# Correlation of Specific Absorption Rates in the Human Head due to Multiple Independent Sources


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*Abstract*— **This paper examines how the SAR in the head is combined when exposed to the field due to multiple sources. The mechanisms when the sources have the same and different frequencies are discussed. FDTD simulation results are included when an anatomically realistic head is excited by various sources including: plane waves, vertically and horizontally orientated dipoles positioned in front and by the side of the head. Results are presented for two sources over the frequency range 0.5 to 4GHz.**


## I. INTRODUCTION

Consumers demand that new communications applications are as portable and user friendly as possible. Therefore, more and more, wires are being replaced with wireless radio frequency links. This in turn means that humans are exposed to more electromagnetic energy, thus increasing concerns of possible adverse health effects. RF transmitting products must comply with the specific absorption rate (SAR) standards. However, if the person is exposed to multiple sources simultaneously, the SAR and the induced heating effects will increase but it is not obvious how the fields from different sources will combine. This paper considers the effect on SAR of multiple independent sources. Situations where this is relevant include: a) a modern mobile phone/PDA that uses multiple systems at the same time, e.g. Bluetooth and GSM, Wi-Fi and GSM, etc b) commuters on a busy train with several people using their phones at once and c) using a phone with a Wi-Fi source in the same room/vehicle.

Previously, the authors have considered the SAR in the head when the user is using a PDA and is wearing metallic jewellery [1] [2] and spectacles [3]. Please see [1]-[4] for a more complete review of SAR and bioelectromagnetics. Metallic objects of a resonant length were found to increase the SAR in the head by a factor of five; the objects were passive and re-radiated the energy from the original source at the original frequency. The addition of jewellery complicates the scenario but is fundamentally different from two independent sources. The authors have also examined the mechanisms of near-field interaction between dipoles and mobile phone models and homogeneous body models [5] [6]. Studies have been conducted in the past on exposure to multiple mobile phone sources inside enclosed spaces such as trains and elevators [7] [8] but studies on multiple radiation sources from a single device are limited.

## II. ANALYSIS OF SAR DUE TO MULTIPLE SOURCES

With regard to multiple sources, two possibilities are discussed hereafter: a) the sources are uncorrelated; b) are correlated. For the sake of simplicity, we will consider the case of sources fed with CW signals with a) different frequencies b) the same frequency.

### A. *Different Frequencies*

If the frequencies are different, the RMS value of the total electric field $E_{tot}$, at each point in space can be simply expressed as a sum of the RMS values of the fields due to each source taken separately. The combined local SAR is then found by calculating the root mean square of $E_{tot}^2$.

$$SAR = \frac{\sigma E_{rms}{}^{2}}{\rho} = \frac{\sigma}{N\rho}\sum_{1}^{N} E_{tot}^{2} \quad (1)$$

Where $E_{rms}$ is the root mean square of the electric field, ρ is the density of the material in kg/m$^3$, σ is the conductivity in S/m and *N* is the number of points in a *period* of the combined electric field. It is well known and can be easily verified by numerical means that if the frequencies are different, the total local combined SAR of three frequencies at a point is always equal to $SAR_{f1}+SAR_{f2}+SAR_{f3}$.

The combined mass-averaged SAR from two sources will vary in relation to the location of the maximum mass averaged SAR cubes in the head at each frequency. Note, mass-averaged SAR refers to either 1g SAR or 10g SAR cubes which will be labelled in this document by 1g(10g) SAR.

The maximum combined 1g (10g) SAR occurs when the two independent sources cause a maximum in the same location in the head and will equal 1g (10g) $SAR_{f1}$+ 1g (10g) $SAR_{f2}$ for two frequencies. The minimum 1g (10g) SAR is the maximum value of ($SAR_{f1}$ or $SAR_{f2}$). Equation 2 shows the possible range of the 1g (10g) SAR. This means that if the two frequencies are different, the 1g or 10g SAR can never be decreased compared to the case with just one source. It is noteworthy that the SAR averaged over the whole head will always be $SAR_{f1}+SAR_{f2}$ and therefore the total heating in the head will increase with multiple sources.

