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Specific Absorption Rate (SAR) Distribution by the Human Eye Due to Mobile Base Station Antennas in Sri Lanka

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ABSTRACT: The remarkable growth of telecommunication industry resulted in boost in the number of cell-phone user every day. It has resulted in an increased number of base stations all over the world. In Sri Lanka, more base stations are being installed in every part of the country. Because of this, radiations are being increased at a rate which badly affects the human body. There are many adverse health effects reported due to the exposure of electromagnetic radiation. This paper presents the calculated SAR values for the human eye with respect to the measured values of the electric field strength in different cities and compared with the FCC (Federal Communication Commission) guidelines. Calculations were carried out using the Finite Difference Time Domain (FDTD) method. The penetration rate of the incident field into the eye, depending on the frequency bands, is also analysed.

KEYWORDS: specific absorption rate, electric field strength, RF exposure levels, FDTD method, Maximum Permissible Exposure.

I. INTRODUCTION

The rapid deployment of wireless communication systems such as cellular phones has caused an increased concern for the potential dangers to public health as a result of exposure to electromagnetic waves. Telecommunication towers or base stations (BS) are continuously being erected. An incredible amount of publicity generated in the mass media about ease of access to cellular phones has also caused great concern among people.

In urban areas, base stations are close to each other but operated at lower power levels than the rural areas where cells tend to be larger in size. Thus people are constantly being exposed to RF and microwave radiation from a variety of wireless communication systems. The electromagnetic waves of different power levels and different frequencies penetrate into the human body causing health risks; this is of great public concern.

The rate at which electromagnetic energy is absorbed by the tissues of the human body is usually quantified by the specific absorption rate or the SAR value. It is a quantity that depends on the tissue mass and the strength of the electromagnetic waves incident on the body as given in equation (1),

$$SAR = \frac{\sigma}{\rho}|E|^2 \qquad (1)$$

where E is the root mean square of intensity of electric field at considered point, σ and ρ are the conductivity and mass density of tissue of the human body organ under examination respectively. To avoid adverse health effects, several reputed organizations such as the Institute of Electrical and Electronic Engineers (IEEE) [1], Federal Communications Commission [2] (FCC), the National Council on Radiation Protection and Measurements (NCRP) [3] and the International Committee on Non-Ionizing Radiation Protection (ICNIRP) [4] and the National Radiation Protection Board (NRPB)[5] have adopted exposure guidelines for the general public as well as for RF workers in the course of their regular duties. According to FCC guidelines, the safety level of SAR for the general public is 1.6 W/Kg in 1 g of tissue [2]. Standards also specify the exposure level in terms of the electric field strength, E (V/m), and the power density, S (W/m^2). '*Exposure Quotient'* is a useful dimensionless quantity that expresses the exposure due to electric fields of multiple radio signals at any location as given in equation (2).

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$$Exposure\ Quotient = \sum_{i=1}^{n} \frac{S_i}{MPE_i} \quad (2)$$

where S_i is the power density and *MPE* is the maximum permissible exposure of power density at the i^{th} frequency. For safety, the '*exposure quotient'* must be less than or equal to one. The RF exposure levels due to mobile base station antennas in different parts of Sri Lanka are known [6, 7]. From several spot measurements taken from 30 major towns in the country, it has been shown that the exposure levels at these locations are below FCC guidelines [2, 7].

Several methods have been described in the literature [8] for numerical calculations of rates of electromagnetic energy absorption. One common technique is the Method Of Moments or MOM which is a frequency domain technique. The other common method is the Finite Difference Time Domain or FDTD which is a time domain method. The FDTD method first proposed by Yee [9] and later developed by many researchers [10-12] is the most often used numerical technique to solve the electromagnetic dosimetry problems [13-15]. This paper reports the SAR values calculated for the human eye, using the measured values of the electric field strength in different cities in Sri Lanka [6, 7] and they are compared with the FCC guidelines. The eye is taken for the calculations because it is one of the most sensitive organs in the human body.

