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Wireless Signals and Male Fertility

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WIRELESS SIGNALS AND MALE FERTILITY

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Dedicated to my parents, husband, and children Ahmad, Sana, and Amr

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ABSTRACT

Rapid advances in wireless technology have increased the number of users of mobile devices. As of 2011, the number of cell phone subscribers have reached 5.3 billion worldwide. Mobile devices have saturated our environment with radio frequency (RF) signals. This situation has created public concern over the effect of such signals on human health.

This dissertation focuses on the correlation of RF signals emitted by cell phones with male infertility. A thorough discussion is provided on the effects of RF signals on the development of central nervous system (CNS) neoplasm, the design of these mobile devices, the range of the RF frequencies they emit, the power with which they operate, their specific absorption rate (SAR), the distance between the user and the device while in use, how and where the devices are used, the duration of usage, and the accumulated exposure associated with the use of multiple RF devices.

The results of our reviews and experimental *in vitro* studies show a significant correlation between the usage of mobile phones and human semen parameters, with a decrease in motility and viability, and an increase in the reactive oxygen species (ROS) score. However, in daily usage, a cell phone kept in proximity to the groin is separated from the testes by multiple layers of tissue. To explore this effect, a computational model of scrotal tissues was designed. Our results show that during *in vitro* experimentation, an effect equivalent to real-life conditions can

be obtained by placing the cell phone a few centimeters farther away from the semen sample. The results of our study can be used to calculate the equivalent distance between a radiation source and a semen sample, and to set up *in vitro* experiments that mimic real-life conditions.

NOMENCLATURE

ACRONYMS AND ABREVIATIONS

CDMA	Code Division Multiple Access
CI	Confidence Interval
DECT	Digital Enhanced Cordless Telecommunication
DGTD	Deployable Ground Data Terminal
EMW	Electromagnetic Waves
FCC	The Federal Communications Commission
FDA	The Food and Drug Administration
FDMA	Frequency Division Multiple Access
FDTD	Finite Difference Time Domain Method
FFHSS	Frequency Hopping Spread Spectrum
FVTD	Finite-Volume Time-Domain
GSM	Global System of Mobile Communications
HSDPA	High-Speed Downlink Packet Access
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	The Institute of Electrical and Electronics Engineers
IR	Infrared
OR	Odds Ratio

PAN	Personal Area Network
PC	Personal Computer
PDA	Personal Digital Assistant
RF	Radio Frequency
ROS	Reactive Oxygen Species
SAR	Specific Absorption Rate
TAC	Total Antioxidant Capacity
TDMA	Time Division Multiple Access
TEM	Transverse ElectroMagnetic
TUNEL	Terminal Transferase dUTP Nick End Labeling
USB	Universal Serial Bus
UTMS	Universal Mobile Telecommunications System
Wi-Fi	Wireless Fidelity
WI-Max	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WHO	World Health Organization
WWAN	Wireless Wide-Area Network

SYMBOLS

V	Volume
E	Root mean square of the electric field (or electric field strength)
σ	Conductivity
ρ	Density of the tissue
J	Current field strength
C	Specific heat capacity of tissue
ΔT	Temperature increment
Δt	Time duration
R	Resistance
u	Electric field energy density
ε	Permittivity
ε_r	Relative permittivity

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CHAPTER I

INTRODUCTION TO RADIO FREQUENCY SIGNALS AND THEIR SOURCES

1.1 INTRODUCTION

The huge increase in the use of wireless devices and the swift advances in mobile communications technology have filled our surroundings with RF signals. This has raised many concerns about the risks of these signals on human health.

While wireless technology dates back five or six decades, the use of mobile devices by the general public has dramatically increased since the development of portable cellular phones about two decades ago. Since then, wireless devices emitting RF signals have become ubiquitous. These include PDAs, mobile phones, MP3 players, gaming devices, wireless LANs, MRI scanners, and a wide variety of devices utilizing Bluetooth technology. As such, it has become imperative to determine if these devices are indeed safe and if there are any limits with respect to short term and long term exposure and strength of RF signal beyond which they become unsafe.

Many organizations, such as the Federal Communications Commission (FCC), have already attempted to set safety limits for these signals, but the available data on whether or not these devices are indeed safe are equivocal, particularly with respect to long-term use.

Organization of Dissertation

The first chapter of this dissertation provides some background on RF signals and introduces some terms and important measures related to these signals (Section 1.2). This chapter also explains various types of wireless signals and compares the effects of the different types of wireless phones and cell phone technologies (Sections 1.3 and 1.4). Then more details on other sources of RF signals such as WLANs and Bluetooth® design and descriptions are provided (Section 1.5). Also, more focused study is provided on the different uses of Bluetooth with its different classes, so one can infer if these uses can accumulate to pose a significant hazard on health (Section 1.5.2).

Chapter 2 includes a discussion on the effects of the various sources of RF signals on health. The specifications of cellular phones and their related possible risks were taken as a reference to compare all other RF sources to that of wireless phones.

Since the relationship between cell phone radiation and risks of brain tumors and infertility in men are of primary concern, Chapter 2 includes a comparison among the studies that claimed risks on brain tumors and the ones that did not, and determines which have stronger evidence or more reasonable results.

Similarly, a comparison among the studies that relate cell phone use to male infertility is provided.

Another step in this dissertation is a pilot study that related the effects of cell phone use on male fertility. This study is the major contribution of this dissertation, the details of which are provided in Chapter 3. The experiment took place at the Cleveland Clinic Andrology Laboratories. This was a collaborative work between Cleveland State University and the Cleveland Clinic. This *in vitro* study was done on human semen samples to relate cell phone use to the effects on the male reproductive system. Frequency, distance, time duration, and power density were measured and related to the possible effects. Measurements of semen parameters, reactive oxygen species (ROS), total antioxidant capacity (TAC), and ROS-TAC, were determined before and after exposure periods and compared. Data and results were subject to statistical analysis to determine significance.

This study is followed by another extension on chapter 4 that involved computational modeling to establish *in vitro* experimentation conditions that represent a cell phone radiation on the spermatozoa in human male reproductive organs. This simulation based approach allowed estimation of the deposition of electrical energy in the testes of the user, which is related to specific absorption rate (SAR).

Finally, Chapter 5 discusses the safety measures and safety standards provided by various organizations. The possibility of recommending additional

standards due to the results of recent research in light of the increase in the usage of RF emitting devices is also discussed.

1.2 BACKGROUND

1.2.1 Radio Frequency Signals

Today there are different types of wireless technology in use, such as infrared (IR) and radio frequency (RF). Television and stereos, for example, use infrared for remote control; but cellular and cordless phones use RF. RF is more practical than IR because it can transfer more information over longer distance and pass through solid objects. RF also uses more diffuse waves, and communicating devices do not need to be in line of sight to exchange information [1].

Radio frequency is a range of frequencies along the electromagnetic spectrum. RF ranges from 3 KHz to 300 GHz. During a cellular phone call, the range of transmitted and received RF signals is between 400 and 2000 MHz. Thus cellular phones operate with RFs that are located between FM radio waves (87.5 to 108.0 MHz) and the waves used in microwave ovens (300 MHz to 3 GHz) on the electromagnetic spectrum [2], [3]. Cordless phones typically operate at frequencies near 50, 915, or 2450 MHz, and newer types go up to 5.8 GHz.

The term used for measuring the amount of RF energy absorbed by the body is called the specific absorption rate (SAR), and it is expressed in units of Watts per kilogram (W/kg) [3]. The electromagnetic energy levels associated with RF energy are not as high as in x-rays or gamma rays, which are known to ionize biological tissues and cause permanent damage to biological components such

as DNA. However, RF and microwave radiation do affect their surroundings (including tissue) by both thermal effects (tissue heating) and nonthermal effects (such as the interference between these signals and some common medical devices, including cardiac pacemakers and hearing aids).

1.2.2 Thermal Effects

Microwave radiation causes dielectric heating. This heating is caused by the rotations of polar molecules generated by the electromagnetic field. Therefore any dielectric material, including components in living tissue, will be heated due to this rotation. In other words, the flow of current gives rise to energy loss by Joule heating, and this heat energy will be absorbed in the biological system when the electromagnetic source is close to the body [3]. Thus when a person uses a cell phone, most of the heating effect will be along the head surface, causing a potential elevation of the head temperature. This may potentially increase the local blood flow to the brain or meninges (protective membranes that cover the central nervous system). If a person is using an earpiece during a phone conversation while holding the cell phone handset on the belt or pocket, then the heating will be on the abdominal area. These effects depend also on the length of the exposure period as discussed in Chapter 2.

Safety standards have posed restrictions to limit the increase of the body core temperature to about 1˚C in animal experiments [3], and this is what has led the responsible institutions to create the specific absorption rate safety limit, or SAR, that will be explained in more detail in an upcoming section (1.2.4.2).

1.2.3 Nonthermal Effects

Nonthermal effects are the biological effects associated with exposure to low-level RF fields. Besides dependency on thermal parameters (SAR and power density) the effect of electromagnetic fields depends on many other non-thermal parameters which are induced at intensities far below heating and might have similar or even more impact on living organisms. Some of these parameters are wavelength and frequency, the overall exposure duration, type of modulation, near field or far field, intermittence, intense and persistent exposures, linear or circular polarization, continuous wave and pulsed fields [4].

Many researchers have studied the effect of RF-EMF at low frequencies in-vitro (experiments on organs, tissues, or cells outside of a living organism), and in-vivo (experiments on a whole living organism such as on animals or humans). These studies presented evidence that RF-EMF at low frequencies, such as those used by mobile communications devices, can cause various biological effects on living organisms even within the standard limits, and at intensities well below those that can cause heating effects on tissues. Many examples have been documented in these studies [5]. The effects include changes at many levels such as DNA damage, free radical formations, changes in the number of subcellular structures as proteins and nucleic acids, etc. [6].

Our study, discussed in detail in Chapter 3 of this dissertation, also found an effect on fertility in men and on Reactive Oxygen Species (ROS) levels. This effect was observed even when the mobile phone used met the safety limits of SAR and power densities.

A pan-European study called REFLEX (Risk Evaluation of Potential Environmental Hazards from Low Energy Electromagnetic Field Exposure Using Sensitive *in vitro* Methods) published in 2004 studied the genotoxic effects in cultured human fibroblasts exposed to RF-EMF at 1800 MHz, and 2 W/kg SAR, with continuous and intermittent exposure. Their results demonstrated that DNA damages cells *in vitro* when exposed to radiation levels between 0.3 to 2 Watts/kg, which includes the range of those emitted by digital phones (0.2–1 W/kg) [7]. But the results of another study in Germany that used similar experimental conditions, contradicted the results of the REFLEX project. They obtained negative results in independently repeated experiments despite the use of the same cells, the same exposure conditions, and the same equipment. They stated that the reason for the differences between the two results was not clear [8]. Recently, the issue of nonthermal effects is becoming more controversial and it is getting researchers' attention. Many research results and conclusions strongly suggest that safety standards should take the nonthermal effects into consideration.

1.2.4 RF Signal Measurements

When discussing the biological effects of RF signals, we usually refer to their frequency, their output power, their power density, and the specific absorption rate (SAR).

1.2.4.1 Power and Power Density

Power density is a term for characterizing an RF electromagnetic field. It is defined as the power per unit area and is measured in units of W/m^2 or $\mu W/cm^2$. In other words, it is a measure of the intensity of the electromagnetic waves in the surrounding area.

As mentioned earlier, RF signals transmit electomagnetic energy in the surroundings. The maximum peak power emitted from most mobile phones is 2 W. For digital cordless systems employing time division multiple access (TDMA), the peak output power is around 1 W. And for Digital Enhanced Cordless Telecommunications (DECT™), the maximum output power is 0.25 W [9].

In most mobile systems, such as Global System of Mobile Communications, GSM®, and code division multiple access, CDMA, a power control mechanism is employed to regulate power. This technique enables the handheld phone to change the transmitted power according to the requirement for keeping an acceptable connection. It is based on the information reported by the mobile device to the base station which in turn determines if it is necessary to decrease or increase the transmitting power of the mobile terminal. Therefore, the power, for example, in a GSM mobile phone that starts at a maximum peak of 2 W can range down to 3 mW of transmitted power [9].

The power control feature can explain the variations in power density that were noticed in our study (Chapter 4) when we measured the power density of the RF signal emitted by the cell phone used. The transmitted power control

feature keeps a good quality connection with minimum interference while it decreases the consumption of power of the handheld terminal and increases its battery life [9].

1.2.4.2 Specific Absorption Rate, SAR

One of the most effective measures of RF energy is the SAR, the specific absorption rate, which is a measure of the amount of power, or heat, that is absorbed in a specified region of a tissue or averaged over the whole body, expressed in units of W/kg. Different exposure standards are deliberated to keep SAR values in the body within safety levels to ensure that harmful temperature increases do not occur in the body.

To determine SAR experimentally it is necessary to measure the increase of temperature in a localized region of a living tissue. To accomplish this and directly map SAR, it is required to insert calorimetric probes into the head of a live cell phone user. Since this is impractical, SAR can be estimated with the use of appropriate physical and experimental models and instrumentation employing head phantoms [10].

The specific absorption rate is usually averaged over a volume *V* containing 1 or 10 g of tissue according to the formula

$$SAR = \frac{\int_{v} \sigma \frac{|E|^2}{\rho} dV}{V} \tag{1.1}$$

where *E* is the root mean square of the electric field, also called the electric field strength, which is a vector field (N/C or the equivalent units of V/m), σ is the conductivity of the medium (*S/m*), and *ρ* is the density of the tissue (kg/m^3) [11].

Another formula that may be used to calculate SAR at a certain point (*x*,*y*,*z*) is as follows:

$$SAR(x, y, z) = \sigma \frac{E^2(x, y, z)}{\rho} \tag{1.2}$$

SAR in this equation is defined based on the electric field strength measurement at a point (*x, y, z*) in a homogeneous medium [12].

Knowing that $J = \sigma E$**,** where *J* is the current field strength, one can also write the formula as follows [3]:

$$SAR = \sigma \frac{|E|^2}{\rho} = \frac{J^2}{\rho\sigma} \tag{1.3}$$

Also, SAR can be related to temperature and time duration through the formula

$$\boldsymbol{SAR = c \frac{\Delta T}{\Delta t}} \tag{1.4}$$

where *c* is the specific heat capacity of tissue (J/Kg ˚C), Δ*T* is the temperature increment (˚C), and Δ*t* is the duration (sec) over which Δ*T* is measured [3]. Also SAR can be determined experimentally.

We can show the link between the two equations (1.3) and (1.4) by looking at their units and making some eliminations. Recall that

$$SAR = c \frac{\Delta T}{\Delta t}$$

Replacing each term with the corresponding units gives

$$\left(\frac{J}{Kg.^{\circ}C}\right)\left(\frac{^{\circ}C}{\sec}\right)=\frac{J}{Kg.\sec}=\frac{W.\sec}{Kg.\sec}=\frac{W}{Kg} \tag{1.5}$$

in the same way we can substitute for the units that correspond to equation (1.3) as follows:

$$SAR=\sigma\frac{|E|^2}{\rho}$$

substituting for the terms with their units and knowing that power *(W)* = V^2 / R where *R* is the resistance in Ω gives

$$\left(\frac{S}{m}\right)\left(\frac{V^2}{m^2}\right)\Big/\left(\frac{Kg}{m^3}\right)=\left(\frac{V^2}{\Omega.m^3}\right)\Big/\left(\frac{Kg}{m^3}\right)=\frac{V^2}{\Omega.Kg}=\frac{W}{Kg} \tag{1.6}$$

so it is clear that equations (1.3) and (1.4) lead to the SAR units of (W/kg).

The FCC provided a SAR standard limit of 1.6 W/kg, averaged over a volume of 1 gram of tissue for most parts of the body, or 4 W/kg averaged over the whole body, to limit the increase of the body core temperature to about 1˚C in animal experiments [3]. A study by Gandi et al. [10] on different head phantoms showed that many cellular phones exceeded the SAR safety limits. The study used both numerical and experimental methods to determine SAR using ten different wireless phones, five at 835 MHz and the other five at 1900 MHz. It was observed in this study that advanced mobile phone system (AMPS) phones may use a time average as high as 600 mW at 800/900 MHz, and the peak SARs averaged over 1 g of tissue would commonly exceed the FCC limit of 1.6 W/Kg if antennas are not carefully designed, and directed or put further away from the head. Also, one can infer from the SAR definition and the related equations that safety standards are based on thermal effects [10].

1.3 TYPES OF WIRELESS PHONES

There are four major types of wireless phones: cordless phones, mobile phones, transportable phones, and portable phones. A discussion of each is provided in the following sections.

1.3.1 Cordless Phones

This type is usually used in homes and offices, where their base units are plugged into telephone jacks. Older cordless phones that operate at 46 MHz use less power than cell phones. Therefore the resulted exposure to the user of these phones is considerably less than to the user of cell phones. However, the use of the newer cordless phones, namely, the Digital Enhanced Cordless Telecommunication (DECT), is becoming much more common. These cordless phones operate on three different frequencies: 900 MHz, 2.4 GHz, and 5.8 GHz. The most common ones used today operate at 2.4 GHz. The power levels used by such phones are comparable to the powers used by the traditional cell phone.

1.3.2 Transportable Phones (Bag Phones)

These phones usually operate with equipment stored in a small case where their antenna extends from the carrying case. These phones allow users to stay connected in extremely remote locations, such as in oil fields, with complete mobility. Since such phones are either carried with the user or kept in a car, they can produce higher RF exposure to users than mobile (car) phones.

1.3.3 Mobile Phones (Car Phones)

Car phones are safer than other types of wireless phones since their antenna is usually mounted on the outside body of a car. Because the antenna is the primary RF source, the metal surface of the car and the distance between the antenna and the user provides protection against RF energy.

1.3.4 Portable Phones (Cellular Phones)

The common cellular phones used today are called portable phones, and it is common today to refer to this type as mobile or cellular phones. The antenna of the portable phone is close to the user's head during a call, and to the user's body when carrying it. Thus the RF exposure is greater in this type than the other types. The analog phone in the USA (as the older type of mobile phones was installed in cars that are not in much use anymore) can emit RF with a power of 3.6 Watts. The new digital models operate at lower power (maximum 2 Watts).

1.4 CELLULAR PHONE TECHNOLOGIES

The second generation digital technology which is in use nowadays replaced the first generation Nordic mobile telephone (NMT) analog technology that was in use in the 70's and 80's, mostly in Europe, and the first generation Advanced Mobile Phone Service technology (AMPS that was in use in the USA in the 70's. The NMT analog technology was based on frequency division multiple access (FDMA) [13]. Also, AMPS had used FDMA, then advanced to the time division

multiple access (TDMA) technique. The most common second generation technologies are the Global System of Mobile Communications, GSM, and code division multiple access, CDMA. Digital mobile communications had overcome the drawbacks of the analog technology by providing better voice quality with less noise, higher battery life, less output power, higher data transfer speed, and the ability to access the Internet [14], [15].

The digital handset type that are in use today in the USA, Europe, and some other parts of the world, is the Global System of Mobile Communications, GSM. GSM phone technology is based on time division multiple access, TDMA. GSM phones are based on a circuit-switched system where each 200 kHz channel is divided into eight 25 kHz time slots, the time is divided into 4.62 ms frames and each time frame is then divided into eight user slots. GSM not only defines the TDMA air interface but also the entire cellular system. But the limiting factor in this technique is that it limits the number of users that can use the same cell simultaneously. When the specified limit is reached it blocks any other new calls [16]. For example, T-Mobile®, and AT&T™-Cingular usually use this technology in the USA.

GSM handsets emit radio waves with power levels up to 2 Watts. There are four main types of GSM handsets. Two types operate in the 900 MHz band in Europe and some other parts of the world, and 850 MHz in the USA, with a maximum power of 2 Watts. The other two types operate in the 1800 MHz band in Europe and 1900 MHz personal communication system (PCS) band in USA, with a maximum output power of 1 W. For example, AT&T-Cingular and Verizon

usually operate on the 850 MHz band, whereas Alltel® and T-Mobile usually operate on the 1900 MHz band. A comparison between the powers of some of the RF sources is summarized in Table I.

Table I: Powers of different RF sources

RF source	Power
Cell Phone, GSM	3 mW - 2 W
Cell Phone, CDMA	< 1 W, typically 0.2 W
Digital Cordless Sys. (using TDMA)	Max. 1 W
DECT (Digital Enhanced Cordless Telecom)	Max. 0.25 W
WLANs	Max 100 mW
Bluetooth	1mW-100 mw (C 1)

In addition to the GSM technology, code division multiple access, CDMA, is used in the USA. CDMA is known for its high security and capacity. By assigning a unique code to each conversation the CDMA spread spectrum technique provides higher capacity by overlapping every transmission on the same carrier frequency, but the price is an increased bandwidth. CDMA digital technology operates in the 800 MHz band and 1.9 GHz band (personal communications system), and it operates at less power than GSM [16], [17].

CDMA provides higher calling capacity (three to five times) than the GSM and TDMA digital cellular phone systems and requires fewer cell sites. This high capacity allows CDMA system to accommodate the recent massive rise in the number of subscribers while providing faster communication speeds with

excellent voice quality. CDMA cell phone technology is used in some parts of the world such as in the Far East. In the USA, for example, Alltel, Verizon, and Sprint usually use this technology.

A newer technology that will be considered the third generation technology is the Universal Mobile Telecommunications System (UMTS) which is based on wide-band CDMA, or W-CDMA. It is expected to replace GSM. UMTS technology is seamless and universal. In fact, it utilizes W-CDMA air interface and GSM infrastructure, and uses 5 MHz carrier in the 2 GHz frequency band rather than the 200 kHz carrier used by the GSM technology. The terms W-CDMA and UMTS are now used interchangeably.

Another third generation (or 3.5 G) is the high-speed downlink packet access (HSDPA). It is also based on W-CDMA technology with improved downlink speed. It allows UMTS to use even higher data transfer, speeds, and capacity [18].

TD-SCDMA is another third generation mobile telephone standard. It was developed by China Academy of Telecommunications Technology (CATT) in collaboration with the Chinese Corporation DTT, known as Datang, and the German corporation Siemens [19–21]. TD-SCDMA stands for time division – synchronous code division multiple access [19]. TD-SCDMA was accepted by the International Telecommunications Union, ITU, in May 2000, and by the Third Generation Partnership Project, 3GPP, in December 2000, as a third generation standard. The development of TD-SCDMA has attracted many international investigators such as Samsung and Nokia. Alcatel, for example, had agreed in

November 2004 to contribute 25 million euro for investment with Datang to advance and support this technology [21]. In January 2006, TD-SCDMA, was formally announced as a 3G standard by China's Ministry of Information Industry [21].

TD-SCDMA had combined the best features from the CDMA and TDMA (GSM) technologies. TD-SCDMA has many things in common with WCDMA on radio interface protocols [22]. Using time division duplexing (TDD), TD-SCDMA was the first standard of the type anticipated by the China Wireless Telecommunications Standard group (CWTS). This technology provides the capability of accessing all 3G core networks and GSM technology [23].

