Human Head Exposure to Bluetooth Frequency - Electromagnetic Dosimetry

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***Abstract*—Bluetooth headsets are extensively used in everyday life, and although these are generally deemed safe for human health, new studies suggest that there could be potential health hazards of long-term exposure. This paper reports on a computational study of the headset's electromagnetic field influence on the IEEE Specific Anthropomorphic Mannequin (SAM) head model where the Bluetooth antenna is placed at two different distances from the head's profile. The obtained near field values are used to calculate the specific absorption rate (SAR) into the head tissue around the peak electric field value and compared to the current electromagnetic dosimetry guidelines.**

***Index Terms*—Computational dosimetry, electromagnetic dosimetry model, thermal dosimetry model, human exposure to EMF, Bluetooth headset, SAR evaluation**

I. INTRODUCTION

BLUETOOTH technology enables low-power wireless communication, at frequencies in the 2.4 - 2.4835 GHz range, between different devices which nowadays include everything from medical devices, personal computers, printers, smartphones and headsets/earbuds. Devices utilizing this technology are classified in one of the following four power classes consisting of high (100 mW), med-high (10 mW) and medium (2.5 mW) and low (1 mW) [1]. The higher the power class, the higher the operating range of the device. Although Bluetooth devices emit non-ionizing radiation in the radiofrequency (RF) spectrum, which is not hazardous below certain power thresholds, the increasing number of devices operating in the same frequency range in the modern-day environment, the cumulative exposure may sometimes exceed those limits. Given their extensive usage in the general population, the Bluetooth headsets, operating in the med-high range, are of particular interest in terms of potential health risks due to long-term exposure.

When classifying the human body-electromagnetic field interaction there are several factors to consider such as frequency, field intensity, exposure interval, field polarization and the dielectric properties of the absorbing material (i.e. the specific tissue) [2]. The effects of these interactions are divided into two groups: principally the thermal effects and more complicated non-thermal effects which refer to biochemical and bioelectrical consequences on the more subtle tissue structure.

The measure used to quantify the thermal effects is the specific absorption rate (SAR) usually averaged over 1 or 10 g of exposed tissue [2], [3].

The influence of the Bluetooth headset on human health has been investigated to some extent from both epidemiological [4], [5], [6] and electromagnetic dosimetry [7], [8] point of view by different authors. Mandalà et al. investigated if Bluetooth devices inducted significant change in cochlear nerve compound action potential (CNAP), a potential generated by a group of neurons in response to an acoustic stimulus [5]. They found that there were no short-term effects of the Bluetooth electromagnetic fields (EMFs) to CNAPs, which is contrary to the EMFs generated by mobile phones (i.e. GSM frequencies of 900 and 1800 MHz) [9]. Balachandran et al. explored weather Bluetooth headset usage causes hearing consequences, but found that there was no statistically significant changes in hearing, regardless if the headset was put at full power (10 minute interval) or at standby mode (6 hour interval) [4]. Gravina et al. performed a computational study of the Bluetooth headset's influence on the human head model using an in-house FDTD code [7]. The headset was modeled by a 2.45 GHz folded dipole with the incident power of 10 mW. Their analysis showed that most of the radiated power is absorbed by less sensitive tissues such as skin, bone and cartilage, while <1 % of the power is absorbed by the brain tissue. However, ~5% of the power was absorbed by head glands, leaving space for further investigations. More recently, Zhou et al. performed an epidemiological study by analyzing data collected from 600 different volunteers, some healthy and some who developed thyroid nodules [6]. To do this, they used Propensity Score Matching (PSM) and the XGBOOST model, supplemented by SHAP analysis, to assess the risk of developing thyroid nodules in case of prolonged Bluetooth headset usage and discovered significant correlation between the two. Cvetković et al. performed a computational study of the EM-thermal dosimetry by exposing two simplified human head models (i.e. the human head was represented with a sphere) to plane EM wave [8]. The obtained induced electric field values and corresponding point-wise SAR values did not exceed the IEEE [10] and ICNIRP [11] exposure guidelines.

However, none of the presented literature offers a systematic overview of Bluetooth's near field influence on the standardized human head model in controlled experimental or computational environments. Therefore, in the scope of this a computational study of the Bluetooth earbud's radiation into the IEEE Specific Anthropomorphic Mannequin (SAM) head model was performed. The results are presented in the form of SAR and compared with the current RF dosimetry guidelines.