A. FIELD DISTRIBUTION INSIDE THE BODY

The electric field intensity at different points that make up the organ under investigation is obtained using the FDTD method. In this method, Maxwell's equations in the differential form are solved when an incident uniform plane electromagnetic wave propagates through the body as shown in Fig.1. This is carried out in a time-stepped manner until convergence is reached.

The Maxwell's time-dependent curl equations are,

$$\nabla \wedge E = -\mu \frac{\partial H}{\partial t} \quad (3)$$

$$\nabla \wedge H = \sigma E + \varepsilon \frac{\partial E}{\partial t} \quad (4)$$

where E – Electric field strength
H – Magnetic field strength
μ - Permeability of the medium
ε - Permittivity of the medium
σ – Conductivity of the medium

The body under investigation is divided into a large number of small cubic cells of size δ_x, δ_y, and δ_z and the investigation is carried out at 'δt' time intervals until steady state is reached.

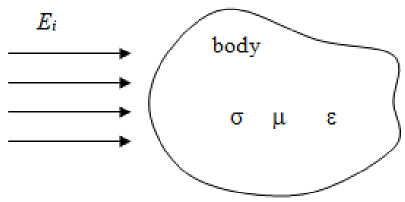

Fig.1. Uniform plane wave incident on the body

The components of *E* and *H* fields are positioned at half step intervals around a unit cell. The vector equations (3) & (4) represent a system of six scalar equations, which can be expressed in the rectangular coordinate system (x, y, z) as;

$$\frac{\partial E_x}{\partial t}=\frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y}-\frac{\partial H_y}{\partial z}-\sigma E_x\right) \quad (5)$$

$$\frac{\partial E_y}{\partial t}=\frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z}-\frac{\partial H_z}{\partial x}-\sigma E_y\right) \quad (6)$$

$$\frac{\partial E_z}{\partial t}=\frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}-\sigma E_z\right) \quad (7)$$

$$\frac{\partial H_x}{\partial t}=\frac{1}{\mu}\left(\frac{\partial E_y}{\partial z}-\frac{\partial E_z}{\partial y}\right) \quad (8)$$

$$\frac{\partial H_y}{\partial t}=\frac{1}{\mu}\left(\frac{\partial E_z}{\partial x}-\frac{\partial E_x}{\partial z}\right) \quad (9)$$

$$\frac{\partial H_z}{\partial t}=\frac{1}{\mu}\left(\frac{\partial E_x}{\partial y}-\frac{\partial E_y}{\partial x}\right) \quad (10)$$

The propagation of an incident RF wave, E_i, through the body having electrical properties, σ, μ and ε is governed by equations (5) to (10). The equations are solved using FDTD method by converting the six partial differential equations into six difference equations from which all 6 field components, E_x, E_y, E_z, H_x, H_y, H_z can be obtained. Following Yee's notation, we assume that the grid points of the body are defined using (i, j, k) with coordinates given as, $(i\delta_x, j\delta_y, k\delta_z)$, where $\delta = \delta_x = \delta_y = \delta_z$ is the size of the unit cubic cell.

For good accuracy in FDTD simulations, the cell dimensions should be less than one tenth of the wavelength in the medium when it has the highest permittivity.

i.e: $$\delta \le 0.1\lambda_m = \frac{0.1c}{f\sqrt{\varepsilon_r}} \quad (11)$$

For stability, the time step is given by,

$$\delta t = \frac{\delta}{2c} \quad (12)$$

In the FDTD method, the radiation condition is not implicit and therefore as the RF wave propagates inside the body, the scattered waves must be truncated at the edge of the field which has been simulated.The truncation used is in accordance with Bayliss and Turkel [16] and it results in an error as given by equation (13).

$$\text{Error} \approx \left[\frac{\text{c}}{2\pi f r}\right]^{2.5} \quad (13)$$

where f is the frequency of the incident signal, r is the distance from the center of the scattering site to the edge of the simulating field and c is the velocity of light in free space.

Equation (13) implies that problems using lower incident frequencies may require a larger volume surrounding the body to avoid errors due to imperfect truncation conditions. Thus the simulating field of approximately 5δ to 10δ is used for minimum truncation error [17].

