Analysis of Biological Effects of Microwave Energy and Safe Distance Calculations

تحليل التأثيرات البايولوجية لطاقة الموجات الدقيقة وحسابات المسافة الآمنة

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ABSTRACT:

Microwave energy has found wide range of applications in the fields of communications, industrial, scientific, medical, commercial and military.

In the Public applications, microwave energy may produce biological effects which may sometimes, lead to adverse health effect.

This paper introduces the relationship between microwave energy and the public health through the analysis of the effects of microwave energy on the biological systems and its hazardous effects on the health of the human body. It starts with the analysis of non-thermal and thermal effects of microwave energy on the tissue of the human body, and then it gives an analysis of the radiation limits of microwave radiation hazard and the different international standards. The safe distance from the radiating source was formulated and estimated for four scenarios, which represents different case studies (On-Beam-Axis of Continuous Transmission, On-Beam-Axis of Pulsating Transmission, Side-Lobe Transmission, and Rotating-Beam Transmission).

The results of these estimations indicate that there is a hazardous distance varies from few meters up to few hundred of meters depending on the coverage, power and type of transmission.

الخلاصة:

اصبحت لطاقة الموجات الدقيقة استخدامات واسعة في حقل الاتصالات، الصناعة، التطبيقات العلمية، الطبية، التجارية والعسكرية.

في التطبيقات العامة ، ان طاقة الموجات الدقيقة قد تنتج عنها تاثيرات بايولوجية والتي يمكن ان تؤدي الى تاثيرات صحية مختلفة.

يتناول البحث العلاقة بين طاقة الموجات الدقيقة (المايكرويف) والصحة العامة من خلال تحليل تاثير طاقة الموجات الدقيقة على الصحة والجسم البشري.

البحث يتطرق الى تحليل التاثيرات الحرارية وغير الحرارية لطاقة الموجات الدقيقة على انسجة الجسم البشري ويتطرق كدلك الى الحدود القصوى المسموح بها للاشعاعات الكهرومغناطيسية وفق القياسات العالمية.

تم اشتقاق المعادلات الرياضية واحتساب المسافات الامينة عن مصادر الاشعاع لحالات مختلفة ومصادر اشعاع مختلفة.

النتائج لهده التخمينات والحسابات تشير الى وجود مناطق تأثير يتغير من بضعة أمتار الى بضعة مئات من الامتار اعتمادا على التغطية ، القدرة ونوع الارسال.

I. Introduction:

Electromagnetic radiation in the 1 mm to 1 m wavelength range (300 MHz to 300 GHz) is referred to as microwave radiation, and is part of what is known as radiofrequency (RF) radiation. The latter covers the 0.5 MHz to 300 GHz range and is considered in the context of adverse biological effects.

Microwave engineering is a diverse and growing field and plays a very important role in our life. Microwave devices can be used to open the supermarket door for a shopper, monitor his car speed on the way home and cook the day purchase which might be eaten while the evening news is relayed at microwave frequencies via satellite, communication with

With the explosive growth of the wireless communication technology and other applications of microwave energy, there have been concerns about the safety aspects of these devices and the potential hazardous effects associated with electromagnetic (EM) radiation interaction with human tissue. The general public is very much aware that people cook food and heat meat in microwave ovens and having handheld devices near the human head and living under transmission masts (In 2000, there were some 22,000 masts in the United Kingdom alone, many sited on schools and in areas of high population density.) is certainly discomforting and a cause of serious concern [1,2,3].

II. Microwave Energy and Public Health:

As is well known, microwave energy has found wide range of applications in the fields of communications, industrial, scientific, medical, commercial and military.

In the Public applications, microwave energy may produce biological effects which may sometimes, but not always, lead to adverse health effect.

The main effect of exposure to microwave is the heating of body tissues, as the energy of the radiation is absorbed by the body.