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II. Numerical Modeling

A. Head Model

Computational study was performed in FEKO 2024 (Altair Engineering Inc., Troy, Michigan) software for high-frequency electromagnetic simulations. It offers a wide range of numerical techniques and hybridizations for a variety of electromagnetic problems: FEM, MoM, MLFMM, Finite Difference Time Domain (FDTD), Physical Optics (PO), Ray Launching Geometrical Optics (RL-GO), Unified Diffraction Theory (UTD), and solver for wave propagation and radio network analysis (WinProp) [12].

The simulation model consisted of two parts, the Bluetooth earbud modeled as a f=2.45 GHz PEC dipole (10 mm length) and SAM head model, designed according to the 90th - percentile anthropometric data corresponding to the adult male head, as reported by the US Army [13] and obtained from the Knowledge Base on Altair Community .The head model is homogeneous with relative permittivity ε_r = 39.2 and conductivity σ= 1.8, 1.8 S/m at 2.45 GHz and density ρ=1000 kg/m^3, according to head tissue properties recommended in IEEE Std 1528-2013 [14]. The antenna was placed at distances of 10 and 15 mm from the head's profile, approximately at the anatomical ear position to mimic the exposure scenario from [15]. The model is shown in FEKO software in Fig.1.

The total radiated power of the antenna was set to 12.5 dBm (the maximum output power from [15]), with no mismatch, representing the worst case scenario (neglecting the radiation efficiency and mismatch of the realistic antenna near human head). This output is larger than transmitted power from some other types of earbud antennas which are usually lower (Bluetooth LE and Bluetooth EDR use max output power of 10 dBm).

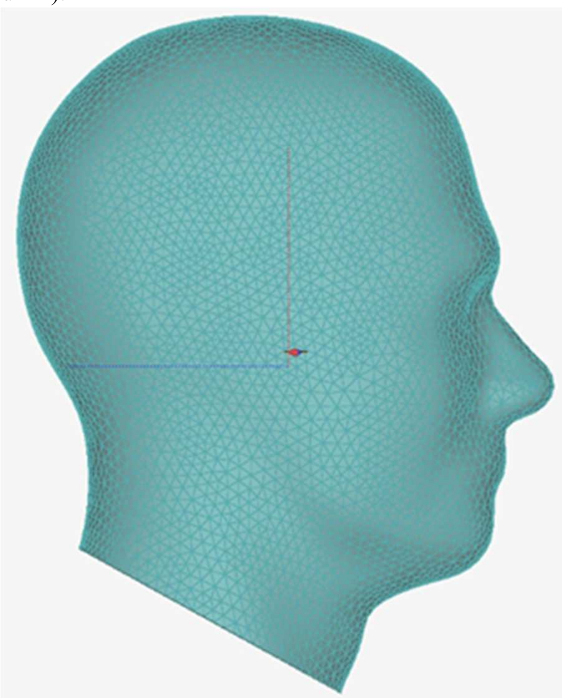

Fig. 1 Human head model exposed to dipole antenna at 2.45 GHz in FEKO simulation software.

The solution method was Method of Moments (MoM) (for dipole) in combination with Finite Element Method (FEM) for head model (103 056 tetrahedra).

B. SAR computation

The SAR, measure used for quantifying the electromagnetic dosimetry at frequencies below 6 GHz, is defined with the following expression:

$$SAR = \frac{\sigma}{2\rho}\left|\vec{E}\right|^2, \tag{1}$$

where $\left|\vec{E}\right|$ is the peak value of the electric field at a specific coordinate in the model.

The SAR value is usually expressed in terms of averaged value over 1 g or 10 g of tissue:

$$SAR_{av} = \frac{1}{V}\int_V SARdV, \tag{2}$$

where V is the tissue volume encompassing either 1 or 10 g if tissue.

In some cases, the eq. (1) is also used to calculate pointwise or differential value of the SAR like in [8].

For the purposes of this study, the SAR averaged over 1 and 10 g was calculated using the functionality offered by the FEKO software around specific coordinates within the head model.

III. Numerical Results and discussion

The human head model was exposed to the EMF radiated from a simple 2.45 GHz dipole antenna placed at 10 and 15 mm from the head's surface. The head model was placed in the center of the coordinate system, and the antennas position was at coordinates x=-3 mm, y=76.5+d (d=10 or 15 mm) and z= 6 mm, as shown in Fig. 2. The induced electric field magnitude and point-wise SAR are plotted in fig. 3 for both antenna distances. The subfigure (a) shows point-wise SAR results in the YZ plane, at the x=-3 mm position, as this plane is perpendicular to the antenna feed position. In both cases, very high SAR values were obtained right below the head model's surface. The subfigure (b) shows the electric field magnitude along the y axis at position x=-3 and z= 6 mm. It can be observed that the electric field's magnitude decreases exponentially after entering the head tissue.

