have presented evidence that blood pressure increases when using a cellular phone, and there has been litigation over cancer and brain tumors allegedly caused by cellular phone radiation.

Furthermore, with the enormous increase of electromagnetic and radio wave radiation emitted by cellular phones, increasing numbers of illnesses such as allergies, fatigue, asthma, heart disease, brain cancer, depression, sleep disorders and ill temper are on the rise. These various biological effects depend upon the amount of energy absorbed from the EMF [1].

While the cellular phone is working, it uses electric power to receive and transmit signals through a base station tower that is linked with other transmission towers. Increasing exposure from the use of devices such as cellular phones and base stations are a growing concern for the community. This is because cellular phone, at distances within a wavelength from a RF transmitter is a region known as the near field. Since cellular phone radiation has a wavelength of 30 cm at 900 MHz (GSM phone) the users head will be within this near field region. The head disturbs the field and alters the manner in which RFR interacts with tissue.

This interaction complicates the absorption of RF energy within the head and makes calculations difficult. This increases the temperature of the brain and surrounding tissue and equally as significant, also affects protective biological mechanisms far below what can be measured at the thermal level using current *Specific Absorption Rate* (SAR) test procedures and standards. SAR standards are used as the basis for determining cell phone safety worldwide.

Therefore, it is important to model the behavior of the electromagnetic waves as they interact with the complex tissues of the human due to GSM frequency (900 MHz). Thus, this research is performed to calculate the propagation of the electromagnetic fields in a human head due to the emissions from cellular phone and to study the effects of SAR due to the operational frequency of the cellular phone and the electrical properties of a human head. Numerical technique has been used in this report as one of the computational methods for analyzing electromagnetic problems.

1.3 Aim of the study

The aim of this study is to model the electromagnetic wave propagation in a 2D human head due to the emissions from cellular phone and thus to evaluate the *specific absorption rate* (SAR) distribution in (W/Kg).

1.4 Objectives of the study

Below are the objectives of this research:

- i. To solve Maxwell's equation for wave propagation using Finite Difference Frequency Domain (FDFD)
- ii. To evaluate the electric field at various points in a 2D human head at 900 MHz
- iii. To calculate the SAR values for comparison with the international standard as set by ICNIRP
- iv. To compare the results of the electric field and *Specific Absorption Rate* (SAR) with commercial software

1.5 Research Scopes

The scopes of this research are:

- i. The modeling is done in 2D human head model
- ii. The operating frequency is set at 900 MHz and linear polarization is assumed
- iii. Only two parameters are considered: a) the operational frequency and b) the electrical properties of the tissues
- iv. The densities and electrical properties of the human head is taken from (Gabriel and Gabriel 1996) model
- v. The numerical technique used in this research is Finite Difference Frequency Domain (FDFD)

1.6 Report Outline

This report aims to outline the research work pertaining to the implementation of the numerical technique to model the EM wave penetration in a human head due to the emissions from cellular phone.

Chapter 2 discusses about radiated EM fields from cellular phone and its penetration into a human head. Besides, the *specific absorption rate* (SAR) distribution is also explained in this chapter. Hence, the review of important research works related to this study is then presented. The previous works on evaluating EM wave penetration and SAR distribution in a human head by using FDTD technique

involve with large memory storage. The efforts to introduce a simple numerical technique for 2D human head model are highlighted for use in Chapter 3.

In Chapter 3, the methodology for the whole project is described in detail. It is started by modeling a 2D human head in a grid system. Then, Finite Difference Frequency Domain (FDFD) technique is applied to evaluate the electric and magnetic fields penetration in a biological medium. It is followed by defining the electrical properties of a human head in each cell. Thus, the results from this technique are then compared with a standard limit set by ICNIRP. Commercial software is used in order to validate the numerical technique used in this report.

Then, Chapter 4 presents and discusses the results of the numerical technique and these results are compared with commercial software to provide an independent check on the validity of the results. Besides, the results are compared with a standard limit set by ICNIRP to ensure that the evaluated electromagnetic fields and the SAR distribution not exceed the limit. All the findings from numerical technique are summarized in the form of guidelines as described in this chapter.

Finally, overall research work and its findings are summarized in Chapter 5. Besides, some suggestions for the future development of this project are presented.