II. METHODOLOGY

A. FIELD MEASUREMENTS

The measurements of field intensity were made at different locations, which represent highly populated flat urban environment, such as Colombo, Gampaha, Jaffna and Kurunegala. Further, along the coastal belt from Jaffna to Trincomalee which are urban, and densely populated areas. Kandy, Matale, Nuwara-Eliya, Badulla and Bandarawela are hilly areas at high elevation and measurements were taken from other areas of the country as well. These cities are shown in Fig.2.

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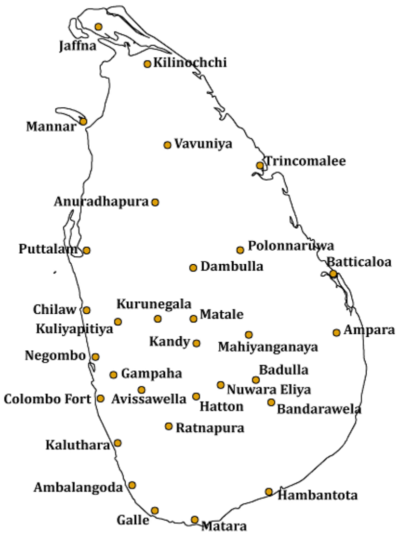

Fig. 2. Site survey map

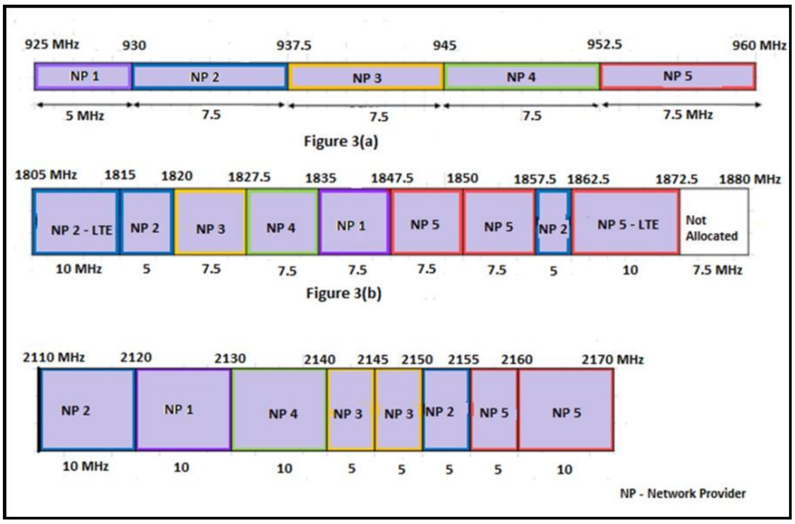

Fig.3. Frequency slots allocated for the network providers in downlink stream [Figure (a) in 900 MHz band, Figure (b) in 1800 MHz band, Figure (c) in 2 GHz]

It consists of standard Yagi-antenna (Telewave product – USA) of different frequency ranges and a spectrum analyzer (Anritsu MS 2712 E – 100 kHz to 4 GHz). Three different antennas are used to measure the signals in 900 MHz, 1800 MHz and 2 GHz bands. All measurements were taken during day time when most of the mobile phones are normally in use. For measuring the field strength in each city, a particular location was selected by considering the most populated areas such as public bus stands, railway stations, playgrounds, etc,. This location was selected by avoiding the large buildings where interferences might be caused. The antenna was mounted 1.4 m above the ground level (i.e., the approximate height of all human beings) and it was replaced according to the frequency band considered. Figure 3 shows the frequency slots allocated to the network providers in downlink stream by the TRCSL in three frequency bands [18].

For a particular network provider, operated in a certain bandwidth, the maximum received voltages were obtained with respective to the different channels operated in that frequency slot from the spectrum analyzer. This was done by rotating the antenna in 360^0 in 8 steps as 45^0 divisions. The approximate time spent for a one step is two minutes. Then finally it gives the maximum received voltages for the corresponding channels belong to the network provider. Likewise for one frequency band, all signals received belong to different network providers within the allocated frequency slots were scanned at a particular location. This was repeated for other two frequency bands as well. The total time spent for a location is approximately five hours.
For a particular city, large number of signals were considered. A typical spectrum analyzer measurement is shown in Figure 4.