Afterwards, for both simulation cases, the position of the maximum electric field was found as it is commonly used as the reference point around which 1 and 10 g SAR values are calculated [15]. However, regardless of the antenna's distance from the head's surface, the maximum field magnitude was obtained on the very surface of the model, more specifically in the case of d=10 mm, the maximum of 74.89 V/m was reached at x=-6.98047, y=77.1139, z=7.49393 mm. In the case of d=15 mm, the maximum of 44.22 V/m was reached at x=-0.414664, y=76.7052, z=8.35908. In both cases, the points of maximum were slightly shifted from the antenna's feed.

The FEKO software SAR evaluation feature requires a specific coordinate as a reference/center around which it creates a cube of

TABLE I
SAR VALUES CALCULATED AROUND DIFFERENT POINTS BELOW THE MAXIMUM SURFACE VALUE

Dist.	Points	SAR1g [W/kg]	SAR10g [W/kg]
10 mm	-6.98047, 72.1139 ,7.49393	1.78	/
	-6.98047, 67.1139 ,7.49393	0.90	0.69
	-6.98047, 62.1139 ,7.49393	0.45	0.42
	-6.98047, 57.1139 ,7.49393	0.22	0.22
15 mm	-0.414664, 71.7052, 8.35908	0.72	/
	-0.414664, 66.7052, 8.35908	0.38	0.31
	-0.414664, 61.7052, 8.35908	0.20	0.20
	-0.414664, 56.7052, 8.35908	0.10	0.11

1 or 10 g of tissue with accordingly adjusted cube edge lengths. Considering the obtained maximums were on the head's surface, and hence the SAR calculation would partially consider air, four reference points, directly below the main one were selected, in the y direction (inside the head), each separated by 5 mm from the previous one. The obtained values are tabulated in Table I. The SAR averaged over 10 g of tissue is not reported for the first points in the table because the considered cube exceeded the boundaries of the head model. Firstly, as expected, the obtained SAR values are lower when the antenna is placed further away from the head's surface. Generally, the obtained values, regardless of the considered point, do not exceed either the ICNIRP or IEEE basic restrictions for electromagnetic exposure in the 100 kHz – 6 GHz range which is 2 W/kg for general public [10], [11].

Besides the established guidelines, the results were compared to the experimental results of the report on Bluetooth earbud mimicked by the simulation [15]. A significantly lower SAR values, averaged over 1 and 10 g are reported (SAR_{1g} =0.071 W/kg and SAR_{10g} =0.035 W/kg). These differences can be attributed to differences between the measurements and simulated scenario: the simulation study used PEC dipole antenna with radiated power od 12.5 dBm (with no mismatch) which can be considered as worst case exposure scenario and in practice electrically small antennas have lower radiation efficiency and mismatch in the near field, the human head phantom has a shell thickness with different properties than simulating liquid inside.

Additionally, the volume averaged SAR for the entire head model was 0.0024 W/kg and 0.00154 W/kg, which also does not exceed the current exposure guidelines.

IV. CONCLUSION

This paper presented the results of dosimetric computational study where a homogenous IEEE SAM head model was exposed to 2.45 GHz radiation from a simplified dipole placed at d=10 and d=15 mm from the head's surface. The obtained electric field values induced into the head tissue are very high, especially if compared to those recently reported by Cvetković et al [8]. However, this can be attributed to the fact that this study analyzed the near field result and the antenna was simulated as a PEC antenna with a 12.5 dBm output which is the worst case scenario Furthermore, it was previously noted that the usage of homogenous head model for the frequency range 1.5 -2.5 GHz could potentially overstate the exposure [3].

Average SAR values for 1 and 10 g of tissue were calculated around four different points in the tissue, selected so that they are positioned directly below the peak electric field which occurred at the head's surface. The obtained SAR at all locations was within the prescribed basic restrictions for electromagnetic exposure for general public [10], [11]. However, they exceeded the measurement results obtained from a physical setup which this computational study mimicked [15]. Nonetheless, the discrepancy between simulated and measured results can be explained by different inconsistencies between the setups such as lower radiation efficiency of the physical antenna and the fact that the actual phantom has a shell of different dielectric properties in respect to those of the interior liquid representing homogenous head tissue.