CHAPTER 2

REVIEW OF THE EM WAVE PENETRATION IN A HUMAN HEAD DUE TO CELLULAR PHONE

The propagation of the EM waves from cellular phone in a biological medium is discussed in this chapter. As the EM waves penetrate in a human head, some of the waves are absorbed by the tissues of human head. The rate of EM energy absorbed by this biological medium from the cellular phone is called as *specific absorption rate* (SAR) and it can be measured using computational methods. The previous works done by other researchers to evaluate SAR are presented in this chapter and a new method is introduced to achieve the same goal.

2.1 Cellular Phone and its Emission

In Malaysia, the frequencies used in mobile communication are basically 900 and 1800 MHz. Cellular phones operate at frequencies in the Radio Frequency (RF) region, which is also known as the non-ionizing part of the electromagnetic spectrum. This implies that electromagnetic waves radiated from cellular phones are not able to ionize atoms or molecules in human body. However, the field penetrating in the body will induce currents which are dissipated and converted to heat energy [1].

Cellular phones emit RF radiation fields which have electric and magnetic components. The effects of magnetic fields vary with frequency, and are probably greatest in biological tissue containing small amounts of magnetite. Magnetite (Fe_3O_4) is a naturally occurring oxide of iron. Magnetite is found in cells of many animals, including human beings. It has been calculated that the interaction resulting from the largest RF magnetic fields generated by cellular phones is extremely small, and that any other effects of magnetic fields at these frequencies should be even smaller. Indeed it seems to be generally agreed that any biological effects from cellular phones are much more likely to result from the electric rather than from the magnetic field [3].

Furthermore, cellular phones operate at frequencies ranging from about 800 MHz to about 1900 MHz and at a maximum power of 2 watts but mostly at less than that. The RF power emitted from a cellular phone decreases with distance from source. Also a cellular phone using 0.6 watts will result in an RF power density measurement double that of a phone using 0.3 watt at the same distance. Thermal effects are those caused by the rise in temperature produced by the energy absorbed from oscillating electric fields. The force produced by an electric field on charged

objects, such as the mobile ions present in the body, causes them to move, resulting in electric currents, and the electrical resistance of the material in which the currents are flowing results in heating. This heat input causes the temperature to rise and it continues to do so until the heat input is balanced by the rate at which it is removed, mostly by blood flowing to and from other parts of the body. It is estimated that it takes several minutes from the moment RF exposure occurs for the irradiated parts of the body to reach their final equilibrium temperatures [3].

2.2 Bioelectromagnetics

Bioelectromagnetics is a vast interdisciplinary field that incorporates physics, engineering, and life sciences to understand the interaction of electromagnetic fields with biological systems. This field has become very important due to the rapid development of electromagnetic applications through the tremendous increase in use of various devices employing EM energy in the workplace and home. In general, the EM properties of matter have been given in terms of permittivity ϵ , permeability μ , and conductivity σ [1]. These quantities express the macroscopic properties of a substance without giving any thought to the microscopic (atomic and molecular) structure, which is responsible for the macroscopic behavior.

2.2.1 Biological Model

Microscopic anatomy covers cell biology, tissue biology, and organ/system histology, with the structure and function of cells, tissues, and organs reviewed at the light and electron microscope level. At the microscopic level, all tissues are composed of cells and extracellular fluids. The cell has two distinct parts: the outer, insulating membrane and the inner cytoplasm and nucleus which, such as the extracellular fluid, has high conductivity. Because of the membrane, the cell appears to be an insulator. Accordingly, almost all the current induced in tissues by low-frequency electric field flows around the cells. The insulating membrane, which completely surrounds the conducting core, makes the cell itself a series combination of the membrane capacitance and the cytoplasmic resistance.

2.2.2 Macroscopic Model

The macroscopic approach deals with the whole biological material exposed to EM fields generated by the exogenous fields. Two basic quantities characterize the electrical properties of any material [1]: one that describes energy *dissipation* and another that describes energy storage. Electrical dissipation is the result of charge motion called *conduction*. Conductivity (σ) is the ability of material to transport a charge through the process of conduction, normalized by geometry to describe the material property. Dissipation (or energy loss) results from the conversion of electrical energy into thermal energy through momentum transfer during collision as the charges move.