Zhang et al. [23] compared TD-SCDMA technology to other competitive technologies such as WCDMA and CDMA2000. The comparison was based on different criteria such as the technological improvement, economic valuation, political and social effects, compatibility, and performance (data rate, mobility, and capacity). The results of this research showed that TD-SCDMA had scored the highest total points of all [23]. TD-SCDMA design is also simpler than CDMA and CDMA 2000, which makes its hardware more cost effective than them [23], [24].

TD-SCDMA features the up-link synchronization technique that is based on time division duplexing, TDD, rather than the frequency division duplexing, FDD, scheme used by W-CDMA [24], [25]. Unlike FDD, TDD uses the same carrier frequency in both directions, the uplink and downlink, for signal transmission. Having the same channel conditions on both directions allows the base station to

presume the information of the downlink from the uplink information. TDD also allows for signal pre-processing at the transmitter rather than at the receiver as in the FDD scheme [25]. On the other hand, the synchronization technique feature allows all mobiles synchronized by a base station and existing in the same cell to achieve transmission timing adjustment continuously. Therefore, all their burst signals that will arrive at the base station must be synchronized. So, by adjusting the number of timeslots used for downlink and uplink dynamically, this technology facilitates asymmetric traffic with different data rate requirements on downlink and uplink more easily than the FDD technique [25], [26]. Another advantage of TDD is the lower hardware cost, since a whole radio frequency transceiver can be integrated into one single chip, while the FDD requires two RF transceivers [25].

1.5 OTHER MODERN SOURCES OF RF SIGNALS

Wireless LANs and Bluetooth are among the most growing wireless technologies and are getting more popular. These technologies are surrounding us with RF radiation, especially at home and in the workplace.

1.5.1 Wireless Local Area Networks (WLAN)

WLAN is a small wireless local area network that allows devices to communicate and transfer data locally using high frequency radio waves rather than connecting them with wires. WLANs enable mobile devices to connect to a

local network using access point devices within a radius of 100 to several hundred feet. WLANs are based on the IEEE 802.11 standards [27].

A WLAN transmits at much less power than microwave ovens and cellular phones. Unlike cellular phones that transmit radio signals continuously (connection oriented), WLANs send radio signals only intermittently during data transmission. Table II describes some WLAN characteristics [27].

Table II: Key characteristics of 802.11 wireless LANs [27]

CHARACTERISTICS	DESCRIPTIONS
Physical Layer	Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS), Orthogonal Frequency Division Multiplexing (OFDM), infrared (IR).
Frequency Band	2.4 GHz (ISM band) and 5 GHz.
Operating Range	Up to 150 feet indoors and 1500 feet outdoors.

1.5.2 Bluetooth Technology

Bluetooth is a short-range wireless technology, or wireless network, that allows wireless communication between different remote devices, such as cellular phones, computers, and PDAs. The IEEE 802.15 has developed a wireless personal area networking (PAN) based on the Bluetooth specifications [27]. Bluetooth and wireless LANs use the same frequency range as that of microwave ovens. However, microwave ovens use concentrated beams of energy to generate heat while Bluetooth energy is dispersed in all directions at

power levels too weak to be noticeable by humans. Also microwave ovens operate at a million times the power of Bluetooth.

Bluetooth networking is based on *ad hoc* networking technology where, unlike WLANs, no fixed infrastructure exists. What distinguishes the Bluetooth networks is the master/slave relationship that exists between the network devices as shown in the topology in Fig. 1.1, where one of the devices (the laptop) is the master and the other two devices (the mobile phone and the PDA) are the slaves [27].

Fig. 1.1: Bluetooth Ad Hoc Topology (modified from reference [27]).

In a Bluetooth piconet, all devices follow the same frequency hopping sequence and operate on the same channel. Only one device in each network is allowed to act as the master and the rest are slaves. However, a slave in one network may be a master for other networks, thereby creating a chain of networks. As a device moves away from or toward the master device during a

given session, that master/slave relation might change, allowing for a dynamic topology [27].

Bluetooth functionality can be added to a host device, such as a computer, by installing a baseband controller along with a Bluetooth radio on a device that connects to a Universal Serial Bus (USB) port or a PC Card. It can also be integrated on a system board. These components are illustrated in Fig. 1.2.

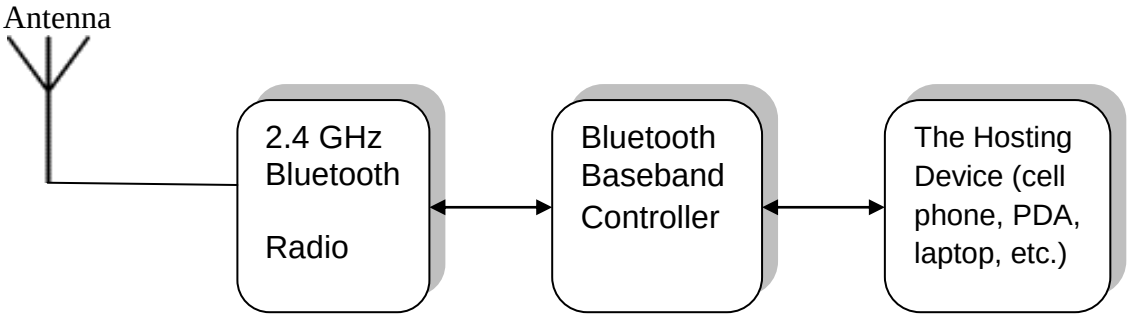


Fig. 1.2: Bluetooth Components (modified from source [28]).

Bluetooth works in the electromagnetically noisy 2.4–2.484 GHz band, as do most cordless phones. It uses the fast frequency hopping spread spectrum (FHSS) technique, where its signals hop 1600 times per second, and corrects errors to guarantee that the transmitted information is not altered.

In general, Bluetooth output power is low compared to cellular phones. There are three classes of Bluetooth. The three classes differ in sensitivity, output power, and range. Class 1 has a maximum output power of 100 mW (20 dBm). Class 1 supports an unobstructed line-of-site range up to 100 meters (328 ft). Class 2 has a maximum output power of 2.5 mW (4 dBm). Class 2 supports up to a 10 meter (33 ft) range. Class 3 has a maximum output power of 1mW (0

dBm) with a very limited range from 0.1 to less than 10 m (less than 30 ft) [27]. This shows that Class 1 operates at power levels closer to those of cell phones, compared to the other two classes that operate at much lower powers. These three classes are described in Table III.

Table III: Bluetooth classes descriptions

Bluetooth Class	Maximum Permitted Power	Max. Range
Class 1	100 mW (20 dBm)	100 m (328 ft)
Class 2	2.5 mW (4 dBm)	10 m (33 ft)
Class 3	1 mW (0 dBm)	0.1 m-10m (less than 30 ft)

Figure 1.3 explains the three classes, including examples of the use of each range. For example, the shortest range (lowest power) is usually good for applications of cable replacement such as mouse and keyboard.

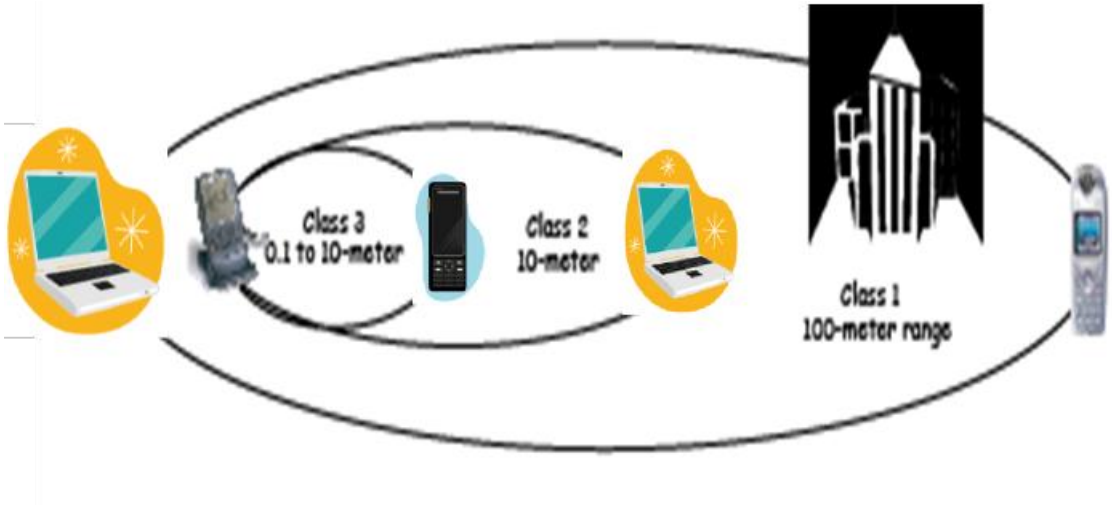


Fig. 1.3: Bluetooth classes and ranges of operation (modified from reference [27]).

1.5.3 Personal Digital Assistants (PDAs)

PDAs are wireless handheld electronic organizers with the capability of sharing information with personal computers (PCs) or another PDA. PDAs are also known as pocket computers or palmtop computers. Newer versions enable their users to download their e-mail and access the Internet. Some cellular phones today are developed to have the capability of integration with Personal Digital Assistants (PDAs), so the user can have increased access to e-mail and the Internet. Such cellular phones, featuring data networking along with information processing capabilities, are commonly called smart phones. Apple announced the iPhone in January 2007. The iPhone is a multi-featured device that integrates the various features of the video-capable iPod with mobile internet and mobile phone capabilities.

Also, some PDAs are integrated with cellular phones, as mentioned before, to form smart phones. Smart phones provide the services of digital cellular phones and PDAs, so they are capable of providing voice services, email, text messaging, voice recognition, and Internet access via Wireless Fidelity (Wi-Fi), a type of WLAN, or wireless wide-area networks (WWANs). Wi-Fi devices operate on IEEE 802.11b standards with a range of 150 feet and a frequency of 2.4 GHz, similar to the frequency range of Bluetooth and microwave ovens.

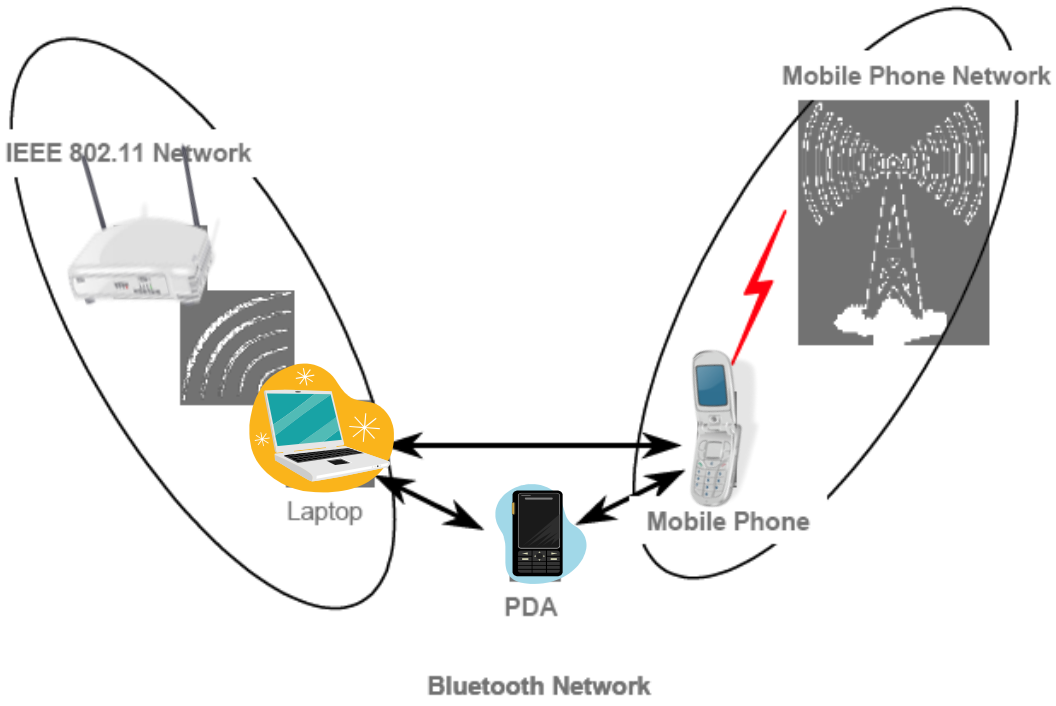


Fig. 1.4: Bluetooth Network (modified from reference [27]).

Figure 1.4 shows an example of an ad hoc network that includes "a Bluetooth-enabled mobile phone connecting to a mobile phone network, synchronizing with a PDA address book, and downloading e-mail on an IEEE 802.11 WLAN" [27].

CHAPTER II

LITERATURE REVIEW

2.1 STUDIES ON RISKS ASSOCIATED WITH RF SIGNALS

Many recent studies investigated possible hazards of cellular phones and their base stations, but the results have been equivocal. A thorough understanding of these issues is not only important for public health officials and medical professionals, but also for engineers who are responsible for the design of these devices and ensuring that they conform to safety limits.

While many investigators concluded that there is no convincing evidence establishing any deleterious effects of RF signals emitted by cell phones on humans, others claim many health hazards of cellular phones, including central nervous system (CNS) neoplasms, hearing loss, headaches, migraines, infertility, skin irritations, eye infections, and memory loss, among others.

This chapter provides a summary of studies that address the risks associated with RF signals emitted by different devices. As all of these studies employ the statistical measure of odds ratio (OR), a brief description of this statistical methodology is included.

2.1.1 Odds Ratio (OR)

The odds ratio of an event represents the number of the subjects experiencing an event divided by the number of subjects who do not. It ranges from zero, which means that the occurrence of the event is not possible, to infinity, which means that the event will certainly happen. It is easier to recognize the odds if they are greater than one. For example, if the OR is 4.0, it means that four subjects will experience the event for every one that does not. However, if the odds ratio is less than one, fewer subjects experience the event than those who do not. For example, an OR of 0.25 means that 0.25 (or 1/4) subjects will experience the event for every one that does not. In other words, one subject will experience the event for every four who do not [29].

2.1.2 Cordless Phones and Health Hazards

Many studies suggest that the use of cordless phones is safe because they emit lower power than cellular phones, and their bases are usually not so close to the body as those of the cellular phones. As a result, the RF signal will fade more as the distance from the user increases. However, it should be noted that these studies were made on the older types of cordless phones, operating at 46 MHz. As noted above, the Digital Enhanced Cordless Telecommunication (DECT) cordless phones operate on three different frequencies: 900 MHz, 2.4 GHz, and 5.8 GHz. The most commonly ones used today operate at 2.4 GHz. Such phones operate at power levels comparable to those used by conventional

cellular phones, and thus their risk is presumably comparable to that of the cellular phones for the same duration of use.

A study in Sweden showed a risk when using cordless phones (even the older types) for a latency period higher than five years [30]. Cordless phones have been in use in Sweden since 1988, starting with the analog types that operated in the range of 800-900 MHZ. The digital types were introduced in 1991 and operated at 1900 MHz. The newer types were not included in this study. This study investigated the risks of Non-Hodgkin's Lymphoma (NHL) associated with the use of cellular and cordless phones. NHL is a neoplasm of the lymphoid tissues, such as lymph nodes, spleen, and other organs of the immune system. The study was made on 910 cases and 1016 controls. Results for T-cell NHL showed an OR of 2.4 with the 95% confidence interval (CI) = 1.09-5.60, for greater than 5 years of use. Results showed no risk for the B-cell type NHL.

A later study with the same group showed an increased risk of different types of brain tumors, with higher odds ratio for using both cordless and cellular phones for periods more than 10 years. The OR for cordless phones was 1.5 with a 95% CI = 1.04 – 2.0 [31].

2.1.3 Cellular Phones Base Stations and Health Hazards

A study conducted by the Dutch Technological Research Institute (TNO) in 2003 reported that the RF signals for the upcoming generation (3G) mobile phones can lead to headaches and nausea. A 3G base station uses microwave

radiation while transmitting signals to cell phones, and its coverage area reaches a few square kilometers [32].

The study was done using radiation that is of similar power levels to base stations that were much lower than those emitted by mobile phone handsets used close to heads. The survey studied two groups; one group included about 76 healthy people and the other group included another 76 people who claimed various health effects due to living nearby a base station. The study “excluded subjects who were suffering from epilepsy, brain injury, claustrophobia, or were using medication to counteract mental health problems” [32].

Both groups experienced statistically significant adverse effects: "When the test group was exposed to third generation base station signals, there was a significant impact. They felt tingling sensations, got headaches and felt nauseous," a spokeswoman for the Dutch Economics Ministry said. But the responsible Dutch ministers said that follow-up research is needed to confirm such results [32].

2.1.4 Possible Effects of Bluetooth and Wireless LANs

Wireless LANs and Bluetooth are among the fastest growing wireless technologies. These technologies are filling the environment with RF radiation with long exposure periods at home and in the workplace.

2.1.4.1 Wireless Local Area Networks

WLAN is a wireless local area network that uses high frequency RF signals to provide wireless connection for the devices in a network. Very little data exist regarding the effects of WLAN on health. However, the output power emitted by wireless LAN systems is much less than that of a cellular phone. The exposure to RF energy in the area of such systems is very little because radio waves fade rapidly over distance [33].

2.1.4.2 Bluetooth

As mentioned earlier, Bluetooth and wireless LANs use the same frequency range as that of microwave ovens. Again, few data exist regarding specific health hazards of this technology, as it is believed that the SAR levels caused by such systems are usually too low to pose health hazards. However, given the development of high power Bluetooth devices and the potential for high accumulated exposure, these systems may need to be tested [34].

As shown earlier in Table III, Bluetooth has 3 classes. Class 1 has a maximum output power of 100 mW (20 dBm), and Class 2 has a maximum output power of 2.5 mW (4 dBm), and Class 3 has a maximum power of 1 mW (0 dBm). It was also mentioned that the output power of class 1 is comparable to that of the cell phones.

Most wireless headsets use class 2. Despite the low power emitted by class 2 Bluetooth, one should consider the duration of the use of these headsets while making a phone call, listening to music, and so on. Another aspect to be

considered is the use of class 1 Bluetooth in headsets. Also, some mobile phones that feature Bluetooth to get Internet access use class 1 transmitters. If the Internet connection stays on while making phone calls in such smart mobile phones, the exposure of the head to RF-EMW will accumulate. Class 3 Bluetooth is also used by some USB adapters that can connect to any Bluetooth device, from Bluetooth cell phones to Bluetooth headsets. They are so small that they can be carried in any pocket all day, thus potentially resulting in a very long-term exposure.

2.1.5 Cellular Phones and Health Hazards

Due to the heating effect of the microwave radiation, the increase in temperature could also affect the eyes, because the cornea of the eye does not have temperature regulation mechanisms. Working on high power radio transmitters can cause premature cataracts. But the low power of mobile phones makes this disease unlikely to occur in their users.

Many symptoms have been reported by users of mobile handsets during and after use such as sleep turbulence, burning and tingling sensations in the skin of the head, fatigue, dizziness, loss of mental attention and memory retentiveness, headaches, depression, tachycardia (heart palpitations), digestive system disorder, and general weakness [3]. Some of these symptoms are also reported by people who live within 300 m of base stations or near high voltage transmission lines. But most studies and reviews show no scientific evidence yet

found for a relationship between exposure to RF radiation in cellular phones and the reported symptoms.

The health hazards that include the nonthermal effects described in the introduction of this dissertation are much greater for telecommunications workers who are exposed to radiation for longer times within short distances from the wireless equipment and live antennas. Other studies showed other effects of RF signals on health such as interference between these signals and pacemakers, decreased skin resistance in male teenagers [35], and some effects on the ear canal.

The issues of brain tumors and infertility in men, due to the exposure of RF signals, are of major concern to researchers and to the public. These two effects will be discussed in more detail in the coming sections.

2.2 CELLULAR PHONES AND BRAIN TUMORS

This section presents different studies on cell phone use and the risk of brain tumors. A comparison and discussion of the various studies is included. A statistical measure of p-value was used in most of these studies to show how significant the results are.

2.2.1 Statistical Methods

The p-value is a measure of credibility of a hypothesis. The smaller the p-value obtained, the stronger the evidence is to reject the null hypothesis.

Therefore, p-value is the probability that the null hypothesis is true and “a large p-value implies that the study is not capable of excluding the null hypothesis as a possible explanation of how the data turned out” [36]. The p-value is a measure from 0 to 1, and from p-values, one can conclude whether there is an evidence of a difference according to the scale shown in Fig. 2.1.

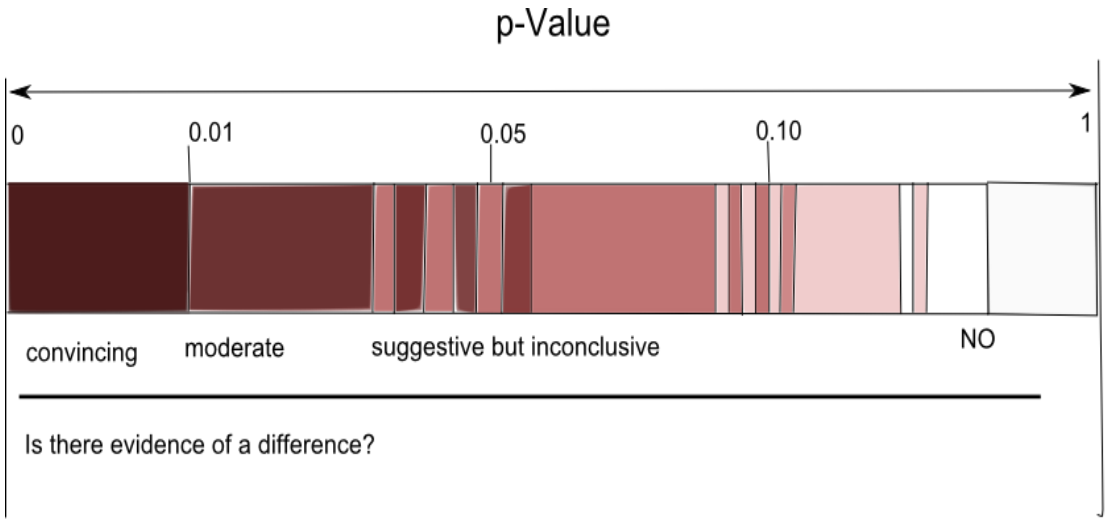


Fig. 2.1: p-value scale (modified from reference [36]).

2.2.2 Studies on Cell Phones and Brain Tumors

An article published in *Neuroscience* in 1999 [37] tested the effects of the different levels of IRIDIUM exposure on the c-Fos gene expression in the mice brains. “The c-Fos protein is the product of an immediate early gene associated with the execution of the apoptotic pathway...Increased c-Fos expression is thought to mediate the genomic program of apoptosis in neuronal death” [38].

The study shows that the expression of c-Fos is not significantly increased in the brain of mice until given one hour of exposure at levels exceeding the peak

dose by six times and exceeding the average whole body mobile phone exposure limits in humans by thirty times. The authors suggest that the majority of brain tumors in humans are glial (neuroglial) in origin, and in the finding of this study, the cell types responding to IRIDIUM exposure appeared to be neurons. Therefore, this study suggests that even high doses of IRIDIUM would not seem to affect the type of cells that may develop later into a brain malignancy.

