

A Theoretical Approach for SAR Calculation in Human Head Exposed to RF Signals

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Abstract

The worldwide use of cellular phones has generated public concern about exposure to the microwave radiation associated with these phones. The probable biological effects due to the use of mobile phones can be regarded as a result of energy absorbed by the head that may damage the brain and nervous tissues.

This paper discusses the probable health effects of mobile phones radio emissions, and presents a theoretical method to calculate the specific absorption rate (SAR) in human head exposed to the microwaves of frequency range used in GSM-900, and GSM-1800 mobile phones.

A mobile phone with a single direction antenna as an electromagnetic fields source positioned near the head is assumed, and a four layers head model is constructed to calculate the penetration depth in human head, to analyze the SAR and heat distribution in head tissues.

طريقة نظرية لحساب الطاقة الممتصة في رأس الإنسان المتعرض للإشارات الراديوية

الخلاصة

أدى الاستخدام الواسع لأجهزة الهواتف الخلوية إلى قلق شعبي حول التعرض للإشعاعات المايكرووية الصادرة من تلك الهواتف الخلوية. إن التأثيرات المحتملة الناتجة عن استخدام الهاتف النقال تعزى إلى الطاقة الممتصة من قبل رأس المستخدم والتي قد تؤدي إلى إتلاف الدماغ والأنسجة العصبية. يعرض هذا البحث الآثار الطبية المحتملة للانبعثات الصادرة من الهواتف النقالة, ويقدم طريقة نظرية لحساب معدل الامتصاص النوعي في رأس الإنسان الذي يتعرض للإشعاعات المايكرووية الصادرة من الهواتف النقالة المستخدمة في نظام (GSM-900) و (GSM-1800).

تمت نمذجة الهاتف كمصدر للمجال الكهرومغناطيسي من خلال هوائي باتجاه واحد موضوع قرب رأس المستخدم, كما تمت نمذجة الرأس بأربع طبقات لغرض احتساب العمق الذي تنفذ به الإشعاعات للرأس, وتحليل الامتصاص النوعي وتوزيع الحرارة في أنسجة الرأس.

Introduction

Widespread utilization of mobile communication systems has caused great concern about the probable health effects caused by the radio frequency (RF) fields emitted from both base stations and cell phones^[1].

When a mobile phone connects to the network, it uses radio signals to communicate with the nearest base station in the network and initiates a call.

The level of RF exposure from base stations are too low to cause significant health effect in human body's as the base stations radiation diminishes rapidly over the distance between the person and the base station antennas. While, the cell phone exposes its user to a non-negligible amount of electromagnetic energy. The RF energy emitted by cell phones is more powerful than that emitted by base stations as the mobile phone is usually held close to the head for a considerable length of time while being used^{[2][3]}.

The power control and discontinuous transmission used in Global System for Mobile Communication (GSM) phones reduces the transmitted power to the minimum levels whilst maintaining good call quality^[4]. Phones operated in ideal mode cause typically much lower exposure compared to mobile phones operated with maximum power. There is no exposure occurs from a mobile phone being switched off as no signal will be sent^[2].

The most important parameter used to assess human exposure to RF electromagnetic fields emitted from cellular phones in the near-field regions is given in terms of the specific absorption rate (SAR). SAR is the rate at which the RF energy is absorbed per time by a particular mass of tissue, and it is measured in watts per kilogram. Nowadays, automatic positioning systems, actual phones and a head-like phantoms filled with the appropriate tissue equivalent liquid is employed to measure the SAR for mobile phones. Many efforts using numerical methods are aimed to define human head models, and phone models to allow the comparison between numerical and experimental procedures for SAR evaluation^[5].

In this paper, a theoretical approach to analyze the electromagnetic field penetration and a thermal effect of radiofrequency signal in human head biological tissues is presented. A model of RF source and an approximate model of human head is constructed to estimate the absorbed energy inside the human head exposed to radiation emitted from GSM cell phones.

Cellular Phones Health Effects

Mobile phone users are exposed to RF radiation in the microwave range. The possible biological effects arising from the use of mobile phones can be regarded as a result of energy absorbed by the head that may affect the brain and nervous system tissue ^{[4][6]}. The RF fields emitted from mobile phones penetrate the exposed tissues producing heat. This thermal effect can cause harm by increasing body temperature, and damaging biological tissue, particularly those of head and brain.