$$1g\ (10g)\ \mathrm{Max}(SAR_{f1}\ ;\ SAR_{f2}) \le 1g\ (10g)\ SAR_{combined} \le 1g\ (10g)\ SAR_{f1} + 1g\ (10g)\ SAR_{f2} \quad (2)$$

*B. Identical Frequencies*

If the frequencies of multiple sources are identical then there will be no alteration in relative phase. Theoretically, if the two sources were exactly out of phase and co-located, then the electric fields could destructively combine and there would be zero electric field. Conversely, if they were in phase, then there would be constructive interference and $E_{tot\_rms}= E_{f1\_rms}+E_{f2\_rms}$. Note, this produces a larger SAR at a single point than if the frequencies were different. In practice, SAR is measured over 1g or 10g cubes and therefore not all parts of the volume will have the same phase difference assuming the two sources are not at an identical point in space. Note, when the two frequencies are $\pi/2$ out of phase, they will be in phase quadrature and at that point the total SAR will be the sum of the SAR from each source. If the sources are in different locations, then the relative phase of the two signals will vary throughout a 1g (10g) cube. The wavelength in the head ($\varepsilon_r$=40) at 1800MHz is 26mm and is of the order of size of a 1g or 10g cube. Therefore, the relative phase of two sources in a 1g (10g) cube will be evenly distributed and will on average be approximately in phase quadrature. In summary: if multiple sources have the same frequency, the local SAR is more complex but the 1g (10g) SAR is likely to approximate the sum of the volume averaged SAR at the same location from each source.

## III. Description of Simulations

Description of the FDTD code used in this work can be found in [3, 9]. Perfectly Matched Layers (PML) with geometric grading are used as absorbing boundary conditions to terminate the grid. The PML is eight cells thick and is positioned at least twelve cells from the head. The Yee cell size used throughout this paper is 2mm. The lowest number of cells per wavelength was always greater than 4.5, and reasonable results have been obtained with only four [4]. The time step was 3.336ps. The simulations were run for at least ten cycles and until stability was achieved (≥ 1660 time steps). Plane wave sources and dipole sources in front of the face have been considered. An anatomically realistic 3D adult male head with 25 tissue types provided by Brooks Air Force (www.brooks.af.mil/), based on The Visible Human Project has been used in this paper. The head data has a 2mm resolution.

## IV. Results

The results in this paper show how the SAR in the head changes when excited by two different frequencies. It is worth noting that the results were not included when the frequencies were identical as the results are dependent on the relative phase of the sources. The results show the combined 1g SAR values and describe how they compare to the range of possible values – see equation 2. Note, the SAR was calculated at each frequency individually and the SAR at each point in the head was stored.

*A. Vertically Polarised Plane Waves*

This section considers the case when the plane waves have the same polarisation and the same direction of propagation. Plane waves were vertically polarised ($E_z$, $H_y$) and travelling in the X direction (towards the face) with a power density of 50W/m$^2$ covering the frequency range from 0.5 to 4.0GHz. Figure 1 shows the combined 1g SAR from two plane waves at different frequencies. The maximum 1g SAR occurs at 1.7GHz. The largest combined 1g SAR occurs when the second plane wave has a frequency close to 1.7GHz. The highest combined 1g SAR occurs when the following two conditions are met; 1) a large 1g SAR from each plane wave individually and 2) when the areas of high SAR due to the two plane waves occur at similar locations in the head. Tables I and II show that the combined 1g and 10g SAR values are close to the upper limit of the possible range (see equation 2) and therefore shows that the maximum 1g and 10g SAR values occur at similar locations in the head as the frequency changes.