A study published on Dec. 20, 2000, concluded that there is no association between the use of handheld cellular phones and the risk of brain cancer, but it was noted that "further studies are needed to account for longer induction periods, especially for slow-growing tumors with neuronal features" [39]. The study was done on 469 men and women with ages between 18 and 80 years with primary brain cancer, and another group of 422 healthy matched controls. The authors interviewed patients and asked them if they had ever subscribed to cellular telephone service, if they had ever used a handheld cellular phone on a regular basis, the number of years of use, minutes used per month, and other related questions. By studying and comparing the collected data, the authors found the multivariate odds ratio (OR) was less than 1.0 for all histological classes of brain cancer (except for a rare type of brain cancer known as neuroepitheliomatous neoplasm). This result suggests that there is no increased risk of brain cancer in association with short-term exposure to RF signals emitted by analog cellular phones [39], [40].

Another study in Japan conducted in 2000-2004 concluded that there is no significant increase in the risk of acoustic neuroma (also known as vestibular

schwannoma, a tumor that develops in the vestibulocochlear nerve within the internal auditory canal) associated with cellular telephone use in Japan [41].

In a study performed in the United Kingdom between the periods of December 2000 and February 2004, researchers interviewed two large groups from all across the United Kingdom. One group included 966 people diagnosed with brain tumors, and the other group included 1716 apparently healthy matched controls. The study did not find evidence to relate the use of mobile telephones to the risk of brain tumors [42].

Some other studies with similar settings indicated similar results and similar conclusions. However, a study in January 2003 by Salford et al. claims serious damage in rat brains that were exposed to microwave radiation from a Global System for Mobile Communications (GSM**)** cell phone [43]. The results of this study showed that weak pulsed EMW such as the signals emitted by mobile phones cause a significant leakage of albumin (a water-soluble protein found in some animals tissues or blood that thickens when heated) through the blood-brain barrier, which in turn causes damage to the neurons. The study was made on three groups, each containing eight rats and exposed to GSM mobile phone electromagnetic fields of different strengths with the means of transverse electromagnetic cells (TEM) for two hours. They found highly significant evidence (with p-value $p < 0.002$) for neuronal damage in the hippocampus, cortex, and the basal ganglia in the brains of the exposed rats. Figures 2.2 and 2.3 show the results obtained by the study.

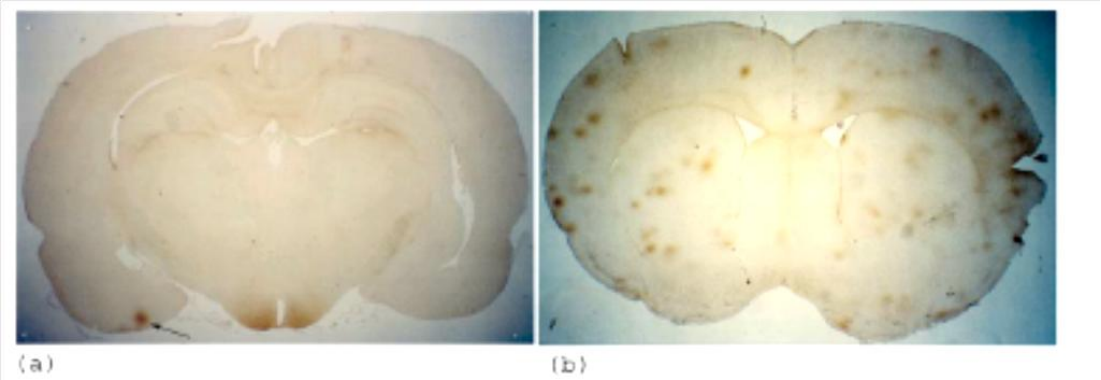


Fig.2.2: (a) Cross-section of central parts of the brain of an unexposed (sham-exposed) control rat. (b) Cross-section of central parts of the brain of an RF EMF-exposed rat to 2 mW/kg for 2 hrs.
The brown spots that appeared in both pictures are due to the albumin staining. The albumin that appeared in the central parts of the brain (the hypothalamus) in (a) is a normal attribute. In (b) albumin occurred in several small foci representing leakage from multiple vessels. The pictures are magnified about x3.
(This figure is reproduced with permission from Environmental Health Perspectives [43]).

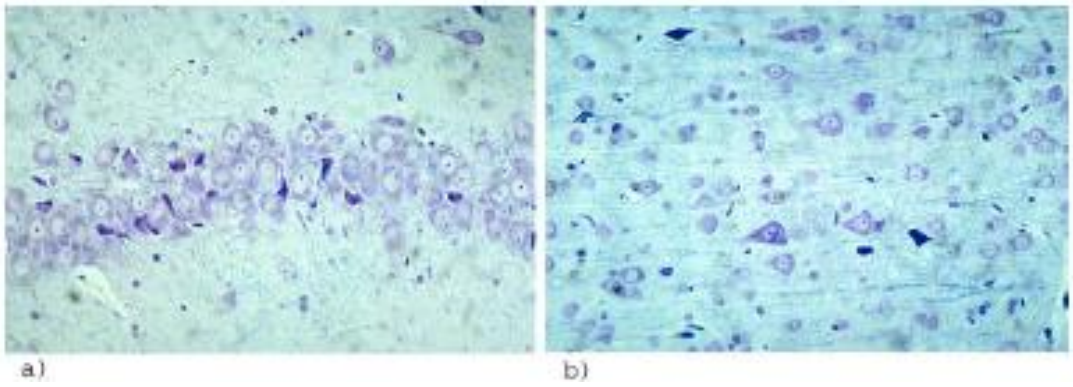


Fig. 2.3: Photomicrograph (magnified x160) of RF exposed rat's brain, sectioned in 1-2 mm thick slices and stained with cresyl violet. Figure (a) shows a row of nerve cells in a portion of the pyramidal cell band of the hippocampus; some abnormal shrunk-black nerve cells appear among the normal (large) nerve cells. Figure (b) shows the normal (pale-blue) nerve cells of the cortex, top left, of the exposed rat mixed with abnormal, shrunk-black (dark neurons) at all depths of the cortex; the least abnormal appearing cells are in the superficial upper layer.
(This figure is reproduced with permission from Environmental Health Perspectives [43]).

Another Swedish study conducted between 1997-2003 and published in March 2006 suggests that long term use of cellular phones can raise the risk of brain tumors. Researchers at the Swedish National Institute for Working Life investigated the mobile phone use of 905 people aged between 20 and 80 years that were diagnosed with a malignant brain tumor. They noticed that there is a greater chance of having the tumor on the side of the head where the hand sets of cellular phones are mostly used. They found “a total 85 of these 905 cases were so-called heavy users of mobile phones, that is they began early to use mobile and/or wireless telephones and used them a lot" [44]. They suggested that such heavy users who have used mobile phones for a total of 2,000 hours or more have an increased risk of 240 percent for a malignant brain tumor on the side of the head where the mobile phone is used. The Nordic countries were amongst the first countries in the world to establish cellular phones. In Sweden, wireless phones have been in use in since 1984, earlier than many other countries in the world. This allowed the Swedish authors to study the effects of a longer-term use of wireless phones [44].

This results shown in Figure 2.4 indicate that analog cellular phones have the most effect (with the highest odds ratios), followed by digital cellular phones, and finally, cordless phones. The results also show that the longer the use periods, the higher the effects.

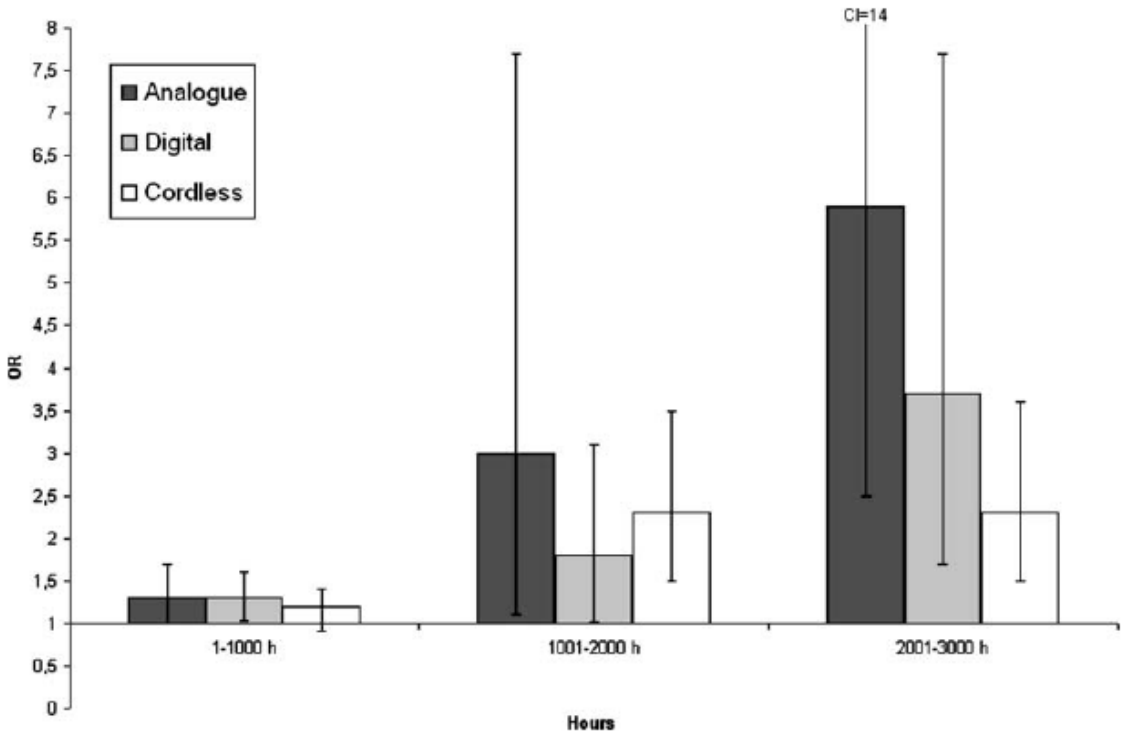


Fig. 2.4: Odds ratio and 95% confidence interval, CI, bars for three different groupings of duration for use of analog, digital, and cordless phones, respectively. All bars represent malignant brain tumors. (This figure is reproduced with permission from Elsevier with license No.: 2736611443341) [44].

Hardell et al. had performed many case-control studies (of about 12 different articles on this topic, seven are case-control studies) at different time periods on people of different ages using different wireless phone types. Their studies showed an increased risk of some types of brain tumors for people who used wireless phones for more than five years, and even higher risk for those who used them for more than ten years.

A later study by Hardell et al., published in October 2006, indicated an increased risk of brain tumors, mostly acoustic neuroma and malignant brain tumors, for all studied phone types with long term users, especially with more

than 10 years of usage [45]. Another study by Hardell et al. indicated that the use of cell phones by children and teenagers increases their risk of having brain tumors by five times [46].

Another study found significant increase in DNA single strand breaks in rat brain cells ($p<0.001$) [47]. In this study two sets of six rats were exposed to low intensity microwave radiation with frequencies of 2.4 and 16.5 GHz, power density of 0.344 mW/cm^2 and 1.0 mW/cm^2, and SAR of 1.0 and 2.01 W/Kg respectively. The rats were exposed to the radiation for two hours per day for 35 days. The increase in DNA single strand breaks was apparent in both cases but it was higher at the lower frequency case (2.4 GHz).

2.2.3 Discussion and Overview of Brain Tumors Studies

From the research reviews summarized above that study the possible relations between cell phone use and brain tumors, it appears that risks are increased as the use period increases, with the heavy users (or long-term users) having the highest risk. Other researchers claim that these studies are inconsistent, not reliable, or not enough to prove the claimed hazards. Studies of the latter researchers showed no link between the RF exposure and health hazards.

Some studies were done experimentally in laboratories and others included surveys on human subjects. Studies showed no risk associated with the short-term (less than five years) use of cellular phones. However, there is stronger evidence that the risk of brain tumors does exist with long-term use (especially

for more than ten years). Most studies that involved surveys showed convincing data that indicate different effects involved with long term use. Their odds ratios were higher than 1 with reasonably short confidence intervals (CI) and reasonable p-values when provided. For example, Hardell et al. provided many case studies on this topic. Three of them discussed different types of brain tumors, and found a significant risk associated with the use of cellular/cordless phones, especially for long-term use.

However, many of the studies that denied the risk involved with long-term use have some flaws. For example, the survey performed by Lönn et al. [48] has many flaws. One major problem with this study is that its data actually show an existing risk even though they are claiming that there is no increased risk associated with long term use. The contradicting data in Tables 5 and 6 provided in their study shows ORs greater than 1 for both glioma and meningioma types of tumors [49-51]. For example, their data show almost double the risk of high-grade glioma among women due to “regular” cell phone use (OR = 1.96, 95% CI: 1.10, 3.5). This reference also includes other flaws due to selection bias, such as the misuse of the term “regular users.” It should also be noted that the cell phone industry was responsible for funding the study [51]. A similar problem is noticeable in the results of the study done by Schüz et al. They concluded that there is no risk of meningioma for those who used cell phones for more than 10 years, even though their data indicated an odds ratio of 1.09 [52].

The study by Tillmann et al. that involved mice indicated in the discussion section that their test results on the tumor types tested are “contradicting the

adverse (neoplastic) health effect by the *long term* RF exposure" [53]. The use of the phrase "long term exposure" here is not proper, and their explanation in their conclusion is more accurate where they say that the mice were exposed for an average of 2 hours per day, 5 days a week, for a period up to 24 weeks. This time duration cannot give a conclusion or indication of long-term exposure, and the frequent use of the phrase "long term study" in their paper shouldn't be confused with the phrase "long-term RF exposure."

The study done by Lahkola et al. [54] concluded that their overall statistical results do not reflect an increased risk of brain tumors. They say that it is possible that the risk exists for long term use (for periods greater than 10 years), although their data show an OR = 1.39 for long time users. Moreover, there does not seem to be any compelling reason for suggesting that this result might be due to chance.

Some studies that are based on lab experiments also showed a risk due to RF exposure. The risks included an elevation of the c-Fos expression in mice brains only when they elevated the exposure levels to SAR levels higher than 4.05 W/kg. This finding might give us a hint about the accumulated risk due to the extensive use of many RF sources and/or for long term use. The other studies reviewed that did not claim health risks reflect short-term use/exposure rather than long term/extensive use.

In short, from the above discussion one can infer that it is likely that there is no significant increase in the risk of brain tumors for short term users of cellular phones. However, it is also likely that there is an increased risk of brain tumors

for long term users. There is no definite evidence available yet and further reliable studies and comprehensive reviews on the available studies are needed for a stronger conclusion regarding this matter.

2.3 CELLULAR PHONES AND THE RISK OF INFERTILITY

This section studies the effects of cell phone radiation on male fertility. It is introductory to the following chapter, which includes the original contribution of this dissertation, and an experimental study on this topic. This section includes a summary of different studies related to cell phone use and male infertility.

An article posted on October 2006 by the Daily Mail [55] referred to a new study performed by US researchers in Cleveland, New Orleans, and doctors in Mumbai, India. The study indicated a link between the reduction in sperm count and an effect on sperm quality for men who use mobile phones for more than four hours a day. The study looked at 361 men undergoing checks at a fertility clinic. The results showed a reduction by 25% in sperm count for those using their phones for more than four hours a day, and the men with the highest usage experienced more problems in sperm quality. The swimming ability of sperm had also lowered by a third, and there was a 50% decrease in sperm morphology (the number of sperm that are shaped properly). This might be due to the electromagnetic radiation produced by the cellular phone handsets carried on a belt or in the pocket.

Dr. Ashok Agarwal, Director of the Reproductive Research Center at the Cleveland Clinic, who led the study, said that it is too early to advise men to limit

the use of cell phones because “we still have a long way to go to prove this, but we have just had another study approved” [55]. The results of a pilot study performed by Dr. Agarwal and his group, presented at the American Society of Reproductive Medicine 2006 in New Orleans, suggest that the use of mobile phones has adverse affects on the semen quality. The study found significant decrease in sperm normal morphology, viability, count, and motility, which may lead to male infertility [56].

This study performed by Dr. Agarwal and his team was further analyzed and published with more details in January 2008. The results showed a significant drop in the mean sperm count, viability, motility, and morphology, in all studied mobile phone user groups. The laboratory results showed further decrease in the values of the mentioned sperm parameters in all tested groups as the time duration of daily use increased. There was a significant difference in these parameters in the group using the cellular phone for more than four hours per day compared to the other groups using it for shorter time durations [57]. Figure 2.5 explains the effects according to the usage time.

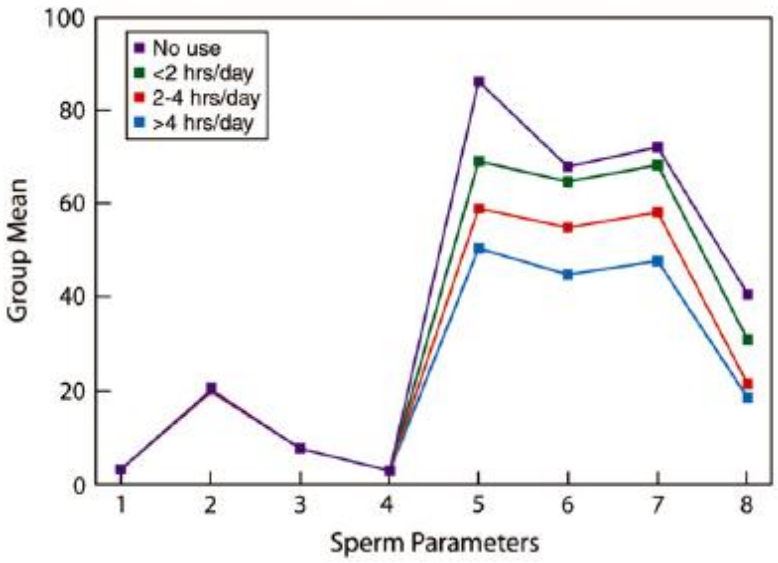


Fig.2.5: Summary of sperm parameters for different cellular phone users. The x-axis shows the eight studied sperm parameters: 1: Volume; 2: Liquefaction time; 3: pH; 4: Viscosity; 5: Sperm count; 6: Motility; 7: Viability; and 8: Percent normal morphology. The y-axis refers to the mean values of the corresponding sperm parameters for each user group [57]. Starting from the upper line it refers to the "no use" group, then "less than 2 hrs/day," then "2-4 hrs/day," and the lowest line refers to "greater than 4hrs/day". (This figure is reproduced with permission from Springer with license No.:2736610296472) [57].

This study agreed with an earlier one performed in 2004 and led by Imre Fejes of the University of Szeged in Hungary. This study included 221 men and included a comparison of the sperm count between subjects who carried their mobile phone for most of the day and those who did not. The study results showed a 30 per cent reduction in sperm count was apparent in mobile phone carriers compared the non-carriers group [58].

Another study by Yan et al. performed on rats showed a significant decrease in sperm motility, and numerous clumps of sperm cells appeared in the exposed groups. The groups of rats were exposed to cell phone radiation for two 3-hour periods (a total of six hours) per day, for 18 weeks [59].

A pilot study conducted by Dr. J. Behari at Jawaharlal Nehru University in India on 20 rats found a significant effect on DNA double strands in sperm cells of the exposed rats. The rats were exposed to radio frequency radiation for 35 days in a chamber. The resulted DNA double strand break could mutate and cause cancer as Dr. Behari indicated. This study also resulted in a significant decrease in sperm count and testis size in the exposed rats [46].

CHAPTER III

EXPERIMENTAL STUDY ON THE EFFECTS OF CELL PHONE RADIATION ON MALE FERTILITY

This chapter and the following chapter present the primary contribution of this dissertation. This study is a collaborative work between Cleveland State University and the Cleveland Clinic [60–63].

3.1 HYPOTHESIS, GOALS, AND ORGANIZATION OF THE PILOT STUDY

Recent studies on this topic have shown various effects of RF EMW related to cell phone use on male fertility [58], [64], [65]. However, they have serious limitations since they used either statistical surveys or animals to obtain their results. However, small surveys are usually not accurate enough to make strong conclusions. Also, the size of rats' bodies and differences in their geometry and physiological responses make it impractical to compare such animal models to humans. It is immoral, of course, to perform the experiments on humans and expose human bodies to these radiations. Therefore, the mentioned

circumstances along with the need to have a strong conclusion on this issue led us to perform our *in vitro* experiments. Our study is unique, more accurate, and more realistic since human samples (*in vitro*) are used.

The goal of our study was to examine the effects of cell phone radiation on a male's reproductive system, or semen quality, using human samples. The testing is conducted on semen samples taken mostly from healthy donors and some others from infertile patients for comparison. Our study assesses the effect of electromagnetic waves (EMW) emitted from cell phones (850 MHz) on semen parameters and oxidative stress on human semen by an *in vitro* exposure study. Samples are divided equally and a portion from each sample is exposed to cell phone radiation. The results of the exposed samples and the sham exposed (unexposed /control) samples are then compared. Basic semen parameters are measured right after each experiment is done. Among the parameters that are measured are the total antioxidant capacity and reactive oxygen species, ROS, in semen samples after exposure to 850 MHz RF signals (refer to Sections 6.6-6.8). This would allow us to estimate the oxidant/antioxidant imbalance induced by EMW in semen. This in turn would allow us to reveal the mechanism of action of RF-EMW and demonstrate the need for protective measures to be taken to prevent or reduce the effects of RF signals on the male reproductive system.

3.2 MATERIALS AND METHODS

3.2.1 The Pilot Study Methodology

Before starting the pilot study, all devices were tested. The power density was checked in the lab with the RF field strength meter to measure the power density in the surroundings, and check for other signals from other sources in the room. A measurement of 0.2-0.3 $\mu W/cm^2$ resulted.

The field strength meter was used to test the power density of one cell phone, giving measurements ranging between 6 and 40 $\mu W/cm^2$. Then two cell phones were put close to the meter together to see how the effects can be accumulated with the presence of more than one source in the surroundings. These gave measurements ranging between 35 and 67 $\mu W/cm^2$ in the same room. This range and variation in the power density measured can be explained by the power control feature that was explained in section 1.2.4.1 of this dissertation.

Another measurement was taken when the field strength meter was placed near the microwave oven while in operation to compare the radiation leakage from the microwave oven to that of the cell phone. The measurements were between 40 and 250 $\mu W/cm^2$ while the meter was moved around the microwave oven. This range of the microwave measurements was dependent on the side of the microwave oven that was close to the meter.

The samples were maintained at room temperature during the experiment. The room temperature was checked with a thermometer throughout the experiment. Then, the phone was put close to the input antenna of the power booster that will receive the signal from the cell phone and amplify it through the

power booster. The output of the power booster was connected to the power meter to check the power after the phone was put in talk mode. Next, the frequency was measured with the spectrum analyzer and the signal was displayed on its screen.

The RF field strength meter was used again to check the power density after the phone was put in talk mode. Then, the connecting cable was removed from the output of the booster and replaced with the receiving antenna, to make sure that the signal was not lost in the room.

It was a critical matter to decide on the exposure duration since talk time on cell phones differs from one person to another. Recent *in vitro* studies have chosen one hour of *in vitro* exposure duration [66]. So, our exposure period and experimental temperature for this study were chosen according to RF-EMW exposure guidelines of an *in vitro* study [60].