The electrical properties of biological materials are summarized by the following two parameters:

- i. Conductivity σ , which relates the in-phase movement of charges (conduction currents) to the electric field.
- ii. Permittivity ε , which relates the out-of-phase movement of charges (displacement currents) to the electric field.

The electrical properties of biological materials and the operating frequency determine the EM interaction mechanism. Biological materials are regarded as a lossy dielectric, which is frequently macroscopically or microscopically heterogeneous [1]. It is defined as

$$\varepsilon'' = \frac{\sigma}{\omega \varepsilon_0} \quad (2.1)$$

where $\omega = 2\pi f$ is the radian frequency of the applied field. For time harmonic (steady-state sinusoidal time dependence) fields, the loss is taken into account by considering the permittivity, ε to be complex. It is represented by

$$\varepsilon^* = \varepsilon_0 (\varepsilon' - j\varepsilon'') \quad (2.2)$$

where $\varepsilon' - j\varepsilon''$ is the complex relative permittivity, ε' is a real part of the complex relative permittivity, also called the dielectric constant, and ε'' is a measure of imaginary part of the complex relative permittivity. Physically, ε' is a measure of the relative amount of polarization that occurs for a given applied electric fields, and

ϵ'' is a measure of both the friction associated with changing polarization and drift of conduction charges. The values of both dielectric constant and conductivity vary substantially with frequency as illustrated in Figure 2.1 [1].

Figure 2.1: The variation of electrical properties of muscle and fat with frequency [1]

The permittivity of biological tissues depends on the type of tissue (e.g. skin, fat, or muscle), water content, temperature, and frequency. The permittivity and frequency may also determine how far the EM wave penetrates into the body. The term *depth of penetration* (D_p) usually quantifies this.

2.2.3 Absorption in Biological Materials

At radio frequencies, biological tissues behave like solutions of electrolytes that contain polar molecules. RFR interacts with biological systems by way of ionic conduction (oscillation of free charges) and rotation of polar molecules of water and protein relaxation. Absorbed RF energy is transformed into kinetic energy of molecules, which is associated with a rise in temperature of the irradiated tissues.

The heat transfer may be accomplished by three mechanisms: *thermal conduction, thermal radiation, convection, and sweat evaporation*. Thermal conduction is the process in which heat transfer takes place by molecular diffusion. The amount of heat energy flowing per second per unit area is proportional to the temperature gradient. Thermal radiation is the heat loss due to radiation from the surface of the human body. Convection is the process in which heat is transferred by the simultaneous action of molecular diffusion and mixing motion. Evaporation is the heat loss due to evaporation at the surface per unit area (including sweat and insensible perspiration), and it depends on the arterial blood flow, the wind speed, and the humidity. Sweating is controlled by the central neural integrative mechanism, which receives signals from the thermosensitive sites within the body.

Thus, the rate of change of the energy transferred to the material is called the absorbed power. This power is also called power transferred and also known as *specific absorption rate (SAR)*.

2.3 Specific Absorption Rate (SAR)

At distances within a wavelength from a RF transmitter is a region known as the near field. Since cellular phone radiation has a wavelength of 30 cm at 900 MHz (GSM phone) the users head will be within this near field region. The head disturbs the field and alters the manner in which RFR interacts with tissue. This interaction complicates the absorption of RF energy within the head and makes calculations difficult. The energy is transferred from the applied E field to the material in the form of kinetic energy of charged particles. The rate of change of the energy transferred to the material is called the absorbed power. This power is also called power transferred, but from the bioelectromagnetics point of view, the term specific absorption rate (SAR) is the preferred one [1] and it is defined as

$$SAR = \frac{\sigma |E|^2}{2\rho} \text{ in (W/Kg)} \quad (2.3)$$

where E is the maximum value of the internal electric field, σ is the tissue conductivity and ρ is the mass density. The maximum values of the SAR, which must not be exceeded under any circumstance, are specified in radiation protection standards like those of ANSI/IEEE(1992) or the European Commission (1999).