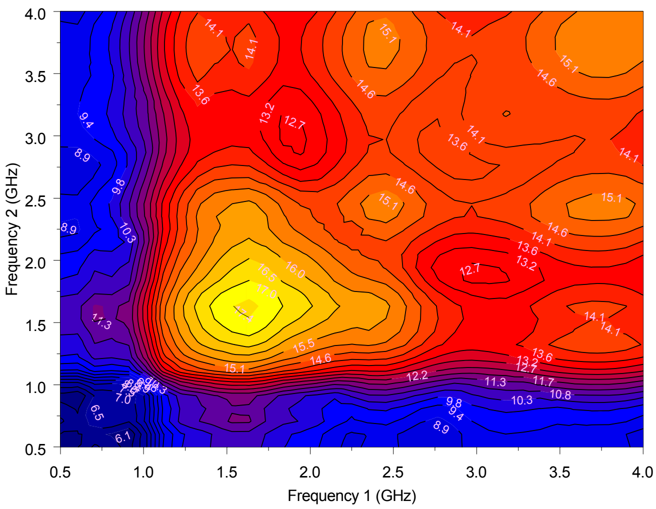


**Figure 1. Combined 1g SAR from two vertically polarised plane wave sources**.

*B. Horizontal and Vertical Dipole Sources in Front of the Face*

In this section the head was excited by two dipoles. The dipoles are fed at their centre with a sinusoidal CW source and all results are normalized to 1W input power. Note, the length of the dipoles changed with frequency (0.7 to 4.0GHz) to match half a wavelength. The centre of the vertical dipole (Z axis) is positioned 8cm in front of the tip of the nose and level with the eyes, see Figure 2. The centre of the horizontal dipole (Y axis) was placed 4cm above this point. The figure also shows the location of the centres of the maximum 1g SAR cubes with the two orientations of dipole individually. With the vertically orientated (Z) dipole, the maximum 1g SAR occurs at the bridge of the nose (from 0.7 to 1GHz and 2.5 to 3.5GHz), in the centre of the nose (from 1.1 to 2.4GHz and at the tip of the nose (from 3.6 to 4GHz). However, with the horizontally orientated (Y) dipole, the maximum 1g SAR is more diverse in location, moving from the nose (0.7 to 0.8GHz, 1.3 to 2GHz and 3 to 4GHz) to the forehead (0.9 to 1.2GHz and 2.1 to 2.9GHz).

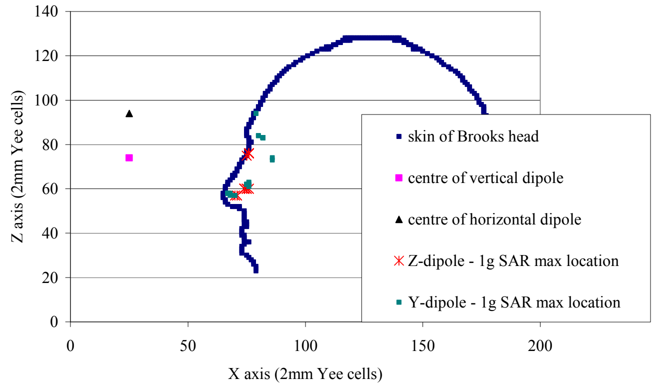


**Figure 2. The location of the maximum 1g SAR in the head with Y and Z dipoles.**

Figure 3 and Figure 4 show the combined 1g SAR with different frequencies of excitation from the vertical and horizontal dipoles respectively. The figures are symmetrical along a diagonal line. The dipoles are different lengths and are centred at the same location. This is not intended to correspond to any realistic exposure situation but indicates how the SAR distributions combine with two dipoles of the same orientation. Note, that with the horizontal dipoles, the 1g SAR generally increases with frequency.