The experiment was performed while placing the samples close to the cell phone. The phone was kept in talk mode for one hour. The samples were tested as soon as the experiment was done and compared to the unexposed samples. While repeating the experiment on different samples, the distance was 2.5 cm between the exposed sample and the source. The room temperature was kept around 66 ^{o}F.

3.2.2 Data Collection and Analysis

Semen samples were collected from 23 healthy donors and 9 patients. After a liquefaction process, each sample was divided in two aliquots, the exposed group and the control, or the non-exposed group.

The exposed and the control samples were both analyzed immediately after the exposure period to the cell phone radiation. The analysis for sperm concentration, viability, and motility was performed according to the World Health Organization (WHO) guidelines [60], [67].

3.2.3 ROS Measurement

Measurements of ROS for both the exposed and non-exposed aliquots were performed by professionals in Cleveland Clinic Foundation laboratories. ROS measurements were performed after one hour of exposure on both aliquots (exposed and unexposed). This procedure was performed by "chemiluminescence assay using luminal (5-amino-2, 3-dihydro-1, 4-phthalazineedione; Sigma Chemical Co., St Louis, Mo). A 100-mmol/L stock solution of luminal was prepared in dimethyl sulfoxide. For the analysis, 10 µL of the working solution (5 mmol/L) was added to 400 µL of neat sperm sample. Chemiluminescence was measured for 15 min using a Berthold luminometer (Autolumat LB 953; Berthold, Bad-wildbad, Germany). Results were expressed as $\times 10^6$ counted photons per minute (cpm)/20×10^6 sperm, and as log (ROS + 0.001), with the 0.001 constant chosen to achieve approximate normality for the ROS scale" [60].

3.2.4 Total Antioxidant Capacity Assay Measurement

Different types of oxidation measurements, sources, and targets are used for the detection of the oxidized product in the assay measurements techniques for total antioxidant capacity (TAC) in plasma. TAC assay included measurements of antioxidant activities of all components, including vitamins, lipids, proteins, glutathione, etc. "All samples were centrifuged at 1000 g for 10 min at 4 ˚C. Clear seminal plasma was aliquoted and frozen at -70 ˚C until the time of the TAC assay. Seminal plasma total antioxidant measurements were performed using the antioxidant assay kit (Cat. No. 709001; Cayman chemical, Ann Arbor, MI) " [60].

3.3 THE PILOT STUDY SETUP/DESIGN

In our pilot study an actual cell phone (Sony Ericsson, GSM, 850 MHz) is used to generate the signal. The SAR for this phone is 1.42 W/Kg according to FCC radiation tests. A wireless power booster (amplifier) is used to amplify the cell phone signal, and is able to display the signal and measure its frequency on the spectrum analyzer. The cell phone was held close to the antenna at the input of the amplifier to make the measurements.

For testing, a wireless field strength meter is used to measure the power density of the emitted radiation from the RF source. A power meter is used to measure the power. A spectrum analyzer is used to display and analyze the signal and its frequency. A thermometer is used to monitor the room temperature. Figure 3.1 shows the equipment used for the pilot study.

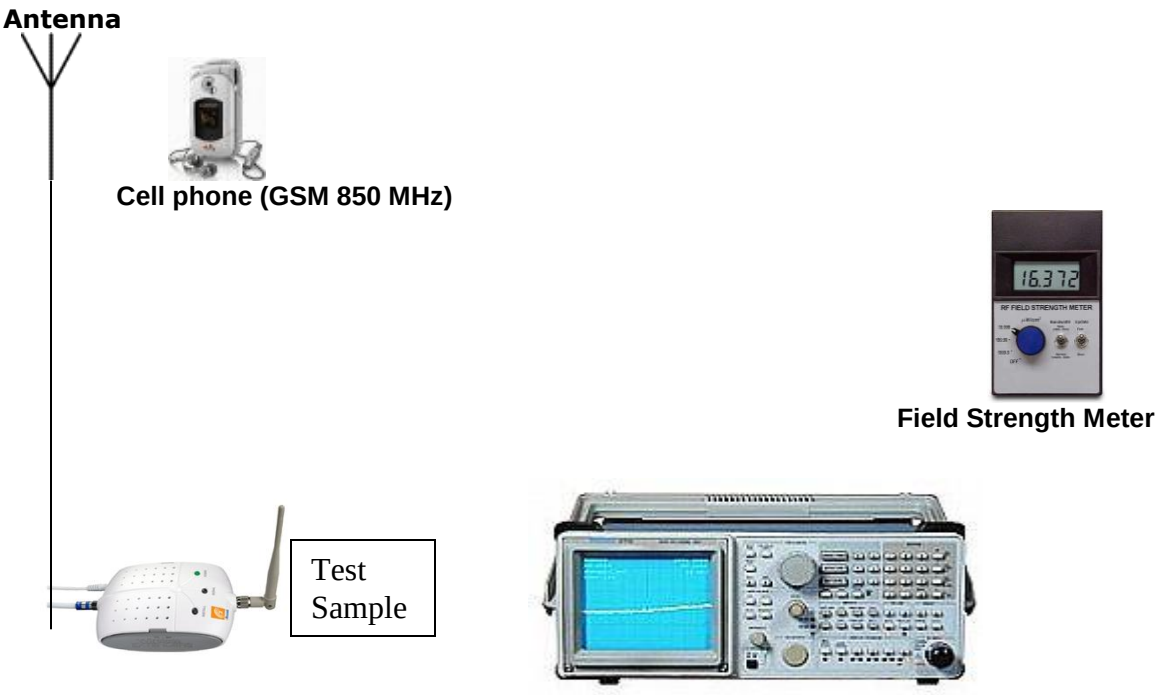


Fig. 3.1: The pilot study setup

The frequency of the signal was verified using the spectrum analyzer with the means of the power booster as shown in Fig. 3.2.

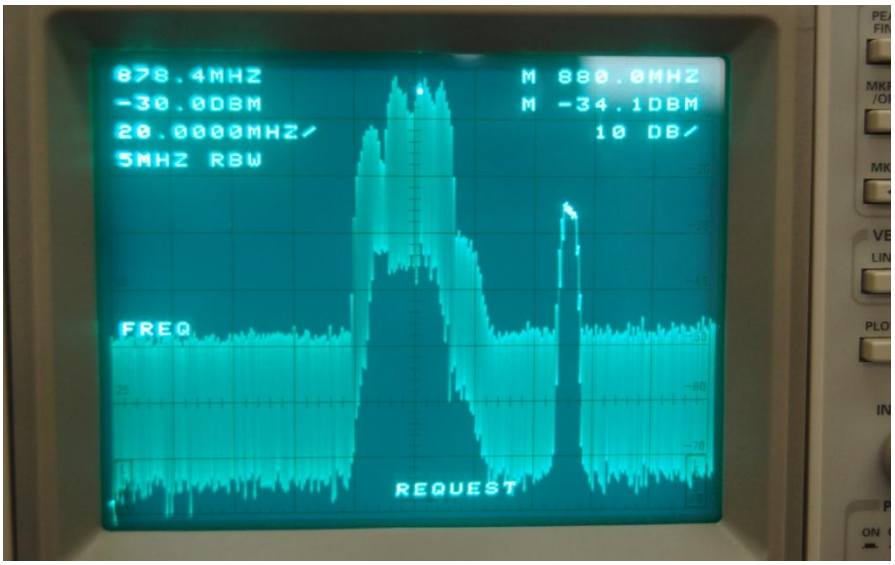


Fig. 3.2: The center frequency of the RF signal emitted by the cell phone used shows a reading of 878 MHz.

3.4 DEVICES/EQUIPMENT DESCRIPTIONS

Table IV explains the type of the equipment used in the pilot study, their use, and their prices. This was provided to the Cleveland Clinic to prepare the necessary equipment for the setup of the *in vitro* experiment.

Table IV: Equipment specifications.

Equipment	Use	Model	Company
Cell phone (GSM, 850 MHz); with a wireless ear piece (Bluetooth)	To generate the desired RF signal	Sony Ericsson 300i, with Singular SIM	Sony Ericsson (Cingular SIM)
Cell phone signal booster (wireless power amplifier), with antennas	To amplify the cell phone signal's power and connect to testing devices	YX500-CEL (single band)	Zboost Universal
Power meter	To measure the output power of the RF amplifier.	HP 437B	Hewlett Packard
Spectrum analyzer	To analyze and display the output signal, determine its frequency.	2712 (9kHz - 1.8GHz Spectrum Analyzer)	Tektronix
Field strength meter	To measure power density, check for other sources effects.	RF Field Strength Meter, Model #11400	AlphaLab Inc.
Leads/connecting wires	To make the necessary connections between devices.		

3.5 THE PILOT STUDY FLOWCHART

The flowchart shown in Fig. 3.3 explains the steps followed in the pilot study in the right order according to the details provided in sections 3.2 and 3.3.

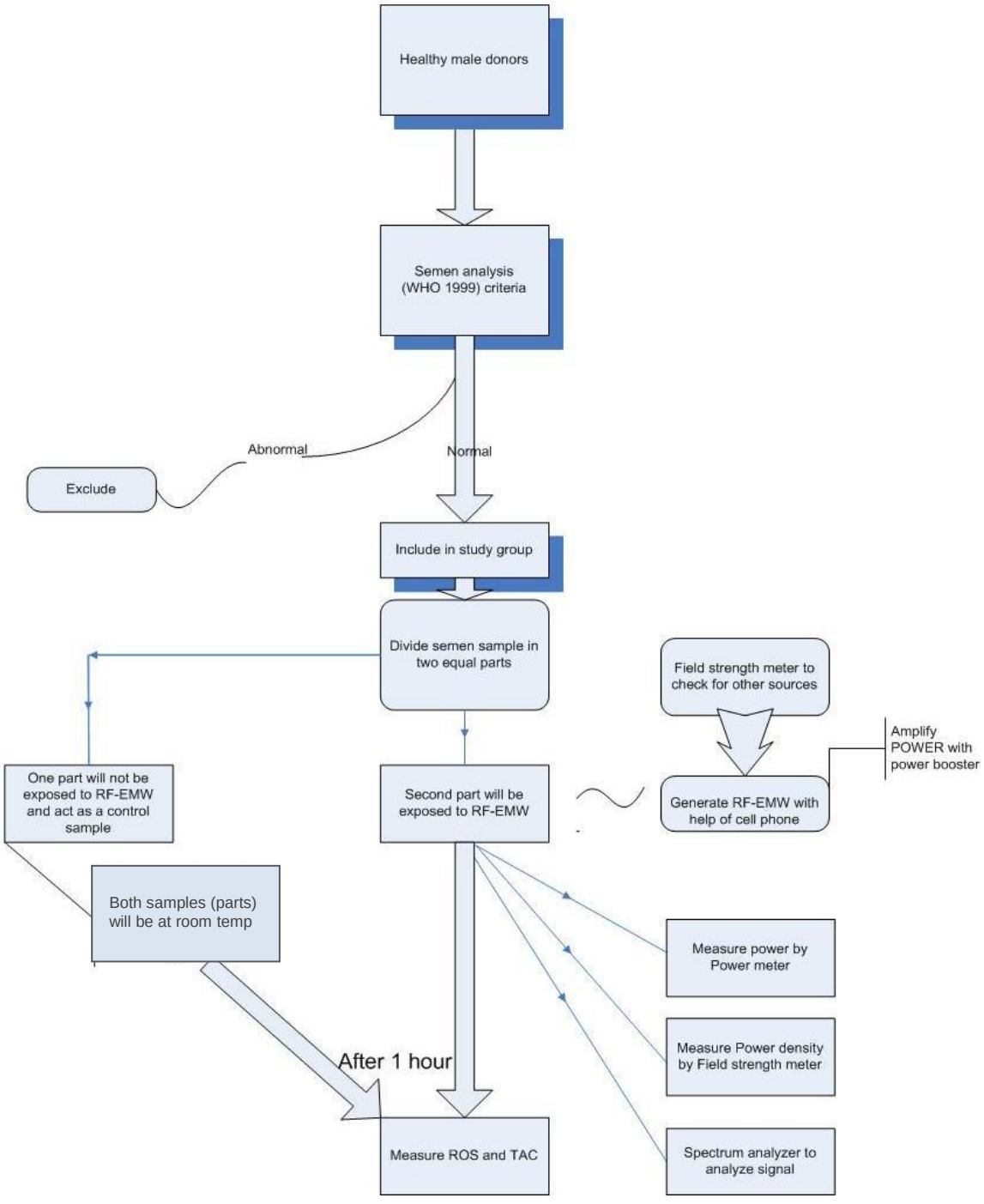


Fig. 3.3: The pilot study flowchart

3.6 THE PILOT STUDY RESULTS

As you can see in the table for raw data used in pilot study (see Appendix A), the data are calculated by taking the values from ROS, Log (ROS+0.001), TAC, ROS-TAC, Viability, Motility, and terminal transferase dutp nick end labeling (TUNEL). Three values were taken into consideration: mean values, standard deviation values, and p-values based on exposed and non-exposed data. The values are generated according to the different number of participants for each category (ROS, TAC, etc.). For example, 32 participants (including donors & patients) were evaluated for ROS and so on. All raw data are tabulated in Appendix A.

3.6.1 Sperm Parameters

Before explaining the effects of the sperm parameters, it is necessary to define these parameters from the medical point of view.

First, the term sperm concentration, or sperm count, refers to the number of sperm in a sample of semen measured as millions per milliliter. A sperm count may be used as a measure of male fertility. The spermatozoa concentration should not be lower than twenty million per ml for a healthy fertile man [67].

Second, the motility of a semen sample refers to the percentage of all sperm moving in the forward direction. At least fifty per cent of the spermatozoa should be swimming in the forward direction for a normal sample [67], [68].

Third, viability is a measure of the percentage of the number of sperm that are alive in a semen sample. In a normal sample at least seventy-five per cent of the spermatozoa should be alive [67], [69].

After testing and comparing the results for the exposed and unexposed samples, the data showed no significant difference in sperm concentration between the two samples. However, a significant decrease in both motility and viability was noticed in the exposed sample for all groups.

The mean motility for the exposed samples was 48.62 ± 17.36%, and for the unexposed samples the mean was 52.11 ± 18.34% with a p-value of 0.03. An even more significant difference was observed within donors' samples with p-value of 0.01. Also, a significant decrease was seen in the viability of the exposed samples with $p < 0.001$. The mean viability for the exposed samples was 52.33 ± 13.21%, and for the unexposed samples the mean was 58.97 ± 14.81%. A more significant difference with $p < 0.001$ was apparent within the Healthy donors samples than the patients samples. The results are summarized in Table V.

Table V Summary of the motility and viability results for exposed and unexposed samples in various groups. Average room temperature 66 °F. Exposure period 1 hr. n stands for the total number of subjects tested.

Group	Motility (%) Exposed	Motility (%) Unexposed	Viability (%) Exposed	Viability (%) Unexposed
OVERALL	48.62 ± 17.36	52.11 ± 18.34	52.33 ± 13.21	58.97 ± 14.81
p-value	0.03		< 0.001	
n	30		32	
DONORS	50.60 ± 17.49	54.80 ± 17.61	53.52 ± 13.05	61.00 ± 13.71
p-value	0.01		< 0.001	
n	23		23	
PATIENTS	43.56 ± 16.94	45.25 ±19.42	48.43 ± 13.99	52.29 ± 17.41
p-value	0.36		0.14	
n	7		9	

Differences between exposed and unexposed aliquots were calculated and values are shown in Table VI.

Table VI Differences in motility and viability results between exposed and unexposed samples in all three groups.

GROUP	Decrease in Motility (%)	Decrease in Viability (%)
OVERALL	3.49	6.64
DONORS	4.20	7.48
PATIENTS	1.69	3.86

The results show that the decrease in both motility and viability was more apparent in the donors group than it was in the infertile patients group as displayed in Fig. 3.4.

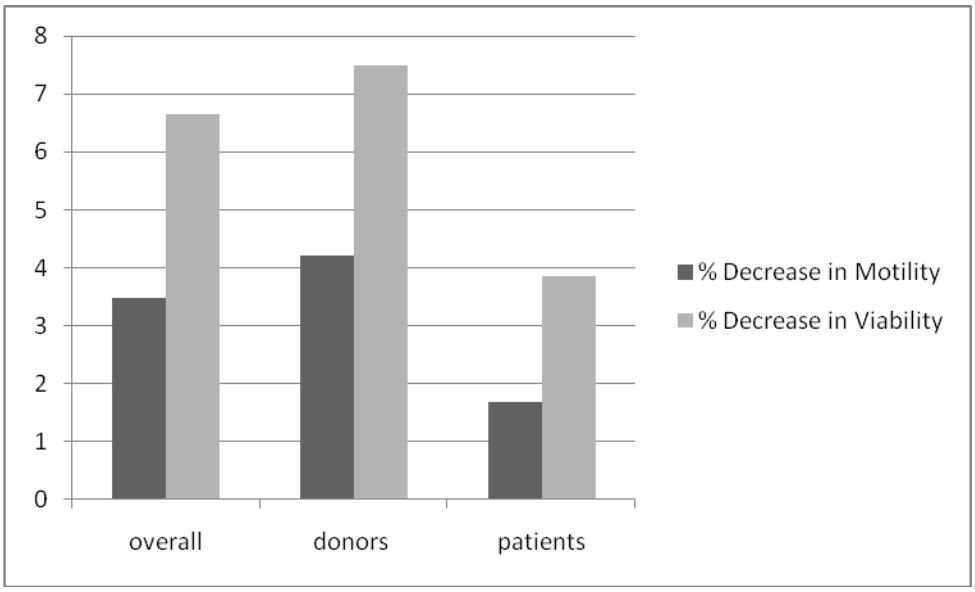


Fig. 3.4: Decrease in motility and viability in all groups.

3.6.2 Reactive Oxygen Species (ROS)

Reactive oxygen species are ions or molecules such as super oxide, or hydrogen peroxide, or free radicals such as hydroxyl radicals. At low levels, these species are beneficial and might function in cell signaling processes and kill some types of bacteria. However, at higher levels, these species become harmful and might cause significant damage to cell structures, cause damage to cellular macromolecules such as DNA and RNA, and participate in apoptosis (programmed cell death) or oxidations of polyunsaturated fatty acids in lipids or amino acids in proteins [3], [70]. ROS measurement is of a major concern in our

study because there is growing evidence that damage caused by reactive oxygen species (ROS) to spermatozoa plays a key role in male infertility [71].

Our data showed a significant increase in ROS levels in the exposed samples compared to the unexposed ones in all groups. As shown in Table VII, ROS values were significantly higher in the exposed samples than the unexposed ones with p=0.002 in the overall group, p=0.048 in donors, and p=0.014 in patients. Also the values for log (ROS+0.001) were significantly higher in the exposed samples compared to the non-exposed ones with p=0.001 in the overall group, p=0.017 for donors, and p=0.014 for patients. The statistical results of ROS included mean, standard deviation (SD), and median (25^{th} and 75^{th} percentiles) values, because the SD was larger than the mean.

Table VII Summary and comparison of the ROS and log (ROS+0.001) results for exposed and unexposed samples in various groups. Room temperature was 64 °F. Exposure period was 1 hr. n stands for the total number of subjects tested. ROS values are shown in the table as mean ± SD; median (25^{th} and 75^{th} percentiles).

Group	**ROS ($\times 10^6$ cpm/20 million sperm)** **Exposed**	**Unexposed**	**Log(ROS + 0.001)** **Exposed**	**Unexposed**
OVER-ALL	0.11 ± 0.21;0.13 (0.0047, 0.1258)	0.06 ± 0.11; 0.0075 (0.0017, 0.0387)	-1.72 ± 0.86	-1.97 ± 0.85
p-value	0.002		0.001	
n	32		32	
DON-ORS	0.06 ± 0.12; 0.01 (0.0035, 0.022)	0.05 ± 0.10; 0.007 (0.002, 0.0305)	-1.85 ± 0.78	-1.94 ± 0.80
p-value	0.048		0.017	
n	23		23	
PATIE-NTS	0.22 ± 0.33; 0.02 (0.012, 0.293)	0.07 ± 0.15; 0.008 (0, 0.062)	-1.37 ± 1.0	-2.03 ± 1.03
p-value	0.014		0.014	
n	9		9	

This increase in both ROS levels was more apparent in the infertile patients group than it was in the donors group (Table VIII and Fig 3.5). ROS values for patients and donors groups were counted by deducting the mean (± SD) value of the exposed aliquots from the mean (± SD) value of the unexposed aliquots.

Table VIII Comparison of the increase in ROS values between patients and donors groups.

Group	Increase in ROS ($\times 10^6$ cpm/20 million sperm)	Increase in Log (ROS + 0.001)
DONORS	0.01 ± 0.03	0.15 ± 0.24
PATIENTS	0.09 ± 0.21	0.66 ± 0.90
P-VALUE	0.022	0.019

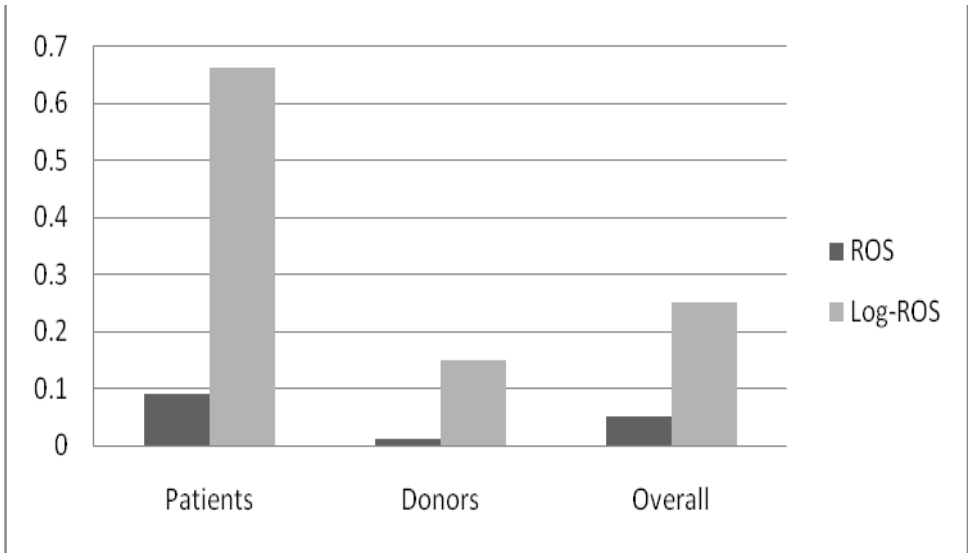


Fig 3.5 Comparison of ROS and log(ROS+0.001) differences in all three groups.

3.6.3 Total Antioxidant Capacity (TAC) and ROS-TAC Score

Antioxidant molecules have an important role in preventing the formation or scavenging of free radical species that in turn delay or even prevent oxidative damage of important macromolecules, lipoproteins, and membrane lipids. Antioxidant molecules are commonly found in plasma and other biological fluids

such as semen fluid [72]. Antioxidant molecules present in the semen neutralize the amount of reactive oxygen species **(**ROS) that are continuously produced by spermatozoa. This can prevent the oxidative stress state that is caused when the production of ROS surpasses the antioxidants' capacity. Oxidative stress has a major effect on sperm function and sperm quality. Oxidative stress is a cause of sperm defect and impairment [73].