A successive step to this research would be performing computational studies on more complex head models with additional tissues and with anatomically accurate ear structure and realistic antenna configuration and position with respect to the head.

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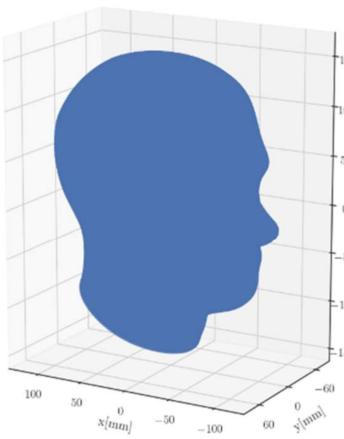

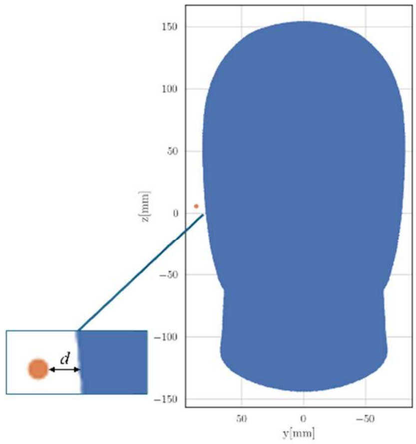

Fig. 2 (a) Illustration of the SAM head model positioning in the coordinate system; (b) Illustration of the antenna's placement (indicated by the orange point) in respect to the head model's surface.

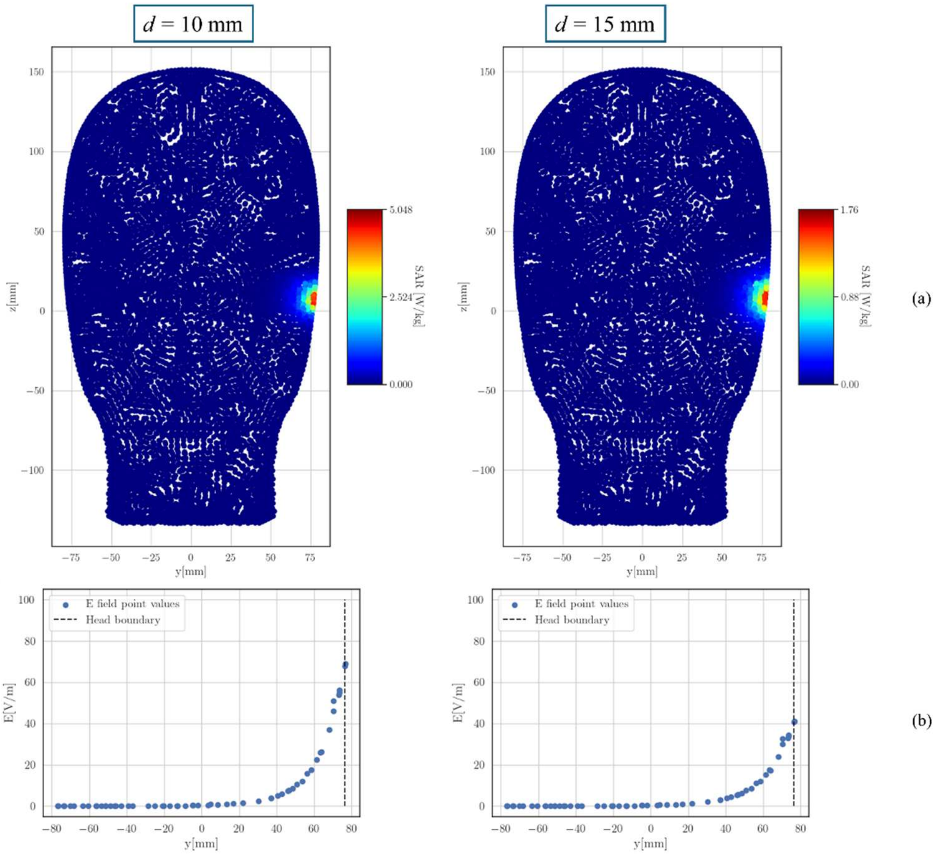

Fig. 3 (a) Visualization of point-wise SAR results in the YZ plane with x=-3 mm; (b) Electric field against increasing distance into the head tissue (i.e. along the y -axis).