Microwave equipments for industrial, scientific, and medical applications operate at legally prescribed frequency bands (ISM bands). Frequencies presently assigned are 915, 2450, 3300, 5800, and 10525 MHz.

Most of industrial and medical applications of microwave utilize the heating effect of microwave, the important property of microwaves, is its ability to penetrate into the material and heat it.

Prolonged exposure increases the amount of heating and could lead to an excessive increase in body temperature. Localized heating or "hot spots" can cause burns to internal tissues, and those organs with poor heat control will be at greatest risk (e.g. eyes and testes).

Recent studies suggesting a relationship between human health and cellular phones or traffic radar have not been substantiated.

It has been recognized that microwave radiation interacts with biological systems and produces complex results. Since there is a possible danger to health from such radiations, various countries have defined microwave emission and exposure standards to protect the health of persons producing, working or living near powerful generators of microwave power [4, 5, 6].

III. Biological Effects of Microwave Energy:

Microwave radiation hazards are a significant threat due to the nature and latent hazards of EM radiation.

The effect of microwave radiations on biological systems are complex and depend on many factors such as frequency of the radiation, power level, irradiation mode, dielectric constant of the tissue, exposure time, ..etc.

Most countries have set guidelines that limit the significant thermal effects of RF exposure. However, public concern has been expressed over the possibility that RF fields can cause non-thermal biological and health effects at levels below those causing thermal effects. The three terms applied to biological effects of RF exposure are *thermal*, *a-thermal*, and *non-thermal*.

These are all relative terms and therefore it is not possible to define the zone at which these cross over. They can be interpreted as follows:

a. Thermal effects occur when sufficient RF energy is deposited to cause a measurable increase in the temperature of the sample, e.g., 0.1°C.
b. A-thermal effects are those that occur when sufficient energy is deposited to cause an increase in the temperature of the sample but no changes of any significance in temperature actually occur because of temperature control in the body.
c. Non-thermal effects are those defined when the energy deposited in the sample is less than those associated with normal bodily functions and is otherwise undetectable.

In general, the biological effects of microwave radiation can be divided into two main categories [1,7]:

- Non-thermal effects,
- Thermal effects.

1. Non-Thermal Effects:

Non-thermal effects are due to conversion of microwave energy within a system in to another form on non-thermal energy (molecular resonance absorption, polarization effect, photo-chemical reactions ...etc.). These non-thermal effects are said to include headaches, sleeplessness, fatigue, memory loss, visual impairment, and morphological change in the central nervous system (CNS), disturbances in cardiac rhythm …etc.

The non-thermal effects are normally due to irradiation by low level of microwave energy i.e. about 0.1 mW/cm^2 for a long duration or repeated irradiations of short duration, and it happens at frequencies lower than 100 MHz .

2. Thermal Effects:

RF radiation can enter deep into the body and heat human organs. Thus, the depth of penetration and the absorption level of radiation in the body are relevant.

- Above 10 GHz, heating occurs mainly in the outer skin surface.
- From 1GHz to 10 GHz, the penetration is deeper and heating higher.
- From 100 MHz to about 1 GHz, penetration is even deeper and because of high absorption, deep body heating can occur.

Thermal effects are due to the integral rise of the temperature of the body and its separate parts during whole body or local irradiation. These effects depend upon the frequency, intensity of the incident radiation, type of tissues, specific area and efficiency of heat dissipation. An increase in the body temperature may cause denaturation of protein, irreversible coagulation of protein, increased permeability of cell membranes, liberation of toxins, decrease in enzyme activity and rate of change of chemical reactions,…etc.

Thermal effects of microwaves include hyperpyrexia, myocardial necrosis, hemorrhage in different organ (lungs, liver, gut and brain), degeneration of body tissues, temporary sterility, ..etc. This type of effect is mainly observed at a microwave power density of 100 mW/cm^2 and above.