The balance of ROS-TAC score is important for measurement of male fertility, and this measure is even superior to ROS alone or TAC alone. The imbalance between ROS and TAC is an indication of male infertility. Infertile men have significantly lower ROS-TAC scores than normal fertile men [73]. The equation used for standardized ROS measurement is as follows [60]:

$$\text{Standardized ROS} = (\log(\text{ROS} + 0.001) - (-2.0238)) / 0.5151$$

For TAC, the following equation was used:

$$\text{Standardized TAC} = (\text{TAC} - 1650.93)\ 532.22$$

Further details about these calculations are provided in reference [60].

Because ROS and TAC are negatively correlated, the original linear combination derived by the first principal component is again the first principal component, which accounts for the most variability among correlated variables as follows [60]:

$$\text{Principal components} = -0.707(\text{standardized ROS}) + 0.0707(\text{standardized TAC})$$

The transformation of the ROS-TAC scores was done in earlier analysis to ensure that the distribution of this score has a mean of 50 and SD of 10.

$$\text{ROS-TAC score} = 50 + (\text{principal component} \times 10.629)$$

As mentioned earlier, when ROS production exceeds the capacity of antioxidants, a state of oxidative stress results. Therefore, the measure of ROS-TAC is more accurate than the measure of either ROS or TAC alone.

The results of the TAC score alone did not show a significant difference between the exposed and unexposed samples. But a significant decrease in the ROS-TAC score was observed in the exposed samples in the overall group as compared to the unexposed ones ($p=0.032$) as can be noticed from the data in Table IX. However, the difference in ROS-TAC score was not as significant in the patients ($p=0.15$) or donors ($p=0.14$) groups as in the overall group.

The TAC results were expressed as µmol of Trolox equivalent. The standard Trolox is a water soluble α-tocopherol (a free radical scavenger) analog. In our experiment the capacity of the antioxidants to prevent the oxidization of the ABTS (the chemical compound: 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) was compared to that of the Trolox standard.

Table IX Summary of the results for TAC, ROS-TAC, and TUNEL (DFI) for exposed and unexposed samples for all groups. DFI is the DNA fragmentation index.

Group	TAC (μmol Trolox)		ROS-TAC Score		TUNEL (DFI %)	
	Exposed	Unexposed	Exposed	Unexposed	Exposed	Unexposed
Overall	1.55 ± 0.38	1.66 ± 0.48	46.29 ± 11.2	51.54 ± 3.37	7.80 ± 6.62	8.44 ± 5.77
p-value	0.24		0.032		0.62	
n	24		23		20	
Donors	1.53 ± 0.41	1.72 ± 0.52	48.63 ± 11.53	51.71±13.75	8.21 ± 7.24	8.66 ± 6.45
p-value	0.08		0.14		0.78	
n	16		15		16	
Patients	1.59 ± 0.41	1.52 ± 0.41	41.91 ±9.74	51.23 ± 13.54	6.16 ± 3.38	7.56 ± 1.24
p-value	0.74		0.15		0.88	
n	8		8		4	

3.6.4 DNA Integrity

The evaluation of the sperm DNA fragmentation was performed in Cleveland Clinic laboratories using the terminal deoxynucleotidyl transferase-mediated fluorescein-dUTP nick end labeling (TUNEL) assay kit (Apo-Direct; BD Biosciences Pharmingen, San Diego, CA).

The TUNEL test results were expressed as percentage DNA fragmentation (% DFI). In summary, 10^6 spermatoza were washed twice. The first time they were washed in phosphate-buffered saline (PBS) and resuspended in 1%

paraformaldehyde, then held for 30-60 minutes. They were washed the second time in PBS to remove the ethanol, and resuspended in 70% ice-cold ethanol. Then, both the sperm pellet samples and the positive and negative control samples were resuspended for one hour in 50 µL of the staining solution at 37 ˚C. "The staining solution contained terminal deoxytransferase (TdT) enzyme, TDT reaction buffer, fluorescein-tagged deoxyuridine tri-phosphate nucleotides (FITC-dUTP), and distilled water. All cells were further washed in rinse buffer, resuspended in 0.5 ml propidium iodide/RNase solution, and incubated for 30 min in the dark at room temperature followed by flow cytometric analysis" [60].

The data in Table IX do not show a significant difference in DNA integrity (TUNEL, DFI %) in all three groups. Only a slight decrease in the exposed samples was noticed in all groups (Table IX).

3.6.5 A Brief Study With Temperature Control

A small follow-up study was performed using samples from healthy donors. In this study the temperature was controlled by placing the samples in an incubator. The temperature used was 36 ^{o}C to mimic the body temperature of the studied area. The same cell phone, separation distance and time duration of exposure were used. The total number of samples was only 10. Most results obtained showed a slight increase in ROS score that averaged between 0.002 and 0.4. Some decrease in motility (2% - 18%) was apparent in most of the samples. However, the difference in viability was insignificant.

In general, the effects were not as significant as our previous study. This might be due to the small number of samples that were available for test and the low volume of semen in some of these samples.

Although the data were not sufficient to reach a conclusion, they tended to support the results of a study presented by Esfandiari et al. [74]. In that study, it was found that ROS levels of the semen samples that are kept at a lower temperature (25 ^{o}C) were significantly higher than those of the samples kept at a higher temperature (37 ^{o}C).

3.7 DISCUSSION AND CONCLUSIONS

The results obtained from our study suggest a relation between RF-EMW emitted by cell phone while in talk mode, and male infertility. A significant decrease in sperm parameters (motility and viability) was noticed in the exposed aliquots when compared to the unexposed ones.

The most notable finding in our study was the relation between cell phone radiation and ROS levels. A significant increase in ROS production and decrease in ROS-TAC score resulted in the exposed samples when compared to the unexposed samples. The decrease of the ROS-TAC score leads to an increase in oxidative stress, which in turn affects fertility in men. “A decrease in motility and viability is linked to concentration of superoxide anion in semen. When superoxide anion is produced extracellularly it can oxidize membrane phospholipids and cause a decrease in viability” [60].

No significant difference in the data obtained was found for DNA integrity and TAC score between the exposed and unexposed samples. Some other studies on mice have shown an effect on DNA integrity due to cell phone radiation. It is felt that the short term exposure in our study, or the scavenging of free radicals by antioxidants in seminal plasma, explains the lack of effect on DNA integrity indicated in our data.

In our study, we used neat semen samples that include both immature and mature spermatozoa to better evaluate the effect of RF-EMW on sperm quality. As noticed from our data, the increase in ROS levels was significantly more apparent in patient samples and overall (patient and donor) samples than in donor samples. This difference suggests that the immature (or abnormal) spermatozoa might be more vulnerable to cell phone radiation.

The increase in ROS levels and decrease in sperm parameters resulted even after short term exposure in our study. This fact suggests that long term exposure to cell phone radiation and EMWs has a higher probability of further affecting sperm quality, and results in even worse infertility levels. This study, however, does have some limitations such as the sperm volume in the available samples used for our measurements.

The results obtained show that there is an effect of cell phone signals on semen quality and thus on male fertility. This study suggests that carrying the cell phone in the pocket or on the belt while in-talk mode might result in deterioration of sperm quality, and lead to oxidative stress. However, another limiting factor in this study was that it did not account for the tissue layers

covering the male reproductive organs. These create another separating medium from the cell phone radiation. In order to better simulate real life situations, this part should be taken in consideration. This will be done in the following chapter.

It should also be noted that although the phone used did meet the safety standard of SAR and power density, as described before, it still caused a significant deterioration of semen quality and ROS score. Therefore, this experimental study strongly suggests that safety standards should be reviewed, and nonthermal effects should also be taken into consideration by the responsible organizations such as FDA.

CHAPTER IV

COMPUTATIONAL BIOMODELING STUDY OF THE EFFECTS OF CELL PHONE RADIATION ON MALE FERTILITY

4.1 INTRODUCTION

Our pilot study results showed that RF-EMW exposure to semen samples for one hour leads to oxidative stress and some other effects on semen quality. The increase in ROS was associated with a decrease in sperm parameters, when the semen samples were stored 2.5 cm from the mobile phone. Therefore, it appears that men who carry their mobile phones during a call in close proximity to their reproductive organs are at risk. This can occur, for example, while using an ear piece (such as Bluetooth) for a call with the phone in the pocket (Fig 4.1a). However, it is difficult to determine the precise amount of RF-EMW exposure, since the testicles are separated from the phone by the scrotal layers (Fig. 4.1b). Thus, a more realistic approach is needed to quantify the effects of RF-EMW on the male reproductive system.

Computational RF dosimetry has been used in previous research to calculate the amount of RF energy deposited in the "head of the user" [75], [76]. In other words, computer simulation can help evaluate the amount of RF energy specific

absorption rates (SAR) deposited in the head of a mobile phone user. Nevertheless, there is a lack of literature on the computational approach to study the impact of RF-EMW on sperm. In addition, there are no guidelines in the literature for *in vitro* studies to simulate real life. We conducted this study to establish guidelines for future *in vitro* studies on the human sperm. We assumed an “equivalent distance” from the cell phone at which our *in vitro* sample experiences the same amount of RF-EMW as the male reproductive organs would in a real life scenario. The equivalent distance, which is greater than the actual distance between the phone and man’s reproductive organs when the phone is in his pocket, accounts for the resistance provided by the scrotal layers, etc. Different real situations, such as the mobile phone in the pocket or on a belt, can be simulated by *in vitro* test systems by varying the distance between the cell phone and the test tubes [63].

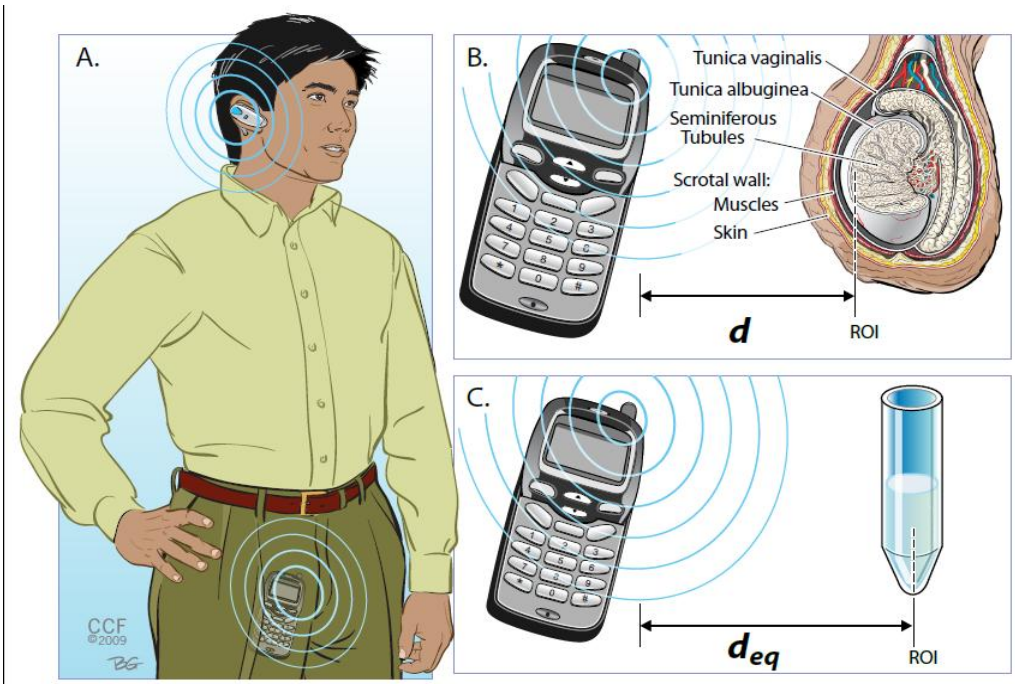


Fig. 4.1 (a) A man having a cell phone conversation via an ear piece while holding the phone handset in his pocket close to his reproductive organs. (b) An anatomical model for the basic testicular tissue layers with the cell phone located at a distance, *d*, from them. (c) The experimental setup of a semen sample in a test tube and the cell phone at an equivalent distance, d_{eq}, from the tube.

4.2 COMPUTATIONAL MODELING STUDY OBJECTIVES

The main objective of this study is to establish the relation between an in-vitro experimental setup and the real life conditions for a male human carrying the cellular phone in close proximity to his reproductive organs. A range of distances can be calculated to adjust the position of the cell phone in an in-vitro experiment so as to represent the real life conditions.

To accomplish the goal of this study, it is necessary to first define the models representing the testicular tissues and the cell phone source, and those representing the in-vitro experiment with the source being in the air medium and

the sample within a test tube as illustrated in Figure 4.1. Second, the region of interest, ROI, in both models where the energy will be compared needs to be defined. Third, we need to show the energy distribution where the source is at different distances from the outermost layer in each model. Fourth, the mean values of energy density in the region of interest need to be quantified. Fifth, we have to compare the values of the energy density in the ROI in order to establish the relation between the range of distances in the tissue model and its corresponding range of equivalent distances in an in-vitro experimental setting. Sixth, the results of our previous pilot study need to be correlated with a real life case.

4.3 MATERIALS AND METHODS

4.3.1 The Anatomical Lifelike Model

A two-dimensional model of the testicular region has been developed to represent the testicular tissue layers. The tissue layers considered in the two-dimensional lifelike computer model consist of the scrotal skin, the muscle layer (dartos, external spermatic, and cremaster muscles), tunica vaginalis, tunica albugenia, and spermatozoa [77], [78] (Fig. 4.1b). As the computer model is two dimensional, only the thickness of the individual layers was represented and not the curvature of the scrotum. Even though it might be possible to create a complex three-dimensional model representative of the intrinsic anatomical details and cell phone characteristics, a two-dimensional model was used in our simulation due to the data and simulation tools available to us. A three-

dimensional approach will likely allow one to predict the electric field more accurately, but the improvement on the precision of comparing different conditions may not be dramatic. Our work required multiple simulations to be conducted. These may have been computationally challenging had three-dimensional models been used. In addition, a three-dimensional model would also have required a full anatomical reconstruction. This would not have been cost-effective, given that our interest lies in studying relative changes between different conditions.

The range of thickness of the layer of tissue were taken from the literature. The most common values in the average adult male human were used for comparison. The scrotal wall thickness is usually reported to be about 3 mm, but it can vary from 2 mm to 6 mm, and can be up to 8 mm [77]-[80]. The difference in the thickness of the scrotum depends on various conditions, such as ambient temperature. It also differs from one person to another [79]. The last layer of liquid represents the sperm inside the seminiferous tubules. The wall thickness in the seminiferous tubules was neglected because it is much thinner compared to the other layers considered for modeling; a tubule wall-to-wall thickness is approximately 0.12 mm only [80]. Nevertheless, the thickness of different tissues was examined for sensitivity analysis to check if they had any significant impact on the results (Section 4.3.8). The tunics layer is very thin and measures only about 0.1-0.2 mm according to Casey et al. [77]. Copenhaver et al. [81] indicated that the tunica albuginea thickness is about 0.5 mm. The size of 0.5 mm was adopted to account for cavities in the envelope vaginalis and other tissues in the

small partition and the septa between the tunica albuginea and seminiferious tubules. The last layer was a fluid representing the spermatozoa and other cells inside the seminiferous tubules.

4.3.2 *In Vitro* Experimentation Model

The two-dimensional model with the same data-processing cell size as in a tissue model was developed. The cell phone was at a distance from the test tube in which the sample of sperm was held. The medium present in the space between the cell phone and the sample was air (Fig. 4.1c). The standard polystyrene tube used is modeled as a pipe with a diameter of 16 mm and 1 mm wall thickness. Since the fluid sample was filled in the test tube, the fluid layer thickness was set to 16 mm, to match the diameter of the tube.

4.3.3 Region of Interest (ROI) for Computational Models

The fluid layer thickness in the experimental model was set to 16 mm to correspond to the diameter of the test tube. For comparison purposes, the fluid layer in the lifelike model was set to 16 mm too. The region of interest (ROI) was positioned at the center of the fluid layer. Therefore, for the *in vitro* setup, the ROI was positioned at the center of the fluid layer that was 0.8 cm from the test tube layer. Similarly, for comparison purposes, the ROI for the anatomical lifelike model was considered in the layer representing the spermatozoa 0.8 cm from the inner layer (i.e. tunica albugenia) of the model.

4.3.4 Calculating Energy Distribution by RF Dosimetry

The finite difference time domain (FDTD) method has been utilized to calculate the exposure of RF-EMW in the human brain [11], [82]. This technique was chosen in our experiments as well, to quantify and compare the amount of electromagnetic energy absorbed by the spermatozoa in the experimental and lifelike models when exposed to mobile phone radiation. FDTD is a common data-processing technique employed in electromagnetic applications to solve Maxwell's equations represented as partial differential equations [83]. We defined the current source which represented the cell phone, and the geometry of the model to represent the sample of sperm in a tube or behind the layers of the testicles. The method of FDTD measures the quantity of density of energy in a layer, and this is related to the specific rate of absorption (SAR).

As explained in Chapter 1, SAR is an important measure employed to set a standardized limit for the quantity of energy absorbed by the tissues of a human body. It is expressed in units of W/kg and is defined as [3]:

$$SAR = \sigma \left| E \right|^2 / \rho \tag{4.1}$$

where E is the electric field strength, which is a vector field (N/C or the equivalent units of V/m), σ is the conductivity of the medium (S/m), and ρ is the density of the tissue (kg/m^3). Given J, the magnetic (or current) field strength (A/m), SAR can also be represented as [3]:

$$SAR = J^2 / (\sigma \rho) \tag{4.2}$$

SAR is commonly evaluated over a volume, V, which contains a tissue mass of 1 g or 10 g [11]:

$$SAR_v = (\int_v (\sigma \left| E \right|^2 / \rho)\, dV\,) / V \quad (4.3)$$

Another important measure of exposure that is directly proportional to SAR is the electric field energy density, u, defined as [84]:

$$u = \frac{1}{2}\varepsilon \left| E \right|^2 \quad (4.4)$$

where ε is the dielectric constant or the permittivity of the material.

Since all of the dielectric parameters, ε, σ, and ρ are constant for the same material under similar conditions, the only variable remaining in equations (4.1) and (4.4) is the electric field strength, E. Thus, for ease of comparison in this study, the electric field strength and the electric field energy density, measured by dosimetry, were the variables of interest to compare the energy distribution at the ROI.

To carry out simulations using FDTD, this study utilized the open source software package Meep, MIT Electromagnetic Equation Propagation, developed for electromagnetic field simulations [85]. The predictions of the electric field in the models were post processed using IPython, an interactive Python programming environment, utilizing PyTables, to access Meep results stored in Hierarchical Data Format (HDF5); NumPy, to carry out matrix operations; and matplotlib for visualization. Based on the data generated by Meep, these tools were utilized to calculate the mean values of the energy density at the ROI, and to illustrate the energy distribution throughout the models under all conditions considered for comparison [63]. Final results for equivalent displacement calculations were conducted using OpenOffice.org™ [63].

4.3.5 Dielectric Parameters

The dielectric parameters (the relative permittivity, ε_r, and electrical conductivity, σ) for each layer were obtained from the literature [76], [86] and using calculations provided by the Italian National Research Council, IFAC [87], at 900 MHz and 1800 MHz frequencies (Table X). The relative permittivity, ε_r, is a unitless value since it is normalized by dividing the permittivity of the material by the air permittivity of 8.854×10^{-12} $C^2/N\cdot m^2$, where we use air and vacuum permittivity interchangeably.

Table X Dielectric parameters of typical tissue layers at 900 MHz and 1800 MHz. Note that the relative permittivity is unitless since it is normalized by the air permittivity.

Tissue Type	900 MHz		1800 MHz	
	Permittivity, ε_r	Conductivity, σ (S/m)	Permittivity, ε_r	Conductivity, σ (S/m)
Skin	41.41	0.87	38.87	1.19
Muscle	56.90	1.00	55.30	1.44
Testicular Tissues (Tunics)	60.55	1.21	58.61	1.69
Fluid (blood)	61.40	1.54	59.37	2.04

Dielectric parameters of sperm at the specified frequencies were not found in the literature. However, since the water content in biological tissues is the factor that has the greatest influence on its dielectric properties, it can be safely assumed that the properties of any human body fluid can be used for the purpose of comparison. This is particularly true when the same type of fluid is

used in all the model comparisons [76]. In this study, the dielectric properties of blood were used for the fluid layer to represent the semen layer in the experimental and tissue layer models. This approximation was considered for both models since the dielectric properties of semen were not found in literature. The dielectric parameters of the testis were used to represent the tunic layer. The air medium was selected to be the default medium that separated the cell phone source and the tissue layers, and filled in the rest of the model.

The modeled computational cell size was of 200 mm on the X axis and 300 mm on the Y axis. This size was large enough to allow the simulation of the electric field in the area of interest without undesirable effects of the model boundaries. The data-processing of the computational cell size was calculated by the progressive increase of cell size until stable conditions were reached. At that point, no more quantitative changes were noticed by further enlargement. This change in cell size was necessary to eliminate any numerical disruption that might occur due to the proximity of the absorbing perfectly matched layers (PML) located at the computational cell boundaries. In FDTD simulations, PML prevents reflection of electromagnetic waves [88].

The relative permittivity and conductivity relating to the polystyrene tube were identified as 2.56 [89] and 1×10^{-16} S/m [90], respectively. For the semen layer, the same fluid dielectric parameters used in the layered tissue model were applied.

4.3.6 Unit Conversion in Meep

The Meep program uses special normalization. To convert frequency to Meep units [91], the following normalization was done:

$$Meep\ Freq. = Actual\ Freq. \times \frac{a}{2\pi c}$$

where a is unit of length chosen in the Meep program and *c* is the speed of light (299 792 458 m / sec ≅ 3 x 10E+8 m/sec). For example, 900 MHz (900 x 10^6 (1/sec)) frequency at a equal to 1 meter can be converted to Meep units as follows:

$$Meep\ freq. = (900x10^6(1/sec))\frac{1(\mathrm{m})}{2\pi 299792458(\mathrm{m/sec})} = 0.4778$$

Since all the units cancel out, it will be unitless.

Since the time *T*=1/*f,* the Meep time is in the units of *a*/2π*c* and should use the same normalization (normalized Meep time * $\frac{a}{2\pi c}$) . And since *a* in our programs is in the units of (m) and *c* in (m/sec) so finally time will be in units of (sec).

The units in Meep are all internally consistent. So if the units of power of the source is in W/cm^2 the units of energy density will be in (Meep time * W/cm^2) so this will be finally in (sec.W/cm^2) or (J/cm^2). Since our simulation is made to support our pilot study and to be used as a reference to relate experimental in-vitro data to actual real life model, the measured power density of the source used (the cell phone in our case) can be used to determine the actual energy density using the following:

$$resulting\ energy\ density = \frac{the\ measured\ power\ density * Meep\ Time}{Meep(normalized)energy\ density}$$

Where Meep time is in units of $\left(\frac{a}{2\pi c}\right)$ as indicated above.