In general, there are two types of SAR. First is the whole-body average SAR, which is defined as the total energy, transferred to the body per unit time, divided by the total mass. The second type of SAR as relates to this thesis is called the localized (partial-body) SAR. It refers to a small part of the body such as head, torso and limb. *Specific absorption rate* (SAR) is an indication of the amount of radiation that is absorbed into a head whilst using a cellular phone, the higher the SAR rating the more radiation that is absorbed into the head. SAR values are usually expressed in units of watts per kilogram (W/kg) in either 1g or 10g of tissue.

Analyzing possible range of variations of the induced field strengths in various tissues requires an extensive effort, since local field strengths strongly depend on various parameters, such as [4]:

- i. operational frequency and antenna input power
- ii. position of the device with respect to the human head
- iii. design of the device
- iv. size and the shape of human head
- v. distribution of tissues within the head
- vi. electrical properties of the tissues

The internal field in any biological material irradiated by RFR is calculated by solving Maxwell's equations. Basically, computational methods for analyzing EM problems fall into three categories: analytical techniques, numerical techniques and expert system [1]. Analytical techniques apply assumptions to simplify the geometry of the problem in order to apply a closed-form solution. Numerical techniques attempt to solve basic field equations directly, due to boundary conditions posed by the geometry. However, expert system estimate, but do not calculate, the values of fields for the parameters of interest based on a rules database.

In Europe, the European Council Recommendation 519/1999/EC for exposure guidelines has adopted the recommendations made by the International Commission on Non-Ionizing Radiation Protection (ICNIRP Guidelines 1998). In the US, the FCC, Federal Communications Commission, sets the radio frequency safety guidelines that all phones must meet before being sold in the US. Current reference standards and limits (status January 2001) is shown in Table 2.1.

Table 2.1: Current reference standards and limits (status January 2001) [5]

Region / Country	-- Reference to -- SAR measurement protocol	Reference to SAR limit	Limit
Europe	European Specification ES 59005 (1998)	ICNIRP Guidelines 1998 (ICNIRP 1998)	2.0 W/Kg in 10g of tissue
Australia	Australian Communications Authority (ACA) Standard (ACA RS 1999)	Australian Standard AS/NZS 2772.1	1.6 W/Kg in 1g of tissue
US	Federal Communications Commission (FCC) Guidelines (FCC 1997)	American Standard ANSI C95.1 (ANSI 1992)	1.6 W/Kg in 1g of tissue

2.4 ICNIRP Standard

In 1992, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) was chartered as the successor to IRPA/INIRC. The ICNIRP's mission is to coordinate knowledge against various nonionizing exposures in order to develop internationally accepted recommendation. In April 1998, the ICNIRP published guidelines as shown in Table 2.2 for limiting RF exposure in the frequency range up to 300 GHz. The development of the guidelines was based on reviews of a large body of studies [1].

Table 2.2: ICNIRP Protection Guidelines [1]

Frequency Range	E-field Strength (V/m)	H-field Strength (A/m)	B-field (μT)	Power Density (W/m ²)
Occupational Exposure				
Up to 1		1.63×10^5	2×10^5	
1-8 Hz	20,000	$1.63 \times 10^5 / f^2$	$2 \times 10^5 / f^2$	
8-25 Hz	20,000	$2 \times 10^4 / f$	$2.5 \times 10^4 / f$	
25-820 Hz	$500 / f$	$20 / f$	$25 / f$	
820 Hz-65 kHz	610	24.4	30.7	
65 kHz-1 MHz	610	$1.6 / f$	$2 / f$	
1-10 MHz	$610 / f$	$1.6 / f$	$2 / f$	
10-400 MHz	61	0.16	0.2	10
400 MHz-2 GHz	$3 f^{0.5}$	$0.008 f^{0.5}$	$0.01 f^{0.5}$	$f / 40$
2-300 GHz	137	0.36	0.45	50
General Public				
Up to 1		3.2×10^4	4×10^4	
1-8 Hz	10,000	$3.2 \times 10^4 / f^2$	$4 \times 10^4 / f^2$	
8-25 Hz	10,000	$4000 / f$	$5000 / f$	
25-800 Hz	$250 / f$	$4 / f$	$5 / f$	
800 Hz-3 kHz	$250 / f$	5	6.25	
3-150 kHz	87	5	6.25	
150 kHz-1 MHz	87	$0.73 / f$	$0.92 / f$	
1-10 MHz	$87 / f^{0.5}$	$0.73 / f$	$0.92 / f$	
10-400 MHz	28	0.073	0.092	2
400-2000 MHz	$1.375 f^{0.5}$	$0.0037 f^{0.5}$	$0.0046 f^{0.5}$	$f / 200$
2-300 GHz	61	0.16	0.2	10