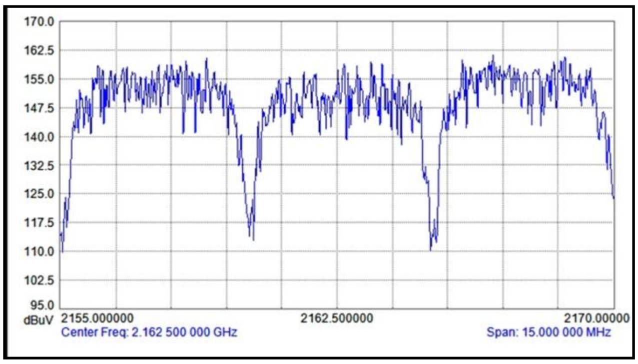

Fig.4. Spectrum analyzer measurement of 2 GHz frequency band signal at Galle

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The measured value of V_m was converted to field intensity E (dBµV/m) using Eq. (14). Then it was converted into the numerical value.

$$E\ (\text{dB}\mu\text{V/m}) = K\ (\text{dB/m}) + V_m\ (\text{dB}\mu\text{V}) + L\ (\text{dB}) \qquad (14)$$

where, K (dB/m) is the antenna factor which is the ratio of electric field strength at antenna to the voltage produced at antenna connector. The value of K is given by the antenna manufacturer. The corresponding antenna factors for the frequency bands of 900 MHz, 1800 MHz and 2 GHz are 17.7 dB/m, 24.1 dB/m and 33.4 dB/m respectively. Here L (dB) is the total system loss. The system loss was measured experimentally using a synthesized signal generator and it was observed that L = 8 dB.

The measured signal field strength is only from one direction and it is in the direction of maximum received field strength for that signal. For the **worst case** (maximum possible) situation we suppose that this field comes from three orthogonal directions. This will added an additional safety factor for the exposure level. Hence,

$$E_{Worst}^2 = E_X^2 + E_Y^2 + E_Z^2 \ ;\ E_X = E_Y = E_Z = E_{Max}$$

Therefore,

$$E_{Worst}\ (\text{V/m}) = \sqrt{3}E_{Max} \qquad (15)$$

Therefore from the measured signal, the worst case electric field strength was calculated using equation (14) and (15). For instance, measurements taken at Colombo - fort showed the highest strength for 2 GHz band and the value is 61.34 dBµV. The calculation process for that signal is as follows.

From equation (14), E_{max} = 24.1 + 61.34 + 8 = 93.44 dBµV/m
Converting dBµV/m to V/m;
E_{max} = 0.047 V/m
From equation (15), $E_{worst} = \sqrt{3} \times 0.047$
E_{worst} = 0.081 V/m

Likewise the worst case electric field strengths for a certain location, all the signals belong to different network providers with respect to three frequency bands were calculated.

B. SAR Calculation

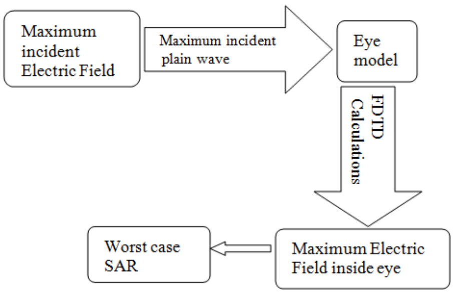

Fig.5. Block diagram of the SAR calculation Process

As the human eye is one of the most sensitive organs in human body, SAR values are evaluated for each site with respect to the human eye. The process of this work is summarized as shown in Figure 5.

For a particular, site there are a large number of signals with respect to the three frequency bands. In one frequency band, the maximum received signal was taken as the sinusoidal incident plane wave and it was allowed to interact with the eye model. According to FDTD method, the equations for E and H are solved as described using the Matlab programming.