The depth to which radio waves penetrate exposed tissues depends on the frequency of the source, and the electrical properties of the tissue. It is given as:

$$\delta = \sqrt{\frac{1}{\pi \mu \sigma f}} \quad (1)$$

where δ is the penetration depth (m), μ is the tissue magnetic permeability (H/m), σ is the tissue electric conductivity (S/m), and f is the RF source frequency (Hz).

The SAR value depends on the incident fields intensity (or equivalent power density), tissue properties, geometry, size, orientation of the exposed object, frequency of the incident fields, and exposure time.

SAR is related to the physical and electrical properties of the absorbing object by the following equations.

$$SAR = \frac{d}{dt} \left(\frac{dW}{dm} \right) = \frac{\sigma E^2}{2\rho} \quad (2)$$

$$E = \left(\frac{\sigma}{\rho} SAR \right)^{1/2} \quad (3)$$

$$J = (\sigma \rho SAR)^{1/2} \quad (4)$$

where W is the absorbed energy (joule), t is the time (second), m is the tissue mass (kg), E is the induced electric field strength (V/m) in tissue, J is the current density (A/m^2) in tissue, ρ is the tissue density (kg/m^3), and σ is the conductivity of the material (S /m) [4].

SAR and temperature are relating by the following heat equation:

$$\frac{dQ}{dT} = \rho V C \quad (5)$$

where Q is the thermal energy (Joule), T is the temperature in Kelvin (K), V is the volume (m^3), and C is the specific heat (J /K. kg) [7].

Human Head - RF Source Modeling

In order to assess human exposure to mobile phone electromagnetic fields, it is required to construct an appropriate model of a human head and the RF source (phone).

In this study, the human head is modeled as a four- layer structure that consist of skin, fat, skull, and brain.

The human head biological tissues may be considered as lossy dielectric materials with permeability equal to free space permeability ($\mu = \mu_0$), and conductivity that depends on tissue properties and signal frequency [8][9]. The electrical and thermal parameters of the human head biological tissues at 900 MHz and 1.9 GHz are given in Table 1 [2][9].

In addition, it is necessary to construct a model of the GSM mobile phone that represent the RF source, whose radiation covers the human head. The mobile phone is assumed to be in transmit mode, that transmits RF energy in a single direction towards the head as it is assumed to be located 2 cm away from the human head. Therefore, the mobile phone antenna is assumed to has a unity gain ($G_t = 1$). The human head, and the RF source models are shown in Figure 1.

Table 1. Human Head Tissue Properties^{[2][10]}

Tissue	Mass Density (kg/m ³)	Radius (cm)	Specific Heat (J/K.kg)	900 MHz		1900 MHz	
				Dielectric Constant ϵ_r	Conductivity σ (S/m)	Dielectric Constant ϵ_r	Conductivity σ (S/m)
Skin	1010	9.00	3662	40.7	0.65	37.21	1.25
Fat	920	8.90	2378	10.0	0.17	9.38	0.26
Bone	1810	8.76	1590	20.9	0.33	16.40	0.45
Brain	1040	8.10	3640	41.1	0.86	43.22	1.29

The GSM-900 system uses the frequency band (890-915)MHz for up-link and the band (935-960)MHz for down-link. While, the GSM-1800 system uses the frequency band (1710-1785) MHz for up-link and the band (1805-1880) MHz for down-link. In GSM systems up to eight users share the same frequency channel and each phone transmits only one eighth of the time as the time division multiple access (TDMA) is used, so the average power is one eighth of the peak power^[6].