The International Council on Non-Ionizing Radiation Protection (ICNIRP) standard provides a two-tier set of RF exposure limits. The ICNIRP standard is used in most European countries and is gaining acceptance in many other countries throughout the world outside of North America including Malaysia. The higher tier is referred to as *Occupational* while the more restrictive tier is referred to as *General Population*. The limits for the electric and magnetic field are very similar to the limits in the 1997 FCC Regulations. The differences occur in the two transition regions: between 1 MHz and 30 MHz and between 300 MHz and 2000 MHz. At the lower frequency transition, Safety Code 6 and the ICNIRP standard have variable limits from 1 MHz to 10 MHz. All the U.S. standards (IEEE, ANSI, FCC, ACGIH, and DOD) plus the NATO standard have variable limits from 3 MHz to 20 MHz. And while all the North American standards have variable limits from 300

MHz to 1500 MHz or 3000 MHz, depending on the limits in the microwave region, the ICNIRP standard has variable limits from 400 MHz to 2000 MHz [5].

2.5 Review of Important Research Works on Electromagnetic Absorption and SAR Distribution

Many researches on the effect of electromagnetic penetration in a human head due to cellular phones have been done in recent years. Most of the researches were done in a different approach but their objectives are almost the same. The research on Electromagnetic Absorption in the Human Head and Neck for Mobile Phone at 835 and 1900 MHz is studied by **Om P. Gandhi** [6]. In this study, SAR has been obtained for two different lengths of monopole antennas of length $\lambda/4$ and $3\lambda/8$. This research is focused on adult male head model and reduced-scaled models of 10-5 years-old children. The computational method used is FDTD and the resolution model of human body is obtained from the MR image. Results shown that larger antenna gives SAR that is smaller than SAR for $\lambda/4$ antennas. Besides that, it is found that higher internal tissues SAR are obtained as the scale of the 10-5 years old children head is used. This is because of the deeper penetration of EM energy in smaller models for both 835 and 1900 MHz. Finally, by using truncated one half and third model of the head and neck, SAR distributions are nearly identical to those for full model. Therefore, this method allows saving computer memory and computational time for SAR distribution.

Andrea [7] with his study on SAR Generated by Commercial Cellular Phone- Phone Modeling, Head Modeling, and Measurements. This paper presents the computation of SAR inside an anatomical model of a head. The geometry of four models of cellular phone working at 900-1800 MHz and the model of a head are input to the mesher which performs the alignment discretizes the space by using FDTD technique. The numerical model of human head is taken from MR Image. Computations have been experimentally validated through measurements performed inside anthropomorphic phantoms irradiated by a dipole and cellular phones. SAR is first investigated in homogeneous and inhomogeneous phantoms irradiated by dipole antenna and the second test is done in a phantom irradiated by commercial phones.

Thus, the results are divided into 2 parts which are SAR distribution and SAR inside a human head. In the first part, it shows that SAR distribution inside the phantoms are slightly difference due to a) shape and dimensions of the phantoms, b) homogeneous phantom does not have the ear, thus the source is closer to the internal liquid and c) side aperture of the inhomogeneous and homogeneous phantoms. The result from the second part shows that skin is the most affected tissue by radiation due to penetration depth. Thus, both computation and measurement results agreed that the SAR inside homogeneous is higher than in inhomogeneous phantom. The differences between the computed SAR into the head and the measurement inside the phantoms are due to different dimensions, physical constitution, position/dimensions of the aperture and phone alignment. Reverse Engineering technique which has been presented in this paper is the effective technique to get CAD representation of any cellular phone or any kind of object. Besides, it is suggested that correct modeling of cellular phone is important since the shape of new cellular phones has a particular design imposed by market requirement rather than simplification in phone modeling as metallic box.