IV. Radiation limits:

The sources of microwave and RF radiation are Air Traffic Control Systems, Police and Military Radar, Earth to Satellite Television Broadcast Systems, Long Distance Telephone Equipment, Medical Diathermy Devices, Cancer Diagnostic & Therapeutic (Hyperthermia) Equipment, Microwave Ovens, Industrial Applications and Microwave Generators.

Determination of exposure standards and safety levels of radio frequency (RF) radiation has been a research area of significant interest for over several decades and, in particular, since 1966 with the publication of a safety standard by the United States of America Standards Association, currently known as the American National Standards Institute (ANSI).

1. Far-Field Radiation Limits:

In far-field radiation, the ANSI standard gives the safety guidelines in terms of the maximum possible exposure of RF power density which can be summarized as follows;

- In The frequency range between 100 MHz and 100 GHz, Personal exposure should not exceed the following :
  - ¬ 10 mW/cm^2 average incident power density for exposures greater than 30 sec, or
  - ¬ 300 milli-Joules/ cm^2 for intermittent exposures between 3 and 30 sec.

  Note: The intermittent exposure criteria of 300 mJ/cm^2 per 30 sec period was established for the case of exposure to rotating or scanning type antennas and is equivalent to a continuous exposure of 10 mW/cm^2 for 30 seconds out of a 30 second time period.

- In The frequency range between 30 MHz and 100 MHz, Personal exposure should not exceed 1 mW/cm^2.

There is disagreement over exactly what levels of RF radiation are "safe," particularly with regard to low levels of exposure.

- ♣ In the Soviet Union and several Eastern and European countries (Russia, Bulgaria, Hungary, Switzerland, and China) occupational and population exposure standards are generally more restrictive than existing or proposed standards in most Western countries. The limits adopted by these countries are 0.01mW/cm^2.
- ♣ Western standards (USA, Germany, Canada, New Zeeland, Japan, and UK) generally are based on levels where hazards are known to exist, and a safety factor is then incorporated to provide sufficient protection. The limits adopted by these countries are 1mW/cm^2.

2. Near-Field Radiation Limits:

For the near field (e.g.: Cellular Phones), where the field is non-uniform, the updated ANSI/IEEE C95.1-1992 RF safety guidelines were not easy to use , the Specific Absorption Rate (SAR) can be used as an alternative instead of the incident fields or the power density.

The exposure condition, for different standards, can be given as follows:

- ¬ ANSI/IEEE Standard:
  - SAR below 0.08 W/kg as averaged over the whole body.
  - Spatial Peak SAR not exceeding 1.6 W/kg as averaged over any 1 g of tissue.
- ¬ Telecommunications Technology Council of Japan Standard:
  - Spatial Peak SAR not exceeding 8 W/kg as averaged over any 1 g of tissue.
- ¬ European Standard:
  - Spatial Peak SAR not exceeding 2 W/kg as averaged over a volume equivalent to 10 g and a period of 6 min.

Both the Japanese and European Standards are clearly less restrictive than the ANSI/IEEE one enforced in the United States.

All areas in which the energy levels exceed the above limits shall be considered hazardous. Accordingly, admittance to area where the exposure levels exceed the above limits shall be restricted and warning signs shall be posted [1,8,9,10,11].

V. Formulation and Calculation of Safe Distance:

According to the radiation limits given in ANSI/IEEE standard, the safe distance from any radiating microwave source can be calculated according to these limitations. The following scenarios represent different case studies for far field; continuous and pulsating radiation systems which will be analyzed, formulated and calculated in this section.

1. On-Beam-Axis Safe Distance for Continuous Transmission:

The power density on the beam axis at a distance d from the radiating source is given by [12]:

$$P_d = P_t G_0 / 4\pi d_s^2 \quad \ldots\ldots\ldots (1)$$

Where: P_d = power density on the beam axis in mW/cm^2.

G_0 = maximum antenna gain.

P_t = average power transmitted in mW.

d_s = distance from antenna in cm.