But since the goal of our study is to find an equivalent distance to relate the experimental model to the real life model and since the same normalization is used in all Meep programs and all of its units are internally consistent, there is no need to convert our results. Our decision on the equivalent distance was made by comparing numerical results of energy density, energy figures, and waveguide figures. The programs were made to test a range of distances and then compare and find best match.

Also conductivity, σ, can be converted to Meep units (σ_D) using the following normalization:

$$\sigma_D = \frac{a}{c} \times \frac{\sigma}{\varepsilon_r \varepsilon_o}$$

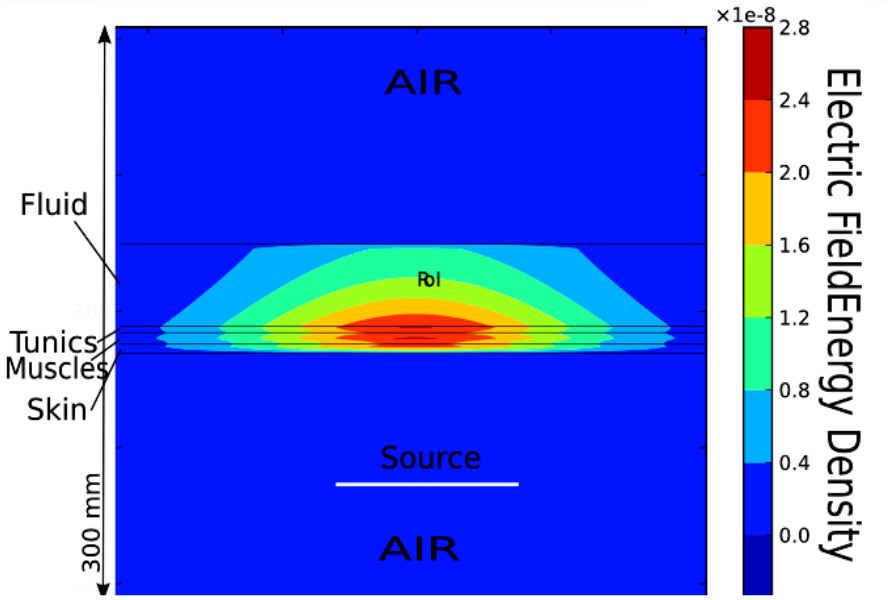
4.3.7 Simulation Conditions

Modeling was carried out for two types of current sources to represent the antenna of the mobile phones, the point source (dimensionless) and the line source (one dimensional), to compare the effect of the size of antenna on the distribution of the energy density. The line source length was selected to be 3.5 cm on the x-axis to mimic the 3.5-cm loop antenna that was used in our *in vitro* pilot study. Two different frequencies were employed to compare the energy density produced by the two common frequency bands in most parts of the world:

900 MHz and 1800 MHz. The vertical distance between the source and the external layer was varied between 0.5 cm and 9 cm in the tissue layer model, and between 0.5 cm and 7.5 cm in the experimental setup model. Each simulation lasted for ten cycles of the electromagnetic field signals to make sure that the electric field energy density had reached a steady state (see Appendix B for sample programs). The time history of the electromagnetic field distribution and the electric field energy density were calculated for all simulation conditions in each model (see Appendix C for more figures). In the ROI, the average electric field energy density in each simulation was also calculated. These values were employed to find equivalent source locations under real life and *in vitro* experimentation conditions that provided similar average electromagnetic effects.

As shown in Figures 4.2 and 4.3, the source was positioned at the center of the horizontal axis (X-axis), and at a specified distance from the outermost layer on the vertical axis (axis Y), in each model.

a.



b.

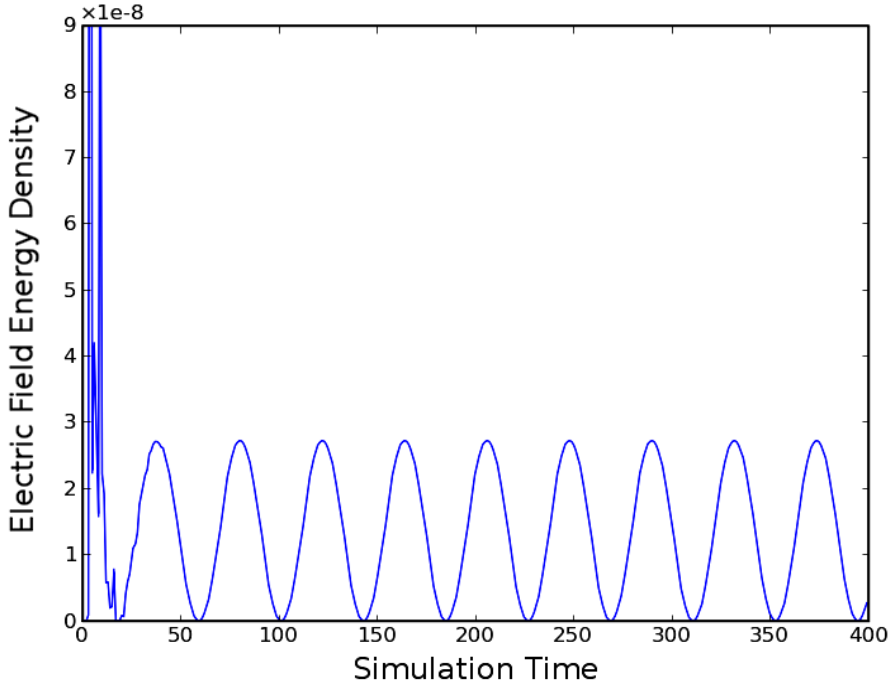
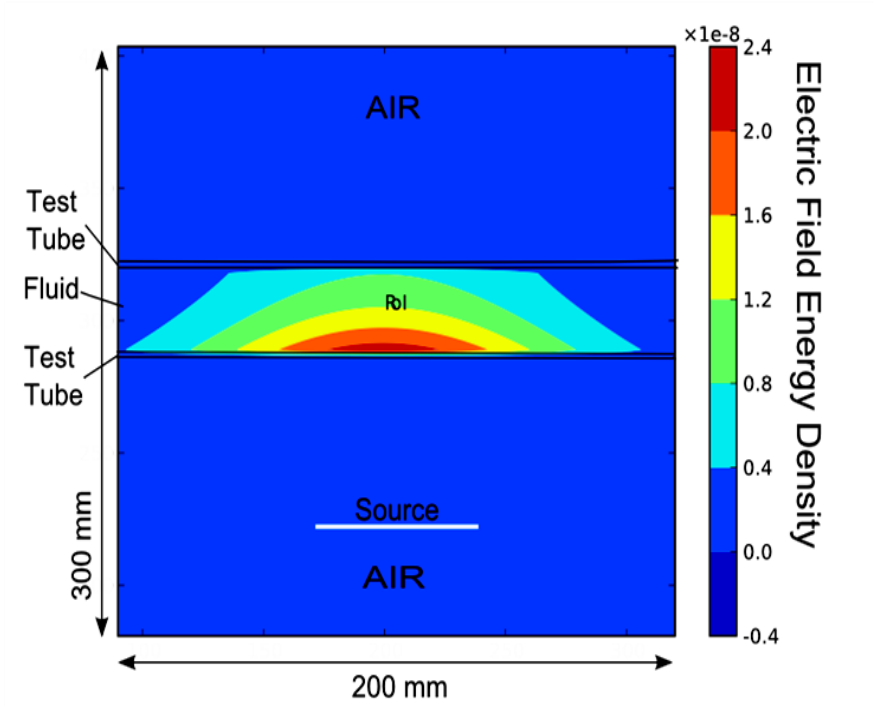


Fig. 4.2: (a) The energy density distribution through the basic lifelike model taken at a time instant representative of the mean values of electric field energy density with the 900 MHz line source 2.5 cm from the outermost layer. (b) The time history of electric field energy density at the ROI for the model in (a). Note that the units are normalized according to Section 4.3.6.

a.



b.

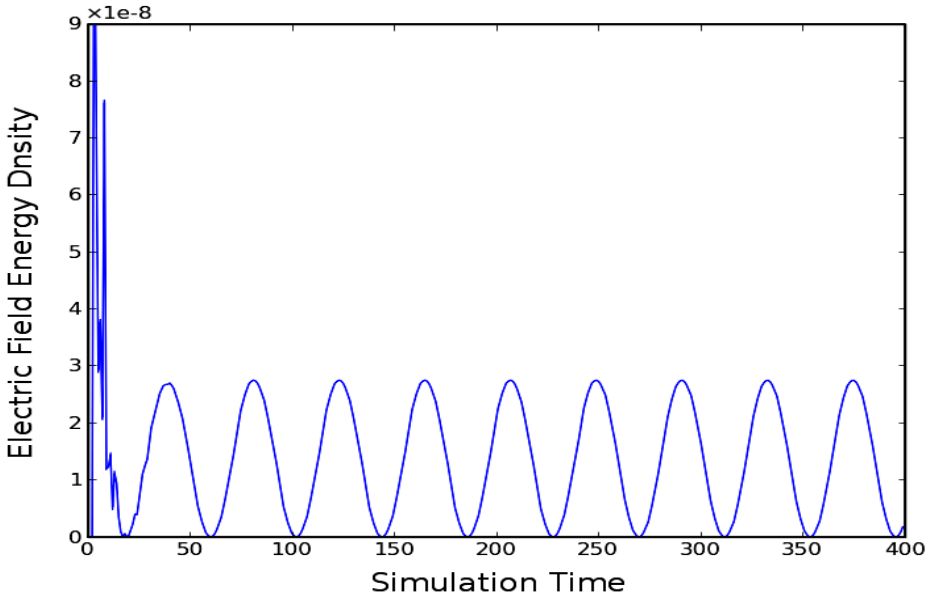


Fig. 4.3: (a) The energy density distribution through the experimental air-tube model taken at a time instant representative of the mean values of electric field energy density with the 900 MHz line source 3.3 cm from the tube layer. (b) The time history of electric field energy density at the ROI for the model in (a). Note that the units are normalized according to Section 4.3.6.

4.3.8 Sensitivity Analysis

A sensitivity analysis was performed to estimate the influence of uncertainty in tissue thickness on the simulations. A point source at a frequency of 900 MHz located 2.5 cm from the outermost tissue layer was used with varying tissue thickness values. A total of six models were developed. The distance between the source and the outmost layer was fixed at 2.5 cm and the scrotal wall thicknesses were varied from 2 mm to 8 mm, with the tunics tissues fixed at 0.2 mm. The tunics layer thickness was also tested for 0.2 mm and 0.5 mm according to numbers found in the literature (Section 4.3.1). In each model, the mean value of the energy density in the ROI was calculated (Table XI).

Table XI Layered tissue models tested with different thicknesses while the source was 2.5 cm from the outermost layer. Model 3 is the base layered tissue model selected for major simulations to represent the most common thicknesses.

Model	Scrotum thickness Skin/Muscle (mm)		Tunics tissues (mm)	Normalized mean of electric field energy density (x 10^{-8})	Equivalent distance in experiment model (cm)
1	1	1	0.2	1.46	3.2
2	2	1	0.2	1.40	3.3
3	2	1	0.5	1.44	3.3
4	4	3	0.2	1.24	4.0
5	4	4	0.2	1.09	4.3
6	6	2	0.2	1.13	4.3

4. 4 RESULTS

Figure 4.2a depicts the distribution of the electric field density throughout the lifelike basic model that has a thickness of 3 mm for the scrotal wall and 0.5 mm for the sector of tunics (model #3, Table XI). In this simulation, the line source at 900 MHz frequency was positioned 2.5 cm from the scrotal skin layer. As expected, the electric field energy density was higher for the regions closer to the source (Fig. 4.2).

Figure 4.2b shows the electric field energy density, u, at the ROI as a function of time. It is noticed from the waveform in this figure that the highest energy values are at the beginning of the time cycle followed by a steady sinusoidal waveform with a mean energy density of 1.44E-08. The results of Meep were normalized, so no unit was assigned to these values. The normalization and unit conversion used in Meep is provided in Section 4.3.6.

A range of distances were tested on the air-tube model and the numerical and graphical results of mean energy densities were obtained. The closest value of mean energy density to the lifelike model was found to be the experimental air-tube model with a 3.3 cm distance from the source. In a similar fashion, Figures 4.3 (a) and (b) show the electric field energy density distribution and the corresponding waveforms at the ROI, respectively, for the experimental air-tube model. In this case, the source was placed 3.3 cm from the first tube layer. The mean value of u calculated at the ROI for this model was 1.404E-08. The electric field energy density values at the ROI of this experimental model were

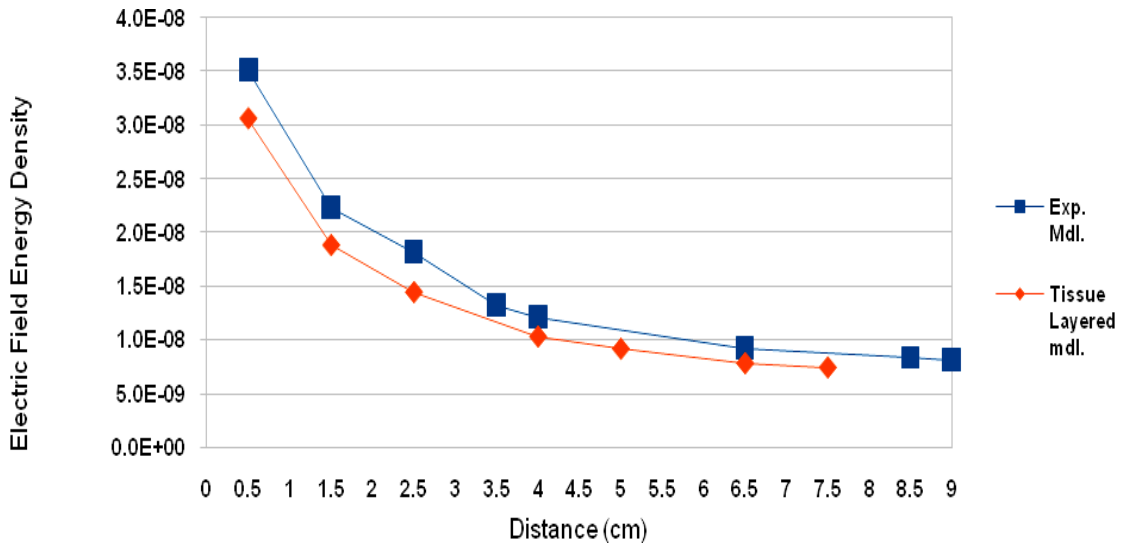
the closest match to the values at the ROI in the lifelike model described in Fig. 4.2.

The simulations were repeated for both models with the source positioned at different locations from the outermost layer (Fig. 4.4a). The mean values of the electric field energy density, u, were calculated for each case. Then the mean values of the electric field energy density in the experimental model at certain distances were matched with their equivalent mean energy density values in the lifelike model. Based on this comparison, the line charts in Fig. 4.4b were constructed to illustrate these values and relate all distances tested in the layered tissue model to their corresponding equivalents in the experimental model, as listed in Table XII.

Table XII The experimental model vs. the lifelike model using a line source. Note that the units are normalized according to Section 4.3.6.

Exp. (Air-Tube Model)		**Lifelike Model**	
Distance (cm)	**Energy Density (normalized)**	**Distance (cm)**	**Energy Density (normalized)**
0.5	3.5156E-08	0.5	3.0588E-08
1.5	2.2283E-08	1.5	1.8779E-08
2.5	1.8171E-08	2.5	1.4384E-08
3.3	1.404E-08	4	1.0241E-08
4	1.2107E-08	5	9.1021E-09
6.5	9.2411E-09	6.5	7.7516E-09
8.5	8.3438E-09	7.5	7.3541E-09
9	8.1099E-09	-	-

(a)



(b)

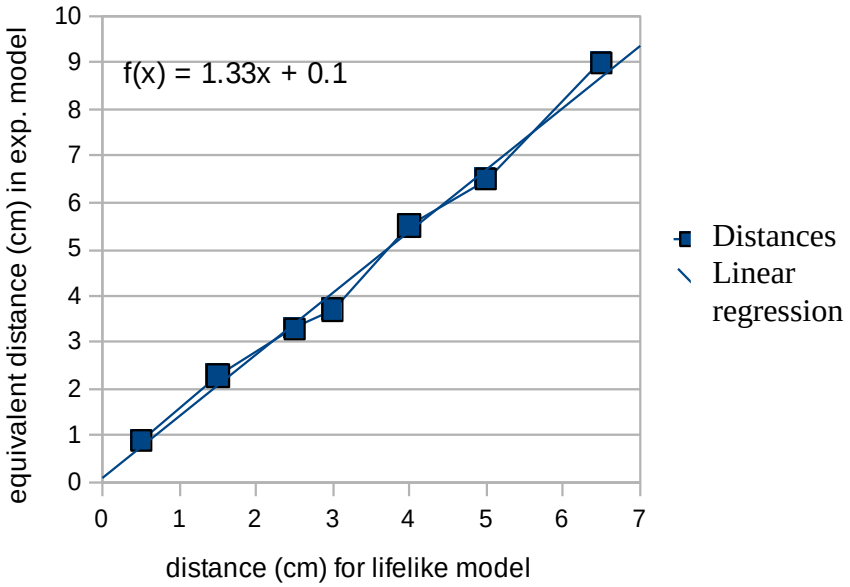


Fig. 4.4: (a) The average values of the electric field energy density at the ROI for the layered tissue model and for the *in vitro* experimentation model, as a function of distance between the source and outermost region of the model. A 900 MHz line source was used for this simulation. The base layered tissue model was utilized for lifelike simulations. (b) Distance for the tissue layered model vs. the equivalent distance in the experimental model.

The simulations were repeated after replacing the line source with a point source to study the effect of the antenna size on the energy density values. It was observed from the results of this simulation that the energy density was significantly higher when the point source was used (Table XIII). While the absolute magnitudes of the electric field changed when the point source was used (instead of a line source), the relative relationship between electric fields predicted for the life-like model and the experimental conditions remained the same (Fig. 4.5). Therefore, it is likely that an equivalent distance relation obtained from point source simulations will apply under line source conditions as well.

Table XIII The experimental model vs. the lifelike model using a point source

Exp. (Air-Tube Model)		**Lifelike Model**	
Distance (cm)	**Energy Density (normalized, unitless)**	**Distance (cm)**	**Energy Density (normalized, unitless)**
1.5	1.949E-05	1.5	1.691E-05
2.5	1.563E-05	2.5	1.204E-05
4	1.005E-05	4	8.597E-06
6.5	7.579E-06		

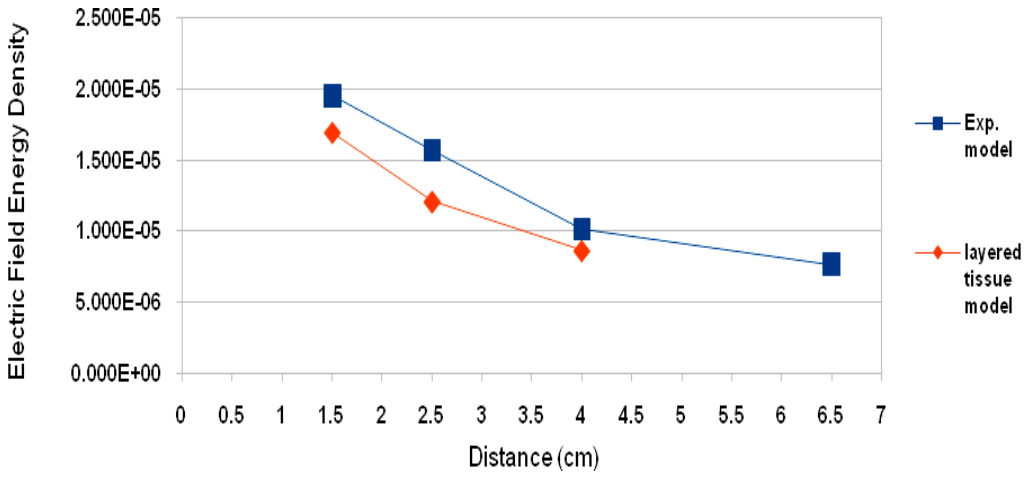


Fig. 4.5: Electric field energy density vs. distance. The two lines in this line chart show that the ratio between the distance between the source and the outer layer of tissue in a realistic model and the equivalent distance in the experimental model using a point source has been retained as in the line source model in Fig. 4.4a.

A source with 1800 MHz frequency was used in place of the 900 MHz source for both models to evaluate the effect of the other frequency band on the energy distribution in the ROI. The distance between the source and the outermost layer was fixed at 2.5 cm for the lifelike model. The simulation result of this model resulted in a mean average electric field energy density, u , at the ROI of 1.897E-08. The closest match of the experimental model at 1800 MHz to the lifelike model was the one having the source 3.3 cm from the tube layer, which had an energy density that averaged 1.809E-08 at the ROI.

Another experimental model was tested after eliminating the test tube layer to study its effect on the results. The difference in the mean value of the energy density that resulted from this simulation was only 1.5%.

4.5 MEASUREMENTS OF POWER DENSITY USING A FIELD STRENGTH METER

Using an Extech® (480836) RF EMF Strength Meter (Fig. 4.6) which features an isotropic antenna and has a frequency range of 50 MHz—3.5 GHz, many measurements were made for the power density of cell phone radiation under different conditions. The measurements were taken for different cell phones individually and two phones together. The measurements were taken with the meter positioned at two different distances to compare the results. These measurements were taken to experimentally verify and compare the amount of exposure due to distance, the exposure of more than one source, and the use of a different cell phone type.

Fig. 4.6: Extech® (480836) RF EMF strength meter

Measurements were taken at different times and on different days. The range and the maximum power density were found to vary. This may be due to the power control feature of the handheld phone which varies the transmitted power in order to keep the connection at an acceptable level. For example, when the power density of a Nokia phone was measured, the maximum reading for that call from a 3 cm distance was 1100 $\mu W/cm^2$. At another time, from the same distance, the maximum was only 234.5 $\mu W/cm^2$. For the Sony Ericsson used in our *in vitro* study, the maximum reading at one time was 215 $\mu W/cm^2$. At another time, it was 940 $\mu W/cm^2$, and at a third time, it was 1096 $\mu W/cm^2$. Therefore, precautions were taken to rule out the variations due to measurements made at different times while comparing the effect of variables such as the distance or an additional source. The experiments were carried out on the same day, at the same time and temperature, and during the same call. When two phones used together, a Sony Ericsson and a Samsung, the power density was much higher which indicates the accumulation of power density when more than one RF source is around. It was also observed that the power density readings for the same call fluctuated as explained earlier in this chapter. Therefore, the meter was set at the maximum setting to detect only the maximum readings during a call. The measurements are shown in Tables XIV and XV.

Table XIV Sony Ericsson (continuous time) on Max setting. Time Period: 5 minutes (there were four readings shown during the first minute). Date (6/29/09).