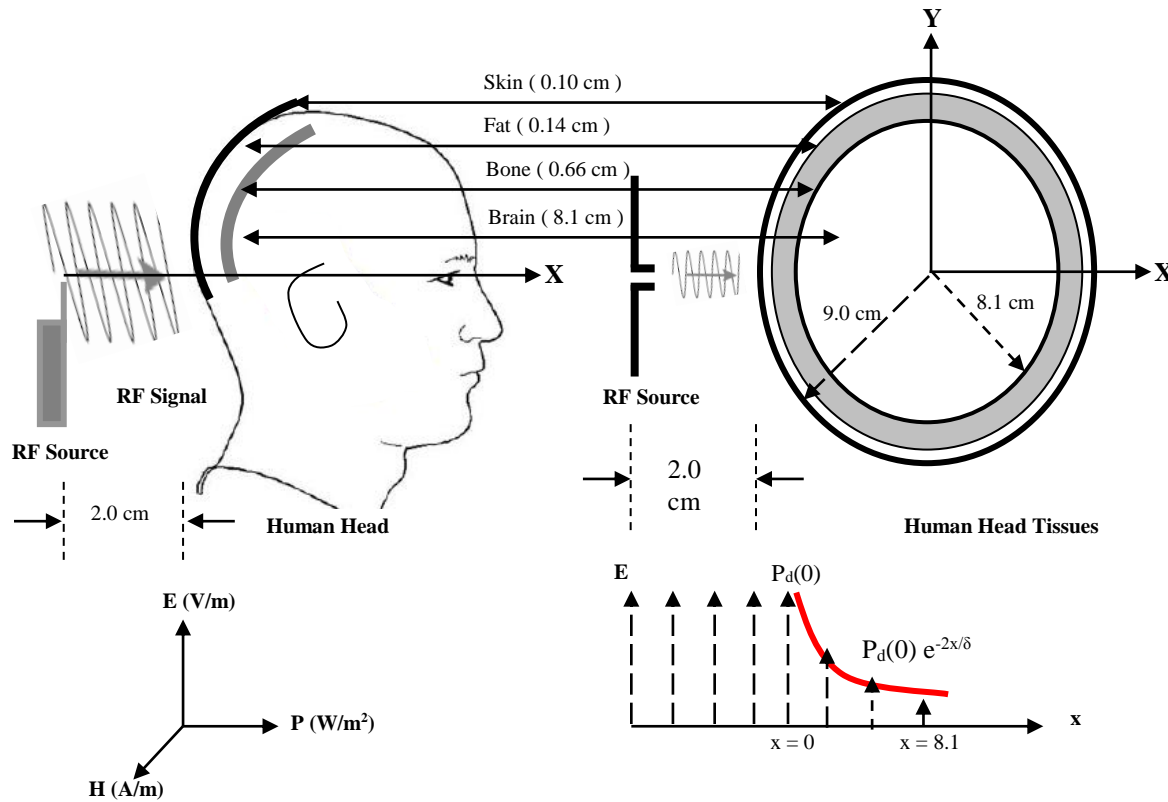


Figure 1. RF Source - Human Head Model

SAR Distribution in Human Head

In order to evaluate the possible risk for human health due to mobile phone usage , it is necessary to assess SAR distribution on human head exposed to RF radiation during the time spent using the mobile phone.

SAR for GSM-900 Systems

When the exposed head is near the antenna phone (the source), the RF fields penetrate the human head tissues as the human tissues are transparent to these fields.

The medium up-link frequency for GSM-900 systems can be calculated to be $(890 + 915) / 2 = 902.5 \text{ MHz}$. Therefore, the maximum penetration depth during the use of the GSM cellular phone in transmit mode, can be determined using equation 1, with the minimum value of conductivity given in Table 1 as :

$$(\delta)_{up} = \sqrt{1 / (\pi \times 4\pi \times 10^{-7} \times 0.17 \times 902.5 \times 10^6)} = 0.0406 \text{ m} = 40.6 \text{ mm}$$

GSM-900 phones have a peak power of 2 W, and as the maximum average power is one eighth of the peak power, hence the GSM-900 mobile phone radiate an average power of 250 mW.

The power density produced by the mobile phone at the maximum penetration depth can be calculated by using the following equation as^[8],

$$S = \frac{ERP}{4\pi d^2} = \frac{P_t G_t}{4\pi d^2} \quad (6)$$

Assuming that the mobile phone (RF source) has an with a single direction in the nearest zone, ($G_t=1$), and the head-antenna separation distance (d) is 2.0 cm, the power density will be:

$$S = \frac{0.250 \times 1}{4\pi (0.02 + 0.0406)^2} = 0.5411 \text{ mW / cm}^2 = 5.411 \text{ W / m}^2$$

The velocity of propagation of electromagnetic waves through human tissue is lower than that in free space as the impedance of tissue compared with that of free space is low. The impedance of the human head tissues (η) can be determined by the formula:

$$\eta = \eta_o \sqrt{\frac{\mu_r}{\epsilon_r}} \quad (7)$$

where η_o is the free-space impedance ($\eta_o = 377\Omega$).

The power density(S), the medium impedance(η), the electric field strength (E), and the magnetic field strength (H) are relating by the equation^{[10][11]}

$$S = \frac{E^2}{\eta} = H^2 \eta \quad (8)$$

The impedance, and the electric field strength for each layer can be calculated by using equations 7 and 8. As an example, the skin impedance was calculated to be 59.094 Ω , and the induced electric field was calculated to be 17.882 V/m.