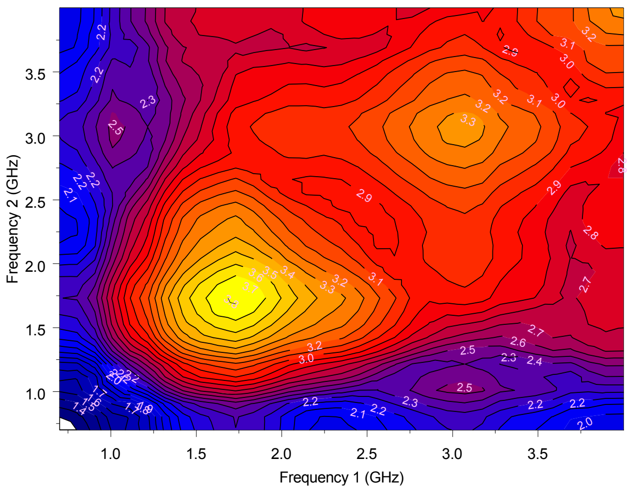


**Figure 3. Combined 1g SAR with two vertical dipoles**

Tables I and II show how the combined 1g and 10g SAR compare to the range of possible values: (0% = Max of $SAR_{f1}$ or $SAR_{f2}$ and 100% = $SAR_{f1}+SAR_{f2}$). Table I shows that generally the combined SAR with the vertical dipole is much closer to the maximum value (84.3% on average) compared to 68.5% with the horizontal dipole and also that the probability of the SAR increasing by more than 50% was much larger. This is because the location of high SAR is more varied as a function of frequency with the horizontal dipole than with the vertical dipole, see Figure 2. Table II shows that the 10g SAR values are close to the maximum value (92% on average), when the head is excited by two dipoles of different frequencies but the same orientation.

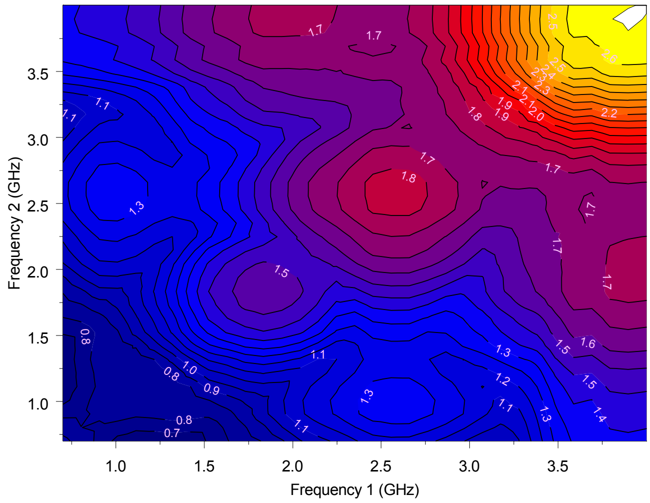


**Figure 4. Combined 1g SAR with two horizontal dipoles**

Figure 5 shows the combined 1g SAR from a horizontal and a vertical dipole. Note, that the second dipole was not present in the simulations as a passive element. This orientation could represent a PDA with multiple functionality. The largest combined 1g SAR occurs when the horizontal dipole is excited at 3.9GHz and the vertical dipole is at 4GHz (and not 1.7GHz where the maximum SAR with the Z dipole occurred). This emphasizes that the combined 1g SAR from two sources is a function of the location of the maximum at each frequency and not just the maximum SAR at each frequency.

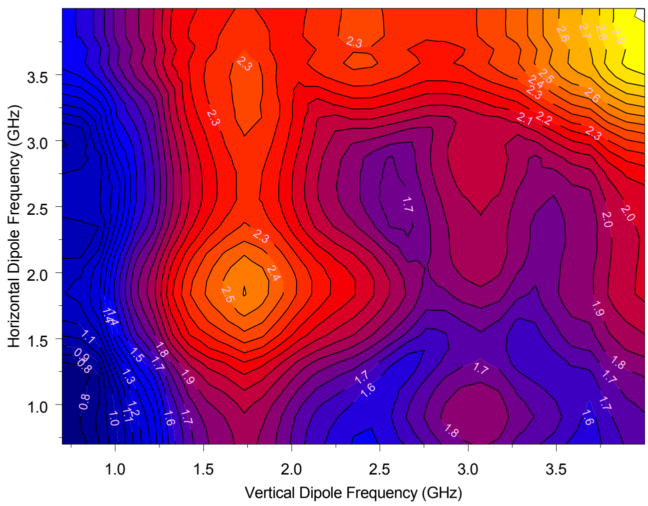


**Figure 5. Combined 1g SAR with one horizontal dipole and one vertical dipole in front of the face.**

The correlation of maximum SAR locations is lower with both orientations of dipole than when the orientation of the two dipoles was the same, see Tables I and II. The combined 1g and 10g SAR values were on average approximately 50% along the range of possible SAR values. Note, that in 111 out of 1122 combinations, the 1g SAR was increased by less than 20% when the second source was added.