Time Period	Max. Pd (uW/cm^2) (distance 3 cm)	Max. Pd (uW/cm^2) (distance 10 cm)
While Receiving The call (before answering)	1301	450
1st min	105	195.1
1st min	666.4	-
1st min	855.2	-
1st min	901.1	-
2nd min.	1082	233.6
3rd min	1136	233.9
up to 5 min	1136	298.1

Table XV Two Phones Sony Ericsson and Samsung. Continuous time for 5 minutes. Distance 3 cm. Date 6/29/09

Time Period	Max. Pd (uW/cm^2)
1st min	795.6
1st min	800.8
1st min	983.4
2nd min	1334

From the tables above, one can observe the following:

1. The highest power density was recorded while receiving a call.
2. There was a significant decrease in the power density when the distance between the meter and the antenna of the phone increased (Table XIV).
3. Adding a source increased the power density as depicted in Table XV when another phone was added.

4.6 DISCUSSION AND CONCLUSIONS

The literature has shown conflicting evidence of cell phone radiation effects on male fertility. *In vitro* studies on human semen is a reasonable way to prove these effects. This study assisted us in establishing a relationship between an *in vitro* experimental setup and the real life conditions for the case of a man carrying out a cell phone conversation via an ear piece with the handset in a pocket near the testicular region. The electromagnetic signals emitted by a cell phone do penetrate the testicular tissues to reach the spermatozoa contained in the seminiferous tubules inside the testis when the cell phone is placed nearby during a call. However, the amount of energy absorbed in the semen in the ROI of the lifelike model was lower than the amount absorbed by a semen sample in a test tube. This decrease in the energy density at the ROI in the lifelike model was due to the existence of the testicular tissues that separate the cell phone and the spermatozoa. The permittivities of these tissues are considerably higher than the permittivity of air. Therefore, these tissues absorbed more of the energy radiated from the cell phone than air. Furthermore, the thickness of these tissues caused an increase in the actual distance between the source and ROI compared to the experimental model.

The results suggest that during *in vitro* experiments, similar values of SAR can be obtained by placing the mobile phone a few centimeters farther away from the ROI compared to real life situations. The difference in distance to be considered to equalize the energy absorption in both models ranged from 0.8 cm to 1.8 cm. This difference becomes larger as the separation distance between

the source and the ROI increases, until the energy density reaches a steady state value. Once the steady state value is reached, further increase in the separation distance does not have a significant effect on SAR (Fig. 4.4a). This relationship suggests that the effect on fertility found in our *in vitro* pilot study [60], where the phone was placed 2.5 cm away from the test tube, would be similar if the phone was placed 1.5 cm from the male's reproductive organs in real life (Fig. 4.4b). Figure 4.4 also provides guidelines for the equivalent distances that must be considered when performing an *in vitro* experiment to mimic real life conditions.

The results indicated that the energy density, u, decreases in the ROI as the tissue thickens. The model tested with the thickest range of tissue layers showed a 22% lower mean value of u at the ROI than the model with the thinnest layers (Table XI). The difference between the distance in the lifelike model and its equivalent distance in the experimental model was increased from 0.8 cm for the thinnest model to 1.8 mm for the thickest model (Table XI). The energy density results are sensitive to tissue thicknesses. Therefore, before performing an *in vitro* experiment, it is recommended to either measure and note the tissue thicknesses of the subject, or to consider the equivalent distance corresponding to the tissue thickness for an average male human, as was done in the base model of this study.

In both setup conditions, the models tested at 1800 MHz frequency were about 24% higher in energy density, u, than the corresponding models at 900 MHz with the source 2.5 cm from the outermost layer, and 20% higher with the

source 3.5 cm from the outermost layer (refer to figures in Appendix C). These results agree with the findings of Flyckt et al. [93] and Dimbylow [94] who reported higher SAR values in the head and eye regions at 1800 MHz than at 900 MHz. Despite the increase in energy density in the 1800 MHz models, the distance relationship between the lifelike model and the experimental model remained the same for both frequency bands as expected since the same change in frequency was applied on both models. It was noticed from the numerical results provided earlier in this study (refer to Section 4.4) and from the line chart (Fig. 4.4) that the closest match to the lifelike model with the source at 2.5 cm from the outer tissue layer is the experimental model having the source at about 3.3 cm from the test tube layer for both the 900 MHz and the 1800 MHz bands. This suggests that the range of equivalent distances determined for the models at 900 MHz can also be used for a source operating at 1800 MHz.

Furthermore, the results show that the energy density values increase as the source size becomes smaller as indicated by the results of the experiments that used the point source (Table XIII and Fig. 4.5). The radiated energy from the current source is distributed along the source. Hence, the power and energy will be more scattered in the surrounding area for a larger source. This resulted in a decrease in the energy density as the source size increased, when both the ROI and the source were positioned at the center of the x-axis. This difference, however, did not affect the relation of the source-layer separation distance as long as the same source was considered for both settings (Fig. 4.5). Therefore, the distance guide provided in this study (Fig. 4.4b) will be applicable for different

antenna sizes and for the 900/1800 MHz frequency bands as long as the same source is considered for both the experimental and the lifelike settings.

Another experimental model was tested after removing the test tube layer to study its influence on the results. The difference between the mean value of energy density between the two simulations (with and without the tube) was only 1.5%. As a result, it can be concluded that the polystyrene test tube does not have a significant impact on energy density values in the ROI. This may be due to the thin wall and low permittivity of the polystyrene tube. Thus, the results of this study may be applicable to other *in vitro* experiments carried out using tubes with similar dielectric properties and wall thickness, such as thin propylene standard tubes.

In summary, the results of this study showed that the electromagnetic signals emitted by a cell phone can penetrate testicular tissues when the phone is kept near the groin during a call. This study established a link between an *in vitro* experimental setup and real-life conditions for men carrying out their cell phone conversation using an ear piece while carrying the handset of the phone within close proximity to their reproductive organs. The results of our study can be used as a base for calculating the distance between the radiation source and the semen samples. Simulation using the Finite Difference Time Domain (FDTD) method demonstrated that the distance between a cell phone and semen sample in a test tube should be 0.8 cm to 1.8 cm greater than the anticipated distance between the cell phone and testicular region. The results of this study can be used as the basis to calculate the distance between a radiation source and a

semen sample and to set up an *in vitro* experiment that will mimic real life conditions. This study was an initiative in a series of related studies that might follow in the future.

CHAPTER V

SAFETY MEASURES AND CONCLUSIONS

This chapter includes a discussion on the existing safety measures for exposure standard limits for RF radiation, and other conditions that are not considered in these safety limits which might affect our health (Section 5.1). An overall discussion and conclusions on our contribution is provided in Section 5.2. Suggested future work is provided in Section 5.3.

5.1 SAFETY MEASURES

The two leading organizations responsible for setting exposure standards and guidelines for RF radiation are the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE). Many other institutes worldwide have adopted these standards [95].

The standards organizations apply substantial safety measures in establishing the limits and guidelines for the public and workers. These standards mainly use the specific absorption rate (SAR) measurement in setting such limits.

The Food and Drug Administration (FDA) shares responsibility for regulating the RF exposure of wireless phones with the Federal Communications Commission (FCC) in the United States. The FCC also regulates the base stations of wireless phones networks. Each of the FCC bureaus maintains its own licensing database system for the services it regulates [96].

The FCC and other regulatory bodies have set strict limits on RF emissions. In the US, current FCC regulations set the output for 802.11x devices at 1 Watt. The FCC safety standards of power density for cell phone base station antenna using the 1900 MHz band for the general population is $1mW/cm^2$, and for the 850 MHz bands the maximum allowed is about 580 $\mu W/cm^2$, averaged over any thirty-minute period.

Most available 802.11x devices have a power output of less than 100 mW, which is sufficiently lower than FCC safety limits of 1 W for 802.11x devices. This is much less than the output power emitted by a microwave oven. A microwave oven can emit up to 1100 W of power. This number is 1100 times higher than the safety limit set for 802.11x devices. Despite the shielding of a microwave oven, the small leakage from its corners is much higher than the power emitted by WLAN components. Some cordless phone handsets operating at 2.4 GHz emit a power of about 5 W. The power emitted by many mobile phone base stations exceeds 25 W. But adding some modifications to WLAN equipment, such as antennas, might increase the emitted power, and thus the risk will be increased [97] .

Both the FCC and the FDA agreed that there is no clear scientific evidence yet to show a danger associated with the use of wireless phones to users, including children and teenagers [95]. But as mentioned earlier, these limits that mainly consider SAR and power density are based on thermal effects only. However, the results of our study, and many other recent research findings, strongly suggest that considering thermal factors is not sufficient. Nonthermal effects should also be considered for the safety of humans.

Some researchers found that exposure to RF emitted by cellular phones poses many risks, such as brain tumors, infertility in male users, nausea, skin problems, headaches, changes in metabolism and cell membrane function, activation of proto-oncogenes, and changes in cell communication, and can also activate the production of stress proteins at exposure levels lower than the standard safety limits [98]. “Resulting effects can include DNA breaks and chromosome aberrations, cell death including death of brain neurons, increased free-radical production, activation of the endogenous opioid system, cell stress and premature aging, changes in brain function including memory loss, retarded learning, performance impairment in children, headaches and fatigue, sleep disorders, neurodegenerative conditions, reduction in melatonin secretion and cancers” [98]. These risks are increased as the use period increases, with heavy users (or long-term users) having the highest risk. Other researchers found no relation between RF signals and the claimed effects. After reviewing the research done on brain tumors, it appears, as mentioned before, that the long term use of cell phones increases the risk of brain tumors.

Not enough studies are done on new wireless systems and devices such as Wireless LANs, Bluetooth, and PDAs. Even though it is reported that Wireless LANs and Bluetooth should not have an effect because they are usually at a long distance from the users and RF radiation fades over distance, further studies are needed to confirm this due to various new usages of such devices, such as smart phones, or the future "smart homes." No research found so far discusses the accumulated effect when using or being exposed to many RF-emitting devices together.

Research done on the effects of RF signals on health has considered one thing at a time, not the accumulated effects. Some examples are the studies on either the effects of cordless phones, base stations, or cellular phones. Even the safety limits were based on each RF source separately. But most people today are exposed to many RF sources combined. After reviewing the effects of these sources and how people are exposed to more than one source these days, one can reach the conclusion that these sources combined are affecting our health. This is based on the fact that the long term use of one source accumulates to have a higher effect on health according to most research available.

This can lead to the conclusion that exposure to many RF sources together increases risk factors such as SAR. Use of many devices results in higher power density in the surroundings and thus more risk factors.

Most of the studies, including our *in vitro* study, found a relation between cell phone use and male infertility. This was noticeable in men who use headsets and keep the cell phone hand set on their belt or in their trouser pocket during

cell phone conversations. The results suggested deterioration of semen parameters and ROS levels that might lead to oxidative stress [60].

The FDA and the FCC are regulating the safety limits of RF exposure even though they agree that no scientific evidence is yet found to prove health risks caused by these radiation. But even their safety limits consider one RF source at a time, not many of them combined; cumulative and chronic effects of such sources must be considered. These organizations also considered thermal effects only while recent research urged for the need of considering nonthermal effects. Further intensive studies are needed to ascertain health risks, and further revisions to the safety standards must be considered [95].

A chronic exposure from ambient broadcast facilities can also elevate the RF levels emitted by AM, FM, and television antenna transmission in the nearby communities. These sources are also of public health concern since it has the potential for very high RF exposures for people living nearby. “RF levels can be in the 10s to several 100s of $\mu W/cm^2$ in residential areas within half a mile of some broadcast sites” [99].

After the review of existing research, we conclude that it is likely that there is increased risk of male infertility, brain tumors, and acoustic neuromas from wireless devices such as cell phones, PDA devices, and other RF sources. This calls for more involvement in research and more precautions while setting the stanard limits with respect to their use. Sage et al. suggests that “redesign of cell phones and PDAs could prevent direct head and eye exposure, for example, by

designing new units so that they work only with a wired headset or on speakerphone mode” [99].

These effects result in a continual and uncontrolled pullution of our surroundings which can produce adverse bioeffects. These effects might be more dangerous on children who are more vulnerable to such radiation and cannot be excluded from these polluted environments.

Based on all research and scientific evidence, new extremely low frequency (ELF) limits are necessary. These limits should reflect environmental levels of ELF that have been established to minimize the risk for all possible health implications such as brain tumors, childhood leukemia, DNA damage, infertility, Alzheimer, neurological diseases, and possibly other health related issues. ELF limits must be set well below those exposure levels that have been linked in such health problems. It is believed that the existing International Commission Specializing on Radiation Protection (ICNIRP) limit of 1000 mG (100 μT) and 904 mG (90.4 μT) in the US for ELF is no longer effective and is based on flawed assumptions. The existing sfety standards are not within the protective limits of public health and they should be reconsidered [98–100]. The new ELF limits must consider “the exposures that are commonly associated with increased risk of childhood leukemia (in the 2–5 mG (0.2–0.5 μT) range for all children, and over 1.4 mG (0.14 μT) for children age 6 and younger)” [99]. The new limits should be carefully reestablished based on recent reliable research. These precautionary limits should also be established for all cases such as special limits

for children. ELF limits must be developed for habitable space for children, libraries, schools, and workplaces [99].

5.2 SUMMARY AND CONCLUSIONS

The remarkable increase in the development and the use of wireless technology poses a concern about its safety. Wireless devices, such as cellular phones, emit RF radiation at different rates. Researchers have expended considerable effort to see whether there is a link between exposure to RF radiation and human health. Many studies found an increased risk of brain tumors due to the long term use of wireless phones. It is apparent from most studies that as the exposure periods increase, the risk of brain tumors will be higher. Moreover, some studies showed that cell phone use by children increases their risk of having brain tumors. The short term use of wireless phones did not appear to increase the risk of brain tumors.

The results of our *in vitro* study show a significant effect of RF signals emitted by cell phones on male fertility. A significant decrease in motility and viability was apparent in the exposed semen samples (Sec. 3.6.1). The most outstanding finding in our results was the correlation between the cell phone radiation and the ROS level. The results indicated a significant increase in ROS production in the exposed aliquots compared to the unexposed ones (Sec. 3.6.2). This increase was more apparent in the infertile patients' samples than in the healthy subjects' samples. This finding is important since increases in ROS levels play a vital role in male fertility. Furthermore, our results showed a significant decrease in the

ROS-TAC score (Sec. 3.6.3). Since the continuous production of ROS by the spermatozoa is neutralized by the antioxidants contained in the semen, the imbalance between ROS and TAC scores, or the decrease of ROS-TAC score, is an indication of male infertility. Therefore, our results suggest that it is likely that men who carry their mobile phones during a cell phone call in close proximity to their reproductive organs are at risk of infertility.

The study discussed in the previous paragraph was conducted at room temperature. The results of a follow-up study at body temperature also showed some effects of cell phone radiation on the semen parameters. However, these results were not as significant as those from our previous study. This might be due to the small number of samples that were available for testing and the low volume of semen in some of these samples.

In our *in vitro* study, we did not consider the scrotal layers that separate the semen from the cell phone radiation in human subjects. Therefore, a computational RF dosimetry study was performed to overcome this limitation. The results of this study established a relation between an *in vitro* experimental setup and real-life conditions. Our results indicated that the outcome of an *in vitro* experiment is similar to real-life conditions if the cell phone was placed a few centimeters farther from the testing tube. The difference in distance to equalize the energy absorption in the models ranged from 0.8 cm to 1.8 cm. The distance relation between the two models was explained in Section 4.4 of this dissertation.

We found that the effect on fertility in our *in vitro* pilot study, where the cell phone was 2.5 cm from the testing tube, was similar to real-life conditions if the

phone was placed 1.5 cm from the male's reproductive organs. Furthermore, the results showed that the closest match to the lifelike computational model (with the source 2.5 cm from the outer tissue layer) was the *in vitro* model having the source about 3.3 cm from the test tube layer.

When the models were tested at 1800 MHz frequency, the energy density values increased compared to the values of the corresponding models tested at 900 MHz. Also, higher energy values were noticed as the source size became smaller, as indicated by the results of the simulations that used the point source instead of the line source. However, this difference did not affect the relation of the source-layer separation distance as long as the same source was considered for both settings (Fig. 4.5). Therefore, the distance guide provided in this study (Fig. 4.4b) is applicable for different antenna sizes and for the 900/1800 MHz frequency bands, as long as the same source is considered for both the *in vitro* and the lifelike settings.

The results indicated that the polystyrene test tube does not have a significant impact on energy density values in the ROI, perhaps due to the thin wall and low permittivity of the polystyrene tube. Our distance guide is still applicable for other testing tubes with similar dielectric properties and wall thickness. In general, our study provided a distance guideline that can be used as the basis to calculate the distance between a radiation source and a semen sample, and an *in vitro* experiment that mimics real-life conditions.

5.3 FUTURE WORK

This section proposes a design that will add more flexibility to the experimental setup. This setup would enable us to test the effects of more factors such as frequency and power.

An RF signal generator will replace the cell phone to be able to generate the signals with different frequencies. A power amplifier device with control knobs will replace the wireless power booster to control the power manually. A power meter will be used to measure the power, and a spectrum analyzer will display and analyze the signal properties.

A transverse electromagnetic (TEM) cell might be used to place the samples in it so they can be exposed evenly to the radiation, and they will be kept isolated from other external radiation in the surroundings. The experiments will be performed with different cell phone frequencies and different powers to see the effects of different cell phone radiation on the samples used.

Also, different distances can be tested in an *in vitro* experiment using the guidelines provided in our modeling study. The time duration of exposure can be expanded and compared to watch for the effect of longer use on sperm parameters. During the period of exposure, many calls can be initiated rather than one since it was noticed from the measurements by a field strength meter that the highest power density was at the time of receiving a call.

Future work can also focus on higher accuracy of the computational modeling study. For example, we can consider multiple clothing layers with different types of fabric for the lifelike model, and we can design a cell phone model rather than

the RF current source used in our study, which was thought to be sufficient for comparison purposes as long as the same source was used in both basic modeling conditions. Also, a three-dimensional model can be developed to improve the precision of the electric field energy density results if the data and simulation tools are available.

The rapid exploitation of wireless technologies that causes a chronic exposure of EMW-RF on the public at levels reported to cause health effects, which in turn could reasonably be considered to lead to serious health impacts, is a public health concern [100]. Besides the effects shown in our experimental study, there is strong evidence from the review of other studies that exposures to RF signal might have different effects on human health. This information now argues for standard limits that are considerably lower than the current FCC and ICNIPR standards for whole body exposure. Hesitation about how much these standards should be lowered or adjusted from a public health standpoint must not thwart researchers' efforts to correlate current information and adopt new standard limits [98]. Therefore, further research and safety limits are required for the possible health risks of wireless WLAN and Wi-Fi systems, including long term and chronic exposures on the whole body. "The lower limit for reported human health effects has dropped 100-fold below the safety standard (for mobile phones and PDAs); 1000–10,000-fold for other wireless (cell towers at distance; WI-FI and WLAN devices). The entire basis for safety standards is called into question, and it is not unreasonable to question the safety of RF at any level" [99].

Suggested target level limits are 0.1 μW/cm^2 (or 0.614 V/m) for the ambient wireless or pulsed RF cumulative exposures for the general public, and an even lower limit of 0.01 μW/cm^2 of exposure inside buldings. These limits apply for all RF sources including cell tower antennas, Wi-Fi, and Worldwide Interoperability for Microwave Access (WI-MAX) [99]. This level of RF is considered a whole body exposure, and can be a continual exposure in areas with wireless coverage for voice and data transmission for RF sources, such as cell phones. Although some anecdotal reports and studies on possible bioeffects have been reported at even lower levels than this, these suggested limits for the time being could lower some of the most possible risks that might affect the public nearest to such wireless sources [100].

Even though studies on RF effects are still under research and their dangers are not all proved, it is still recommended to implement wired alternatives to Wi-Fi technologies wherever possible, especially at schools to protect children from RF exposures at an early age. These precautions must be considered as preliminary guidelines, and further safety measures must be implemented based on current and future studies in this field. Advances in technology are vital in our modern world but our health must not be the price.

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APPENDICES

APPENDIX A

Tables for Raw Data for the Pilot Study

ROS values are shown in the table as mean ± SD; median (25^{th} and 75^{th} percentiles).