When the electric field distribution inside the head tissues is estimated, the SAR distribution can be easily obtained. The region with the maximum field corresponds to the region with maximum SAR value. The SAR in the skin can be calculated using equation 2, by substituting the values of the electric conductivity (σ), and the density (ρ) given in Table1.

$$SAR = \frac{\sigma E^2}{2 \rho} = \frac{0.65 \times 319.787}{2 \times 1010} = 0.1029 \text{ W / kg}$$

The wave amplitude attenuates exponentially with the factor $e^{-x/\delta}$, and the energy of the wave attenuates by the factor $e^{-2x/\delta}$. Thus, the power per unit area (power density) flowing past the point ($x = 0$), i.e. $P_d(0)$ in the forward x-direction (towards the head) can be expressed by means of the penetration depth as:

$$P_d(x) = P_d(0) e^{-2x/\delta} \quad (9)$$

The power attenuation in dB per meter (A_{dB}) can be obtained by taking logs of equation 9, and using the numerical value ($10 \log_{10} e^2 = 8.686$), the power attenuation at the distance x , relative to $x = 0$, can be expressed as^[12]:

$$A_{dB}(x) = 8.686 \frac{x}{\delta} \quad (10)$$

Assuming that there is no attenuation in signal power till it reaches the outer surface of the brain (worst case) as the distance is too low, the power attenuation at the brain ($x = 8.1$ cm) can be calculated as:

$$A_{dB}(x) = 8.686 \times \frac{0.0406}{0.081} = 4.356 \text{ dB}$$

The power received at the brain surface will be equal to the difference between the transmitted power (250 mw or 23.979 dBm), and the attenuation through the penetration depth. It can be determined as

$$P_{Brain} = 23.979 - 4.356 = 19.6225 \text{ dBm} = 91.67 \text{ mw}$$

The power density caused by the effective power of 91.67 mw can be determined to be

$$S = \frac{0.09167 \times 1}{4\pi (0.081)^2} = 1.1118 \text{ W / m}^2$$

By using equation 7, the impedance of the brain was calculated to be 58.8 Ω, the induced electric field was calculated to be 8.08 V/m, and the SAR was determined as:

$$SAR = \frac{\sigma E^2}{2 \rho} = \frac{0.86 \times (8.1)^2}{2 \times 1040} = 0.027 \text{ W/kg}$$

The maximum SAR for all tissues in human head can be determined from the electric field distribution using the same steps for skin explained above. The results are given in Table 2.

Table 2. Calculated Electric Field and SAR With GSM-900 Phones

Tissue	Power Density (W/m ²)	Impedance Ω	Conductivity (S/m)	E V/m	Density (kg/m ³)	SAR (W/kg)
Skin	5.435	59.094	0.65	17.921	1010	0.1029
Fat	5.435	119.217	0.17	25.454	920	0.0596
Bone	5.435	82.464	0.33	21.170	1810	0.0406
Brain	1.1158	58.805	0.86	8.08	1040	0.0270

The attenuation of the RF signal due to the propagation in human brain can be expressed as the difference between the power transmitted from the cell phone and the power received by the brain tissue

$$A_{dB}(x) = 10 n \log_{10}(x_o / x) \tag{11}$$

where n is the power exponent value.

$$4.356 = 10 n \log_{10}(0.11/0.02) \Rightarrow n = 0.588$$

This means that the absorbed power decays roughly as (x)^{-0.588} at the brain tissue during the use of GSM-900 phone.

SAR for GSM-1800 Systems

The medium up link and down-link frequencies can be calculated to be 1747.5 MHz and 1842.5 MHz respectively. The maximum penetration depth during up-link, and down link can be calculated to be 23.6 mm, and 22.99 mm respectively.

GSM-1800 phones have a peak power of 1 W, hence the GSM-1800 mobile phone radiate an average power of 125 mW. Assuming that the head-antenna separation distance is 2.0 cm, the power density will be:

$$S = \frac{0.125 \times 1}{4\pi (0.02 + 0.0236)^2} = 5.232 \text{ W/m}^2$$

The skin impedance and the induced electric field can be calculated to be 61.803 Ω, and 17.983 V/m. Therefore, the SAR in head skin can be calculated

$$SAR = \frac{\sigma E^2}{2 \rho} = \frac{1.25 \times (17.982)^2}{2 \times 1010} = 0.200 \text{ W / kg}$$