TABLE I. NUMBER OF FREQUENCY COMBINATIONS THAT OCCUR WITHIN 20% SECTIONS OF THE RANGE OF MINIMUM TO MAXIMUM 1G SAR VALUES

| | $E_z$ Plane waves | Z dipoles | Y dipoles | Y & Z dipoles |
|---|---|---|---|---|
| 0-20% | 0 *(0%)* | 0 *(0%)* | 60 *(5%)* | 111*(10%)* |
| 20-40% | 8 *(0.6%)* | 0 *(0%)* | 62 *(6%)* | 329*(29%)* |
| 40-60% | 88 *(7%)* | 98 *(9%)* | 300*(27%)* | 416*(37%)* |
| 60-80% | 364*(29%)* | 322*(29%)* | 264*(24%)* | 166*(15%)* |
| 80-100% | 800*(64%)* | 702*(63%)* | 436*(39%)* | 100 *(9%)* |
| **Minimum** | **36.5%** | **43.9%** | **8.6%** | **3.8%** |
| **Average** | **83.4%** | **84.3%** | **68.5%** | **46.6%** |

TABLE II. NUMBER OF FREQUENCY COMBINATIONS THAT OCCUR WITHIN 20% SECTIONS OF THE RANGE OF MINIMUM TO MAXIMUM 10G SAR VALUES

| | $E_z$ Plane waves | Z dipoles | Y dipoles | Y & Z dipoles |
|---|---|---|---|---|
| 0-20% | 0 *(0%)* | 0 *(0%)* | 0 *(0%)* | 6 *(0.5%)* |
| 20-40% | 0 *(0%)* | 0 *(0%)* | 2 *(0.2%)* | 207*(18%)* |
| 40-60% | 40 *(3%)* | 0 *(0%)* | 16 *(1%)* | 594*(53%)* |
| 60-80% | 468*(37%)* | 136*(12%)* | 154*(14%)* | 187*(17%)* |
| 80-100% | 752*(60%)* | 986*(88%)* | 950*(85%)* | 128*(11%)* |
| **Minimum** | **52.3%** | **72.3%** | **35.8%** | **19.0%** |
| **Average** | **84.4%** | **92.7%** | **92.1%** | **54.2%** |

### *C. Vertical Dipoles in Front of the Face and by the Side of the Head*

In this section, the head has been excited by two vertical dipoles; one was positioned in front of the face as in Figure 2 and a second vertically orientated source centred 8cm to the side of the head at cell; X=124, Z =74 (see Figure 2). When the SAR was combined from two vertically orientated dipoles by the side of the head, the average combined 1g SAR was 76.5% of the possible range, and 81.5% of the possible range for the average 10g SAR. Therefore, the maximum SAR location is more varied when two vertical dipoles are by the side of the head as opposed to in front of the head.

When the SAR was combined from the dipole in front of the head with the dipole by the side of the head, there was very little enhancement in the combined SAR over the range 0.7 to 4GHz. The combined 1g SAR increased by 1.2% on averaged compared to the case when either dipole was excited individually. The largest effect was a 5% increase over the spectra considered. The combined 10g SAR increased by 1.6% on average and the largest increase was 8%. These results show that the SAR at the front of the head is small when due to a dipole by the side of the head and vice-versa.

## V. CONCLUSIONS

This paper has investigated the effect on the SAR in the head from multiple sources. It can be numerically shown that if the frequencies are different, the local SAR at each point in the head equals the sum of the SAR from the individual sources. However, the situation is more complicated when the frequencies are the same. Neverthelessthe combined SAR is expected to approximate the case where the frequencies are different as the phase difference changes over a mass averaged SAR volume. The mass-averaged (1g or 10g) SAR is a function of the correlation of the maximum SAR locations from each source. For uncorrelated sources originated from the same direction, the combined SAR generally approached the maximum value ($SAR_{f1}$ + $SAR_{f2}$). This was reduced if the sources had different polarisations. However, when two sources were located on different sides of the head, there was negligible increase in the combined SAR over the spectra considered. However, the total power absorbed in the head will equal the sum of the power absorbed from the individual sources. This may have physiological implications as the body may find it harder to dissipate more energy

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