	ROS (×10^6 cpm/20 million sperm)		Log(ROS+0.001)		TAC (µmol Trolox)		ROS-TAC		Viability %		Motility %		TUNEL (DFI %)	
Group	Exposed	Non-exposed	Exp	N-E	Exp	N-E	Exp	N-E	Exp	N-E	E	N-E	Exp	N-E
Over all	0.11 +/- 0.21; 0.013 (0.0047, 0.1258)	0.06 +/- 0.11 ; ;0.0075 (0.0017, 0.0387)	-1.72 +/- 0.86	-1.97 +/- 0.85	1.55 +/- 0.38	1.66 +/- 0.48	46.29 +/- 11.20	51.54 +/- 13.37	52.33 +/- 13.21	58.97 +/- 14.81	48.62 +/- 17.36	52.11 +/- 18.34	7.80 +/- 6.62	8.44 +/- 5.77
p value	0.002		0.001		0.24		0.032		<0.001		0.003		0.62	
n	32		32		24		23		30		32		20	
Donors	0.06 +/- 0.12; 0.01 (0.0035, 0.022)	0.05 +/- 0.10; 0.007 (0.002, 0.0305)	-1.85 +/- 0.78	-1.94 +/- 0.80	1.53 +/- 0.38	1.72 +/- 0.52	48.63 +/- 11.53	51.71 +/- 13.75	53.52 +/- 13.05	61.00 +/- 13.71	50.60 +/- 17.49	54.80 +/- 17.61	8.21 +/- 7.24	8.66 +/- 6.45
p value	0.048		0.017		0.08		0.14		<0.001		0.01		0.78	
n	23				16		15		23		23		16	
Patients	0.22 +/- 0.33 0.02 (0.012, 0.293)	0.07 +/- 0.15 0.008 (0, 0.062)	-1.37 +/- 1.00	-2.03 +/- 1.03	1.59 +/- 0.41	1.52 +/- 0.41	41.91 +/- 9.74	51.23 +/- 13.54	48.43 +/- 13.99	52.29 +/- 17.41	43.56 +/- 16.94	45.25 +/- 19.42	6.16 +/- 3.38	7.56 +/- 1.24
p value	0.014		0.014		0.74		0.15		0.14		0.36		0.88	
n	9		9		8		8		7		9		4	

APPENDIX B

Sample Meep Programs

This program is using a point source for the lifelike model # 3 with 2.5 cm distance and 900 MHz frequency.

```
(reset-meep)
;The dielectric parameters
(define-param seps 41.4)            ;skin permittivity,epsilon,at 900
MHz
(define-param meps 56.9)            ;muscles (musc-fascia lyrs))
permittivity,epsilon,at 900 MHz
(define-param teps 60.553)          ;Tes. permittivity,epsilon,at 900
MHz
(define-param beps 61.4)            ;fluid permittivity,epsilon,at 900
MHz
(define-param sseg 7.92)           ;skin D-conductivity, sigma, at 900
MHz
(define-param mseg 6.62)            ;muscle (muscular-fascia layers) D-
conductivity, segma, at 900 MHz
(define-param tseg 7.5255)          ;Tes. D-conductivity, Tsig,at 900
MHz
(define-param bseg 9.449)           ;fluid D-conductivity, bsig at 900
MHz

;the cell dimentions
(define-param sw 0.002)    ; Skin thickness in m
(define-param mw 0.001)    ; muscle thickness in m
(define-param tw 0.0005)    ; tes. tissue thickness in m
(define-param bw 0.016)    ; fluid layer thickness in m
(define-param xl 0.196)    ; layer size (length) on the x-axis in m
(define-param dpml 0.001)  ; PML layer thickness
(define-param sx 0.200)     ; size of cell in x direction
(define-param sy 0.300)    ; size of cell in y direction

; sizes of the x-axis is changed to (200 mm)
(set! geometry-lattice (make lattice (size sx sy no-size)))

; sizes of the layers is changing on the x-axis (196 mm)
; thickness is changed for test. tissues .5 mm, for skin 2 and muscle
to 1 mm
(set! geometry
 (append
  (list
      (make block (center 0 -0.0045) (size xl bw infinity)
         (material (make dielectric (epsilon beps)(D-conductivity
bseg))))
      (make block (center 0 0.00375) (size xl tw infinity)
         (material (make dielectric (epsilon seps) (D-conductivity
sseg))))
```

```
      (make block (center 0  0.0045) (size xl mw infinity)
         (material (make dielectric (epsilon meps) (D-conductivity
mseg))))
      (make block (center 0  0.006) (size xl sw infinity)
         (material(make dielectric (epsilon seps) (D-conductivity
sseg)))))))

(set! sources (list
               (make source(src (make continuous-src
                        (frequency 0.477)))
                 (component Ez)
                 (center 0 0.032) (size 0 0.002))))

(set! pml-layers (list (make pml (thickness dpml))))

(set! resolution 2000)
; Need to somehow output this, this the energy in a 5 mm x 5 mm box at
the region of interest
;(electric-energy-in-box (volume (center 0 -0.0045) (size 0.005
0.005)))
(use-output-directory)
(run-until 10 (at-beginning output-epsilon)
(to-appended "out" (at-every 0.025 output-efield-z output-dpwr))
;(to-appended "roi" (at-every 0.025 (in-volume (volume (center 0 -
0.0045) (size 0 0)) output-efield-z output-dpwr)))
)
```

This program is using a line source for the lifelike model # 3, with 2.5 cm distance and 900 MHz frequency.

```
(reset-meep)
;The dielectric parameters
(define-param seps 41.4)            ;skin permittivity,epsilon,at 900
MHz
(define-param meps 56.9)            ;muscles (musc-fascia lyrs))
permittivity,epsilon,at 900 MHz
(define-param teps 60.553)          ;Tes. permittivity,epsilon,at 900
MHz
(define-param beps 61.4)            ;fluid permittivity,epsilon,at 900
MHz
(define-param sseg 7.92)           ;skin D-conductivity, segma, at 900
MHz
(define-param mseg 6.62)            ;muscle (muscular-fascia layers) D-
conductivity, segma, at 900 MHz
(define-param tseg 7.5255)          ;Tes. D-conductivity, Tsig,at 900
MHz
(define-param bseg 9.449)           ;fluid D-conductivity, bsig at 900
MHz
```

```
;the cell dimentions
(define-param sw 0.002)    ; Skin thickness in m
(define-param mw 0.001)    ; muscle thickness in m
(define-param tw 0.0005)    ; tes. tissue thickness in m
(define-param bw 0.016)    ; fluid layer thickness in m
(define-param xl 0.196)    ; layer size (length) on the x-axis in m
(define-param dpml 0.001)  ; PML layer thickness
(define-param sx 0.200)     ; size of cell in x direction
(define-param sy 0.300)    ; size of cell in y direction

; sizes of the x-axis is changed to (200 mm)
(set! geometry-lattice (make lattice (size sx sy no-size)))

; sizes of the layers is changing on the x-axis (196 mm)
; thickness is changed for test. tissues .5 mm, for skin 2 and muscle
to 1 mm
(set! geometry
 (append
  (list
      (make block (center 0 -0.0045) (size xl bw infinity)
         (material (make dielectric (epsilon beps)(D-conductivity
bseg))))
      (make block (center 0 0.00375) (size xl tw infinity)
         (material (make dielectric (epsilon seps) (D-conductivity
sseg))))
      (make block (center 0  0.0045) (size xl mw infinity)
         (material (make dielectric (epsilon meps) (D-conductivity
mseg))))
      (make block (center 0  0.006) (size xl sw infinity)
         (material(make dielectric (epsilon seps) (D-conductivity
sseg)))))))

(set! sources (list
               (make source(src (make continuous-src
                        (frequency 0.477)))
                 (component Ez)
                 (center 0 0.032) (size 0.035 0.002))))

(set! pml-layers (list (make pml (thickness dpml))))

(set! resolution 2000)
; Need to somehow output this, this the energy in a 5 mm x 5 mm box at
the region of interest
;(electric-energy-in-box (volume (center 0 -0.0045) (size 0.005
0.005)))
(use-output-directory)
(run-until 10 (at-beginning output-epsilon)
;(to-appended "out" (at-every 0.025 output-efield-z output-dpwr))
(to-appended "roi" (at-every 0.025 (in-volume (volume (center 0 -
0.0045) (size 0 0)) output-efield-z output-dpwr)))
)
```

This program is using a line source for the lifelike model # 3 with 2.5 cm distance and 1800 MHz frequency.

```
(reset-meep)
;The dielectric parameters
(define-param seps 38.87)            ;skin permittivity,epsilon,at 1800
MHz
(define-param teps 58.605)           ;Tes. permittivity,epsilon,at 1800
MHz
(define-param meps 53.55)            ;muscle permittivity,epsilon,at
1800 MHz
(define-param beps 59.37)            ;fluid permittivity, beps at 1800
MHz
(define-param sseg 11.48)           ;skin D-conductivity, sigma at 1800
MHz
(define-param tseg 10.87)            ;Tes. D-conductivity, Tsig,at 1800
MHz
(define-param mseg 9.434)            ;muscle D-conductivity, sig, at
1800 MHz
(define-param bseg 12.945)           ;fluid D-conductivity, beg at 1800
MHz

;the cell dimentions
(define-param sw 0.002)    ; Skin thickness in m
(define-param mw 0.001)    ; muscle thickness in m
(define-param tw 0.0005)    ; tes. tissue thickness in m
(define-param bw 0.016)    ; fluid layer thickness in m
(define-param xl 0.196)    ; layer size (length) on the x-axis in m
(define-param dpml 0.001)  ; PML layer thickness
(define-param sx 0.200)     ; size of cell in x direction
(define-param sy 0.300)    ; size of cell in y direction

; sizes of the x-axis is changed to (200 mm)
(set! geometry-lattice (make lattice (size sx sy no-size)))

; sizes of the layers is changing on the x-axis (196 mm)
; thickness is changed for test. tissues .5 mm, for skin 2 and muscle
to 1 mm
(set! geometry
 (append
  (list
      (make block (center 0 -0.0045) (size xl bw infinity)
         (material (make dielectric (epsilon beps)(D-conductivity
bseg))))
      (make block (center 0 0.00375) (size xl tw infinity)
         (material (make dielectric (epsilon seps) (D-conductivity
sseg))))
      (make block (center 0  0.0045) (size xl mw infinity)
         (material (make dielectric (epsilon meps) (D-conductivity
mseg))))
      (make block (center 0  0.006) (size xl sw infinity)
         (material(make dielectric (epsilon seps) (D-conductivity
sseg)))))))

(set! sources (list
```

```
               (make source(src (make continuous-src
                        (frequency 0.956)))
                 (component Ez)
                 (center 0 0.032) (size 0.035 0.002))))

(set! pml-layers (list (make pml (thickness dpml))))

(set! resolution 4000)
; Need to somehow output this, this the energy in a 5 mm x 5 mm box at
the region of interest
;(electric-energy-in-box (volume (center 0 -0.0045) (size 0.005
0.005)))
(use-output-directory)
(run-until 10 (at-beginning output-epsilon)
;(to-appended "out" (at-every 0.025 output-efield-z output-dpwr))
(to-appended "roi" (at-every 0.025 (in-volume (volume (center 0 -
0.0045) (size 0 0)) output-efield-z output-dpwr)))
)
```

This program is using a line source for the experimental (air-tube) model with 3.3 cm distance and 900 MHz frequency.

```
(reset-meep)
;The dielectric parameters
(define-param geps 2.56)             ;polystyrene permittivity,epsilon

(define-param gseg 1.4716e-14)        ;polystyrene D-conductivity,
segma

(define-param bseg 9.449)             ;fluid D-conductivity, begma



;the cell dimentions
(define-param gw .001)   ; polystyrene plastic test tube wall-thickness
in m
(define-param xl .196)   ; layers size on x-axis (length) in m


(define-param dpml .001)  ; PML layer thickness
(define-param sx .200)    ; size of cell in x direction
(define-param sy .300)   ; size of cell in y direction

(set! geometry-lattice (make lattice (size sx sy no-size)))

(set! geometry
   (list
      (make block (center 0 -.0105) (size xl gw infinity)
```

```
         (material (make dielectric (epsilon geps) (D-conductivity
gseg))))
      (make block (center 0 -.002) (size xl .016 infinity)
         (material (make dielectric (epsilon 61.4)(D-conductivity
bseg))))
      (make block (center 0 .0065) (size xl gw infinity)
         (material (make dielectric (epsilon geps) (D-conductivity
gseg))))))

(set! sources (list
               (make source(src (make continuous-src
                        (frequency .477)))
                 (component Ez)
                 (center 0 .040) (size 0.035 0.002))))

(set! pml-layers (list (make pml (thickness dpml))))

(set! resolution 2000)
(use-output-directory)
(run-until 10 (at-beginning output-epsilon)

;(to-appended "out" (at-every 0.025  output-efield-z output-dpwr))
(to-appended "roi" (at-every 0.025 (in-volume (volume (center 0 -0.002)
(size 0 0)) output-efield-z output-dpwr)))
)
```

This program is a sample for a PyLab program used to graph the energy

distribution.

plotb-power.py

```
# run this file using
# %run -i plot_power.py <hdf5filename for all outputs> <output varible> <region row #>
<region column #>
# e.g. %run -i plot_power.py mdl5-out.h5 denergy 35 9
# after invoking
# ipython -pylab
# in terminal window
# -pylab allows access to matplotlib functions for plotting
# to extract the array r= Var[304, 50, :], to print it use  Print(r)
#to get the mean value of the past array use: mean(r)


import scipy
# gives access to scipy functions
import tables
```

```
# gives access to pytables (for hdf5 read, write)

Col = int(sys.argv[-1])
Row = int(sys.argv[-2])
h5fname_var = sys.argv[-4]
varname = sys.argv[-3]
# read solution from hdf5 file
h5f_var = tables.openFile(h5fname_var, mode = "r")
# read variable of interest
VarObject = h5f_var.getNode("/", varname)
Var = VarObject.read()
Var = swapaxes(Var, 0,1)
Var = flipud(Var)

# contour plot of variable of interest at final time
figure(1)
contourf(Var[:,:,112])
text(Col, Row, 'RoI')
colorbar()
jet()
axis('equal')
#axis('off')
box('off')
matplotlib.pyplot.xlabel('size in mm X2')
matplotlib.pyplot.ylabel('thickness in mm x2')
matplotlib.pyplot.text(200, 236, 'source location')
matplotlib.pyplot.text(80, 286, 'test tube layer')
matplotlib.pyplot.text(250, 288, 'fluid layer (begins)')
matplotlib.pyplot.text(180, 320, 'test tube layer')
matplotlib.pyplot.legend('efield density', loc=1)
show()

figure(2)
plot(Var[Row,Col,:])
#xlabel('Simulation Time')
#ylabel('Electric Field Energy Density')
show()
```

APPENDIX C

Additional Sample Figures for the Biomodeling Study

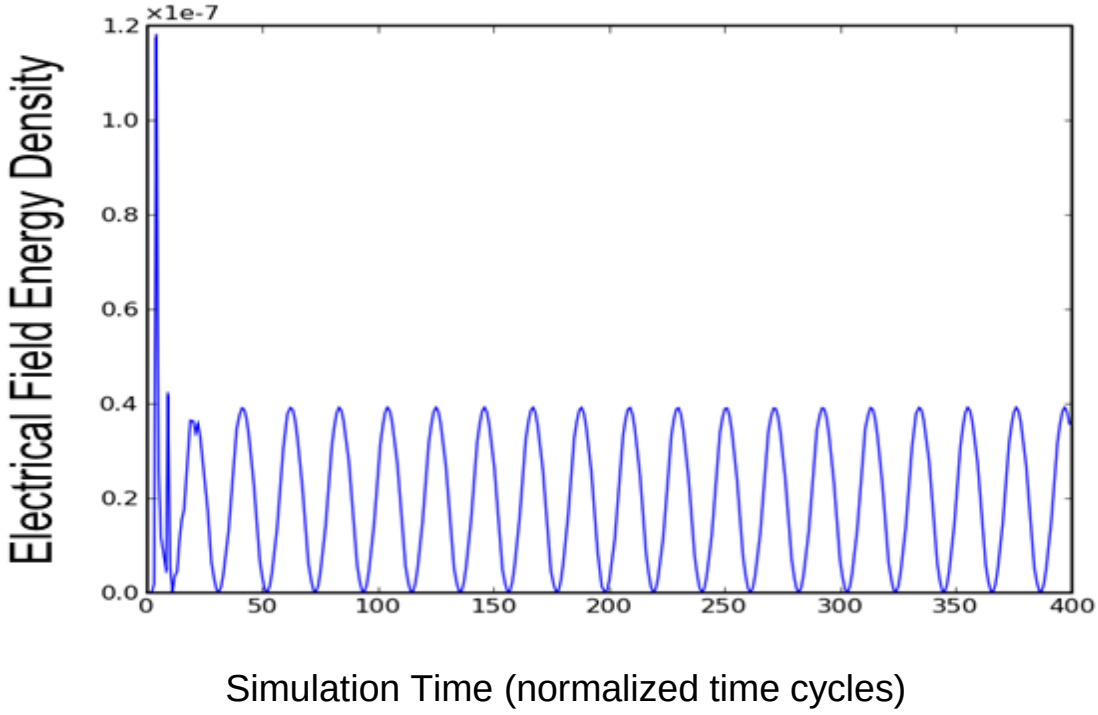

Fig. C1: The ROI of the Lifelike Model # 3, frequency 1800 MHz, separation distance 2.5 cm. Note that the units are normalized according to Section 4.3.6.

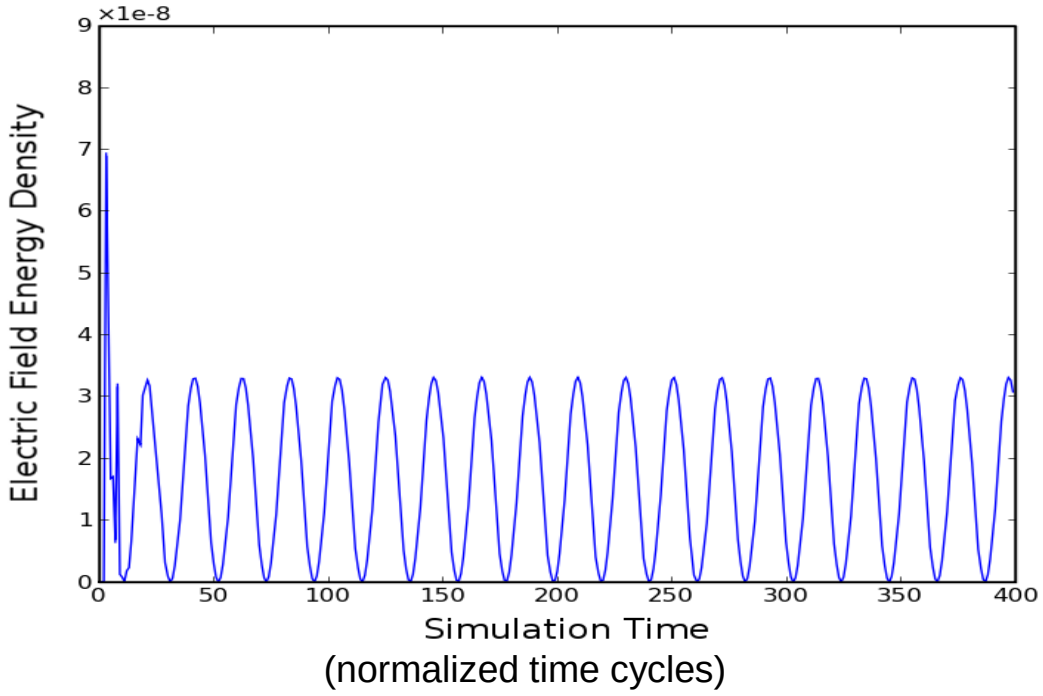

Fig. C2: The ROI of the experimental Model, frequency 1800 MHz, separation distance 3.5 cm (between source and tube). Note that the units are normalized according to Section 4.3.6.

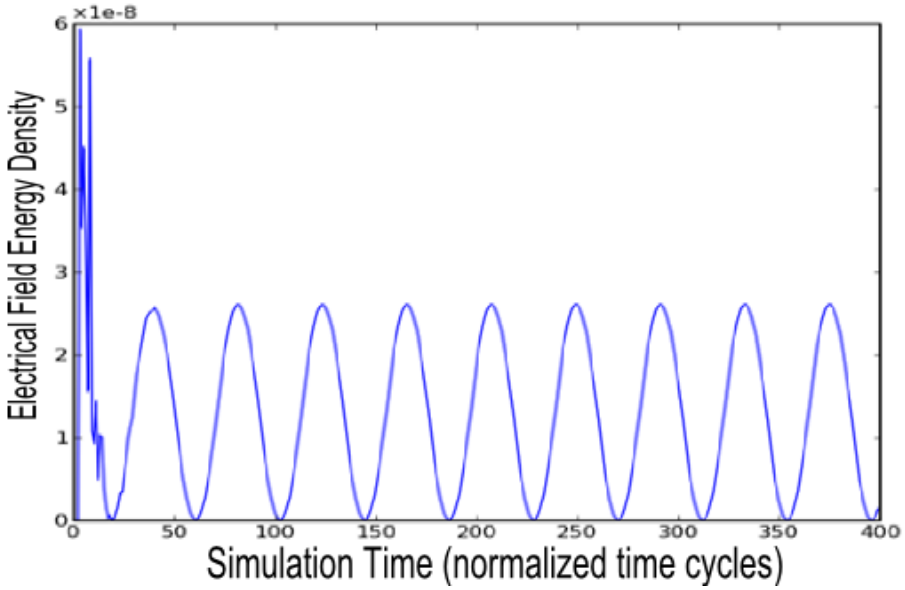

Fig C3: The ROI of the experimental Model *without tube*, frequency 900 MHz, separation distance 3.5 cm (between source and fluid layer). Note that the units are normalized according to Section 4.3.6)

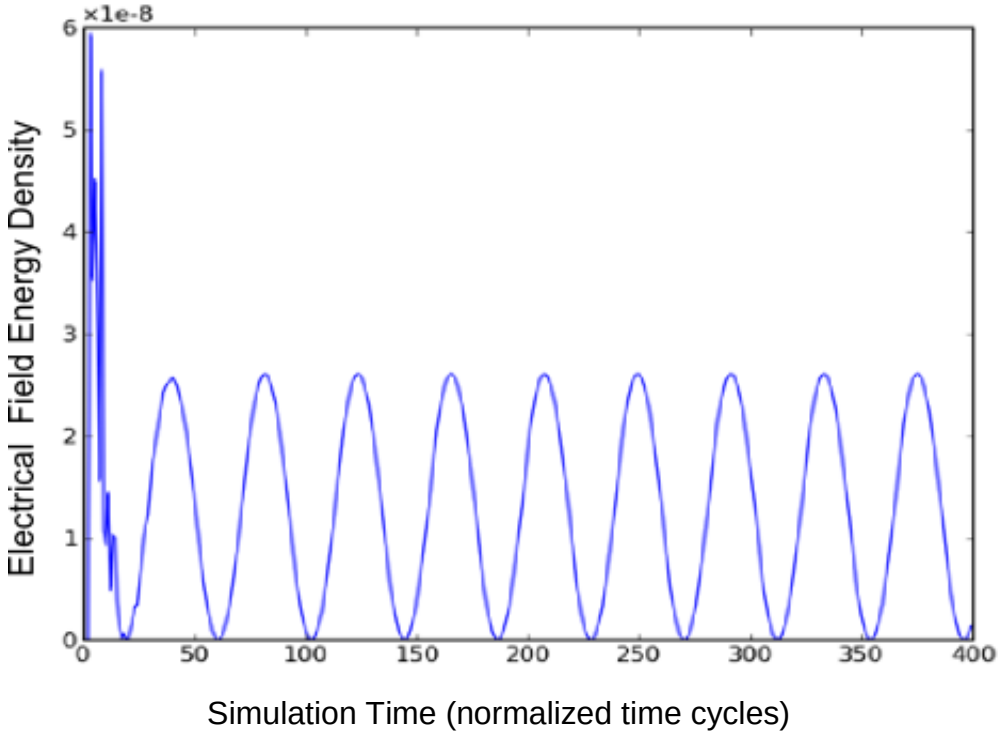

Fig. C4: The ROI of the experimental Model, frequency 900 MHz, separation distance 3.5 cm (between source and Tube layer). Note that the units are normalized according to Section 4.3.6.

APPENDIX D

Additional Background on Electromagnetic Waves and Maxwell's Equations

In electromagnetism, Maxwell's equations are mainly four partial differential equations that portray the properties of both the electric and the magnetic fields. These equations establish the relation between both fields and the charge and current densities. These equations also show that light is an electromagnetic wave. These four equations are as follows [D-1].

The first equation is called Faraday's law and it relates the change in magnetic field *B* to the electric field intensity *E* as follows:

$$\frac{\partial B}{\partial t} + \nabla \times E = 0$$

where ∇ is the vector differential operator and $\nabla \times E$ refers to the vector product or *curl* of *E*

The second equation is called Gauss's law and shows the effect of the charge density *ρ* on the electric displacement *D* as follows:

$$\nabla . D = \rho$$

where $\nabla . D$ refers to the divergence of *D.*

The third equation is called Faraday's law of induction :

$$\frac{\partial D}{\partial t} - \nabla \times H = -J$$

where *H* is the magnetic field intensity and *J* is the current density function.

The fourth equation is called Gauss's law for magnetism which describes the structure of the magnetic field and shows that the total magnetix flux within a Gaussian surface equals zero, so the net magnitude of the vector components going outward from a surface and the components pointing inwards must be equal as follows [D-1]:

$$\nabla . B = 0$$

For free space with the absence of the imposed current and the electric charge, and after eliminating the nonphysical quantities *H* and *D,* the four equations will be simplified as follows:

$$\frac{\partial B}{\partial t} + \nabla \times E = 0$$

$$\nabla . D = 0$$

$$\frac{\partial E}{\partial t} \mu o \, \varepsilon o - \nabla \times B = 0$$

$$\nabla . B = 0$$

where μ_o is the magnetic permeability, ε_o is the electric permitivity in vacuum or free space, and $\mu_o \, \varepsilon_o = c^{-2}$ where *c* is the speed of light [D-1]. As mentioned in this dissertation, all radio waves, including those emitted by wireless devices, are electromagnetic waves.

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