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For evaluation of the SAR in the human eye at frequencies of 900, 1800 and 2000 MHz, the eye was divided into a number of cubic cells of size δ =1.25 mm and enclosed in to a rectangular box of size $39\delta \times 39\delta \times 39\delta$, and lattice truncation condition was applied for the FDTD method. Fig.6 shows one fourth of the eye model at this frequency. The incident plane wave is assumed to propagate in the *+y* direction. This wave is generated at the lattice plane $y = 3\delta$. At planes $y = 0$, $y = 39\delta$, $x = \frac{1}{2}\delta$, and $z = 0$, the field components E_z and H_x are determined using lattice truncation conditions.

Fig.6. The eye model and the axes

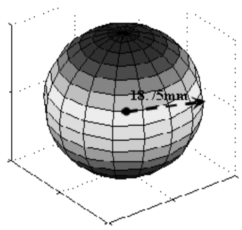

Fig.7. Eye model for SAR evaluation

The model selected for SAR evaluation in the eye is shown in Fig.7. As the EM field is being stepped through the eye model, a peak detector is constantly monitoring each point for new maximum amplitude. When steady state is reached, i.e., typically after the incident wave has been generated for approximately three periods of oscillation, these stored values of maximum amplitude are retained. Then the SAR can be calculated at each point by,

$$SAR(x, y, z) = \frac{\sigma}{2\rho} \times E_{\max}^2 (x, y, z) \qquad (14)$$

Then the highest value of these maximum amplitudes from all the cells is selected to calculate the worst case SAR_{1g} value.

$$SAR_{1g} = \frac{Maximum\ SAR\ value\,(W/kg)}{Volume\ of\ a\ cubical\ cell\,(cm^3)}$$

If the number of received signals from a particular frequency band is *N* and the maximum field strength from these signals is E^i_{max}, the maximum SAR_{1g} can be calculated letting E^i_{max} to interact with the eye model. Then the total maximum SAR_{1g} of that location due to that particular frequency band is $SAR_{1g} \times N$. Likewise the total maximum SAR_{1g} values due to the signals from other two frequency bands are calculated.

If the maximum SAR_{1g} values and number of available signals for those three bands are $SAR_{1g}1$, $SAR_{1g}2$ and $SAR_{1g}3$ and *N1*, *N2* and *N3* respectively; the maximum possible SAR_{1g} due to all considered networks of a location would be,

worst-case SAR_{1g} of the site = $(SAR_{1g}1 \times N1) + (SAR_{1g}2 \times N2) + (SAR_{1g}3 \times N3)$

Then this total worst-case SAR_{1g} is compared with the standards for general public i.e., 1.6 W/kg for compliance testing of that site. The process is repeated for each of the RF measured sites.

Frequency dependency of SAR factor in human eye model is also examined. Here the strength of 1 V/m was given to the three frequency bands of 900, 1800 and 2000 MHz bands to examine the SAR distribution in the eye model.

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III. RESULTS AND DISCUSSION

The maximum SAR values for each of the city with respect to the received signals are given in Table 1.

Table 1. Maximum SAR in the eye of the general public.