Volker et. al [4] comes out with another approach where he studied on The Dependence of EM Energy Absorption upon Human Head Modeling at 900 MHz was studied by. In this paper, the effects of the head properties such as size, shape, and inhomogeneities on the absorption were investigated. Therefore, two techniques were used: 1) numerical/simulation technique using FDTD methods and Finite Integration method. In this technique, 3 different models of adult head were translated from MR image, 2) experimental technique using 0.45λ dipole antenna located 15mm from the head and parallel to the body axis. Three different phantoms were studied. Then, the numerical results were compared with measurements in a multitissues phantom and two homogeneous phantoms with different shape and size. As a result, the region with high absorption value is small and close to the feedpoint while the most parts of the head, SAR is low. Besides that, SAR maxima were found at 2 parts: 1) skin's surface and 2) brain's surface. Furthermore, the distance dependence dominates the field attenuation due to absorption and the ratio of power absorbed due to input power is typically equal to 70%. As a conclusion, the peak SAR is scarcely affected by the size and shape of human head and a peak SAR in homogeneous is smaller than in inhomogeneous phantom. These techniques can be extended for frequencies down to 300 MHz but for 1.5 to 2 GHz must be subject of further study.

EM absorption in man model using FDTD method has been investigated by **Allan Taflove et. al [8]**. In this study, the SAR distributions are calculated using incident frequencies of 100 and 350 MHz. All the tests have been done in 3 different cases: 1) a homogeneous man model in free space, 2) an inhomogeneous man model in free space and 3) an inhomogeneous man model standing on a ground plane. The main objectives of this study are to evaluate the advantage of inhomogeneous models over homogeneous models and grounded models versus free space models.

Thus, the results show that the higher rate of energy absorption for a high frequency does not allow much energy to penetrate to an organ that is located towards the back of the body. Furthermore, grounding the model gives an effect on absorption throughout the body and the contour diagrams illustrate the SAR distribution at various levels for the different models. Finally, the results obtained at 350 MHz are compared with the experimental result of Stuhly. From the comparison results, the magnitude through the torso region is substantially different by greater than 2:1 variation in many places because of the uncertainties in determining the SAR.

It can be concluded that FDTD is capable to calculate detailed SAR distribution for human models. However, this method requires large number of cells for the man model in a higher frequency. This method also places a limit on the lower frequency due to the need for additional computer resources. Therefore, it is suggested to use higher order radiation boundary conditions for extending the lower range. For instance, use 3-pole expansion instead of only two poles.

2.6 Numerical Method used in this project

Finite Difference Frequency Domain (FDFD) is applied in this project as a numerical technique to solve wave equation or Helmholtz's equation. FDFD stands with its own advantages and disadvantages. It is chosen because of its ability to work in 2-D models. Frequency Domain (FD) is used to model the interior 2D region with a simple mathematical formulation. Besides that, FDFD generates a

sparse matrix which is not excitation dependent in general. With the sparse mesh, larger problems can be solved using iterative solvers over direct matrix inversion. Therefore, only small computational storage is needed in the simulation process.

FDFD also able to get transient time domain results by an inverse Fourier transform of a wide frequency sweep. Thus, the value of electric field at each point will be automatically changed as the constitutive parameters in the mathematical formulation are changed. However, FDFD is not suitable for 3-D models since it involves with complex equations. In this case, Finite Difference Time Domain (FDTD) is a better numerical technique to choose.

FDTD is a versatile modeling technique used to solve Maxwell's equations. It is intuitive, so users can easily understand how to use it and know what to expect from a given model. Besides, FDTD is a time-domain technique, and when a broadband pulse (such as a Gaussian pulse) is used as the source, then the response of the system over a wide range of frequencies can be obtained with a single simulation. This is useful in applications where resonant frequencies are not exactly known, or anytime that a broadband result is desired.

In bioelectromagnetic purpose, FDTD is able to show the behavior of SAR distribution at each time slot. However, Since FDTD requires that the entire computational domain be gridded, and the grid spatial discretization must be sufficiently fine to resolve both the smallest electromagnetic wavelength and the smallest geometrical feature in the model, very large computational domains can be developed, which results in very long solution times. Discrete Fourier Transform (DFT) process is also important to apply in this method in order to transform time domain to frequency domain.

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