ϖ For Mobile phone base station of: $P_t = 15W$, $G = 20dB = 100$

ANSI Standard:

y substituting $P_d = 10\ mW/cm^2$ in the equation and solving for d_s, the minimum safe-on-axis distance for personnel may be found. Thus:

$$d_s = (P_t G_0/40\pi)^{1/2} = 0.0892\,(P_t G_0)^{1/2} \quad cm \quad (2)$$

$$d_s = 0.0892\,(15\times10^3\times100)^{1/2} = 109\ cm = 1.09\ m.$$

Western Standard:

$$P_d = 1\ mW/cm^2$$

$$d_s = (P_t G_0/4\pi)^{1/2} = 0.282\,(P_t G_0)^{1/2} \quad cm$$

$$d_s = 0.282\,(15\times10^3\times100)^{1/2} = 3.446\ m.$$

Eastern Standard:

$$P_d = 0.01\ mW/cm^2$$

$$d_s = (P_t G_0/0.04\pi)^{1/2} = 0.282\,(P_t G_0)^{1/2} \quad cm$$

$$d_s = 2.82\,(15\times10^3\times100)^{1/2} = 34.46\ m.$$

2. On-Beam-Axis Safe Distance for Pulsating Transmission:

For pulsating transmission, if the peak power output is known, the average power can be determined by multiplying the peak power by the transmission duty cycle:

$$P_{av.} = P_t\times\tau / T = P_t\times\tau\times PRF = P_t \,.\, \delta \quad \ldots\ldots\ldots (3)$$

Where: $P_{av.}$ = Power in mW.

P_t = Peak power in mW.

τ = Pulse width in μs.

T = Pulse train period in μs.

PRF= Pulse repetition frequency.

$\delta = \tau / T$ = Duty cycle.

$$\therefore d_s = [P_t G_0 \tau / (4\pi T P_d)]^{1/2} \quad \ldots\ldots\ldots (4)$$

ϖ For pulsating transmission station of: P_t =400kw, G_0 =43dB ($=2\times10^4$), τ =2 μs, T =1msec.

ANSI Standard:

$$P_d = 10\ mW/cm^2$$

$$d_s = [400\times10^6\times2\times10^4\times2\times10^{-6}/(4\pi \times 10^{-3}\times10)]^{1/2}$$

$= 11.28$ m.

Western Standard:

$P_d = 1$ mW/cm^2

$\therefore d_s = [400\times10^6\times2\times10^4\times2\times10^{-6}/(4\,\pi\,x10^{-3}x1)]^{1/2}$

$= 35.67$ m.

Eastern Standard:

$P_d = 0.01$ mW/cm^2

$d_s = [400\times10^6\times2\times10^4\times2\times10^{-6}/(4\,\pi\,x10^3x\,0.01)]^{1/2}$

$= 356.7$ m.

3. Side-Lobe-Axis Safe Distance:

The transmitting antenna for the majority of the systems was deployed at a suitable height, so it is more probable for the person on the ground to be on the side lobe axis rather than to be on the main beam axis. For this case the equation of the safe distance is modified to be in the following form:

$d_s = [P_{av.}\,G_0 / (4\,\pi\,x\,P_d\,x\,SLL)]^{1/2}$ .... (5)

Where: SLL = Side lobe level.

ϖ For the transmission system in the previous example (in V-2), if the side lobe level is -15dB:
Where: -15dB = 1/30 , $P_{av.} = 400\times10^6\times2\times10^{-6}/10^{-3} = 8x10^5$

ANSI Standard:

$P_d = 10$ mW/cm^2

$\therefore \quad d_s = [8\times10^5\times2\times10^4/(4\,\pi\,x10x30)]^{1/2}$

$= 2.06$m.

Western Standard:

$P_d = 1$ mW/cm^2

$d_s = [8\times10^5\times2\times10^4/(4\,\pi\,x1x30)]^{1/2}$

$= 6.5$m.