The power attenuation at the brain can be calculated to be ,

$$A_{dB}(x) = 8.686 \times \frac{0.0236}{0.081} = 2.53 \text{ dB}$$

The power received at the brain surface will be equal to the difference between the transmitted power (125 mw or 20.969 dBm), and the attenuation through the penetration depth. It can be determined as

$$P_{Brain} = 20.969 - 2.53 = 18.439 \text{ dBm} = 69.8 \text{ mw}$$

The power density caused by the effective power of 69.8 mw can be determined to be

$$S = \frac{0.0698 \times 1}{4\pi (0.081)^2} = 0.846 \text{ W / m}^2$$

The impedance of the brain was calculated to be 57. 345 Ω, hence, the induced electric field can be calculated to be 6.96 V/m, and the SAR was determined as:

$$SAR = \frac{\sigma E^2}{2 \rho} = \frac{1.29 \times 48.513}{2 \times 1040} = 0.03 \text{ W / kg}$$

The maximum SAR values produced in human head tissues through the use of GSM-1800 mobile phone are given in Table 3.

The absorbed power decays at the brain tissue during the use of GSM-1800 phone can be calculated to be proportional to $(x)^{-0.34}$.

The SAR in a unit mass can be calculated for both GSM systems with the consideration of percentage representation of tissue in one kilogram of the head. This can be carried out by assumption of a uniform spherical head shape and evaluate the mass of each tissue as $(m = (4/3)\pi r^3 \cdot \rho)$ using the values of the radius (r), and the density (ρ) that are given in Table1.

Table 3. Calculated Electric Field and SAR With GSM-1800 Phones

Tissue	Power Density (W/m ²)	Impedance Ω	Conductivity (S/m)	E V/m	Density (kg/m ³)	SAR (W/kg)
Skin	5.232	61.803	1.25	17.982	1010	0.200
Fat	5.232	123.094	0.26	25.377	920	0.091
Bone	5.232	93.093	0.45	22.069	1810	0.060
Brain	0.846	57.345	1.29	6.96	1040	0.030

Heat Distribution in Human Head

The absorption of power from electromagnetic fields causes temperature rise in human tissues. The high levels of absorbed power can cause irreversible tissue damage. The relationship between the SAR and temperature can be established by using the heat equation 5, which can be written as:

$$dQ = \rho V C dT \quad (12)$$

Dividing both sides in equation 12 by $(\rho V dt)$, and rearranging terms, we can write the following relationship:

$$\frac{dQ/dt}{\rho V} = C \cdot \frac{dT}{dt} \quad (13)$$

The left side term of equation 13, represents the value of the SAR, so it can be used to determine the thermal distribution in tissues for a period of (Δt) . It can be written as^{[10][13]}.

$$\Delta T = \frac{SAR \times \Delta t}{C} \quad (13)$$

By using equation 13, with the substitution the values of SAR shown in Table 2, the temperature increase in head tissues during using GSM-900 phone can be easily calculated for a period of six minutes. It was calculated to be 0.010115 K in skin, 0.009022 K in fat, 0.009192 K in bone, and 0.002670 K in brain. The same method can be followed to determine the temperature increase in human head tissues during the usage of GSM-1800 mobile phone. It was calculated to be 0.019661 K in skin, 0.013776 K in fat, 0.013584 K in bone, and 0.002967 K in brain.

Conclusions

In this study, a theoretical approach to evaluate the specific absorption rate (SAR) distributions in human head tissues due to the use of GSM cellular phones have been presented. Penetration depth, electric field strength, SAR values, and temperature rise were calculated for human head tissues considering a model of four homogenous tissue layers human head, and single direction mobile phone antenna that is assumed to be located 2 cm away from the user head.

The results show that,

- the rate of energy absorption in head tissue depend on the ability of the tissue to conduct electricity, the relative permittivity, and the density in addition to RF source power and frequency.
- the SAR value at the skin layer is greater than other head layers for both types of GSM phones.
- it was observed that during the use of GSM-900 phones, the maximum temperature increase of 0.010115 K was estimated in skin, with a maximum SAR of 0.1029 W/kg. For GSM-1800 phones, SAR has a maximum value near the closet surface to the RF source

(skin) it was calculated as 0.20 W/kg, with a maximum increase in temperature of 0.019661 K.

- it was also noticed that the absorbed power decays roughly as $(d)^{-0.588}$ at the brain tissue during the use of GSM-900 phone, while the power absorption proportional with $(d)^{-0.34}$ during the use of GSM-1800 phone.

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