Cities	Maximum received signal voltage in dBµV			$SAR_{1g} \times 10^{-5}/Wkg^{-1}$ for human eye			
	900 MHz	1800 MHz	2 GHz	900 MHz	1800 MHz	2 GHz	Total
Ambalangoda	54.17	45.82	50.67	21.67	345.32	461.19	828.18
Ampara	60.70	39.02	45.15	341.06	151.21	855.72	1347.99
Anuradhapuraya	54.46	44.97	52.01	97.51	579.67	229.47	906.65
Awissawella	47.30	34.40	45.07	4.71	46.88	37.41	88.99
Baddulla	60.76	43.95	53.75	507.85	100.32	387.72	995.89
Bandarawela	56.32	45.44	53.68	56.09	123.98	647.07	827.14
Batticaloa	41.91	44.93	52.88	4.60	551.94	1524.3	2080.84
Chilaw	58.16	47.10	50.57	211.31	4520.52	35.91	4767.74
Colombo Fort	60.17	54.13	61.34	40.65	174.70	1149.54	1364.89
Dambulla	45.78	38.93	51.33	15.23	27.06	353.07	395.36
Galle	53.87	43.92	52.82	50.40	14562.44	299.16	14912.00
Gampaha	58.89	59.78	58.70	1966.13	1855.86	2458.89	6280.87
Hambantota	53.38	49.70	51.14	233.47	239.44	550.29	1023.20
Jaffna	42.67	45.02	46.06	2.03	59.95	125.37	187.35
Kalutara	51.67	48.14	54.12	79.71	2744.70	507.99	3332.40
Kandy	67.21	61.71	54.67	1523.95	2987.07	1551.81	6062.83
Kilinochchiya	51.87	44.98	54.22	3.19	5017.26	6526.5	11546.94
Kurunegala	64.91	55.86	56.74	716.38	1339.54	7642.8	9698.72
Mahiyanganaya	47.39	31.13	43.58	1.33	30.62	38.49	70.44
Mannar	57.99	51.02	56.75	406.00	2261.98	951.84	3619.82
Matara	52.44	42.88	44.59	3.41	21.91	31.29	56.61
Negombo	64.59	46.04	51.13	113.12	298.51	367.23	778.86
Nuwara Eliya	58.97	42.68	52.68	25.62	415.08	471.84	912.54
Polonnaruwa	35.36	46.13	53.96	0.14	2000.67	356.22	2357.03
Puttalum	53.29	37.58	41.32	79.24	933.19	225.84	1238.27
Ratnapura	47.62	43.39	54.23	4.48	67.27	3983.4	4055.15
Trincomalee	56.34	37.35	52.85	347.04	7382.32	426.45	8155.82
Vavuniya	62.33	54.75	56.03	143.94	627.22	12193.5	12964.66
Matale	62.06	48.66	52.51	184.73	2162.73	277.53	2624.99
Hatton	47.44	38.21	47.73	18.94	20.49	97.83	137.25

As seen in the results, the total SAR_{1g} values in each city are well below the safe limits. The highest SAR value of 0.1491 W/kg was observed from Galle; measurements were made at a place which is close to the main bus stand. The highest contribution to RF absorption by the human eye at this site is due to 2 GHz band. However the exposure level is approximately eleven times lower than the permissible levels.

The other significant point is most populated areas such as Colombo Fort and Jaffna, the SAR level is more than 100 times below the limits. That is due to the installation of micro cellular base station antennas by replacing macro cellular base station antennas. Because of this they can reduce the coverage area thereby reducing the transmitting power.
For the hilly areas such as Badulla, Bandarawela, Nuwara Eliya and Hatton most of the base station antennas are mounted on top of the hills and comparatively higher power levels are transmitted to cover the town limits.

Results predict that when the frequency of the incident signal is increased, SAR value also increased. Also the position of the highest SAR gets shifted towards the center of the eye as the frequency increases. This implies that when the eye is exposed to higher frequencies, “hot spots” are created towards its center as seen in following figure 8.

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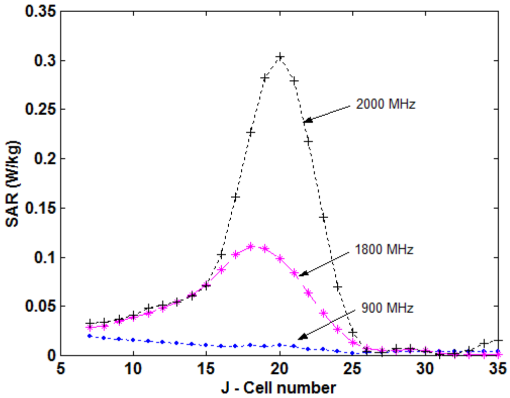

Fig.8. SAR distribution of eye with frequency

There are no such field measurements or SAR calculations reported from neighbouring countries for comparison. Up to now there are very few results reported from other parts of the world [19] and they include only emissions from one or two transmitters and as such the estimated SAR values are very low.

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