Eastern Standard:

$P_d = 0.01$ mW/cm^2

$d_s = [8\times10^5\times2\times10^4/(4\,\pi\,x0.01x30)]^{1/2}$

$= 65$m.

4. Rotating-Beam Safe Distance:

The exposure time to the main beam radiation, while antenna is rotating is given by:

$t = (2\theta/360^o)\times(60/N)\times(\tau/T) = \theta\tau/3NT$ .... (6)

Where: θ = 3dB beamwidth.

N = Antenna RPM.

τ = Pulse width.

T = Pulse period (T = 1/PRF).

ϖ For rotating-beam of: $P_t = 400$KW , $G_0 = 43$dB $= 2\times10^4$, $\tau = 2\mu$sec.,
$\theta = 1.5^o$, N = 2RPM, $T = 10^{-3}$ sec

ANSI Standard:

Using 300mJ/cm^2 per 30 seconds period criteria:

For One revolution, the maximum exposure energy is given by:

max. exposure energy = (300mJ/cm^2) / t

max. exposure power density = (300mJ/cm^2)/(30×t)=(300mJ/cm^2)/(30×θτ/3NT=30 NT/θτ mJ/cm^2...........(7)

By substituting Eq. (7) in Eq.(1) and solving for d_s, thus:

$P_t\,G_0/4\pi\,d_s^2 = 30NT/\theta\tau$

$\therefore d_s^2 = P_t\,G_0\,\theta\,\tau/120\pi\,NT$

$d_s = 0.0515\,(P_t\,G_0\,\theta\,\tau / NT)^{1/2}$ .... (8)

$\therefore \quad d_s = 0.0515\ [400\times10^6\times2\times10^4\times1.5\times2\times10^{-6} / (2\times10^{-3})]^{1/2}$

$= 5.64$ m.

Western Standard:

Using $30 mJ/cm^2$ per 30 seconds period criteria:

$$d_s = 0.1628 (P_t G_0 \theta \tau / NT)^{1/2}$$

$$= 17.835 \text{ m.}$$

Eastern Standard:

Using 0.3 mJ/cm^2 per 30 seconds period criteria:

$$d_s = 1.628 (P_t G_0 \theta \tau / NT)^{1/2}$$

$$= 178.35 \text{ m.}$$

VI. Results and Discussion:

Four different scenarios was formulated and calculated for three standards (ANSI, Western and Eastern). The results of this calculation are shown in Table-1. It shows that the safe distance within the ten meter for ANSI standard, and about three times that for the Western standard, while for Eastern standard it is ten times that of Western standard.

Table-1: Results of different scenarios for different standards.

Scenario	ANSI Standard	Western Standard	Eastern Standard
On-Beam-Axis Safe Distance for Continuous Transmission	1.09 m	3.446 m	34.46 m
On-Beam-Axis Safe Distance for Pulsating Transmissions	11.28 m	35.67 m	356.7 m
Side-Lobe-Axis Safe Distance	2.06 m	6.5 m	65 m
Rotating Beam Safe Distance	5.64 m	17.835 m	178.35 m

VII. Conclusions:

Microwave radiation hazards are a significant threat due to the nature and latent hazards of EM radiation. Based on present knowledge, human exposure at or below the permissible levels recommended by the IEEE and other organizations is not harmful to human health.

For safety purposes and as a regulation, areas in which RF or microwave power density in excess of 10 mW/cm^2 (as a maximum limits) is suspected or detected will be considered potentially hazardous areas.

The safe distance from the radiating source was formulated and calculated for four scenarios, which represents the practical case studies.

The results of these calculations indicate that the safe distance within the ten meter for ANSI standard, and about three times that for the Western standard, while for Eastern standard it is ten times that of Western standard. Also it shows that the required safe distance for rotating beam is less than that of the continuous transmission.

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