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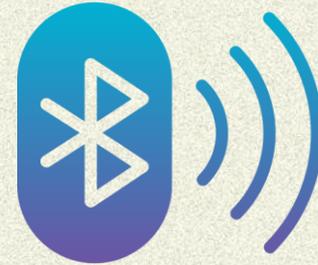
Human Head Exposure to Bluetooth Frequency - Electromagnetic Dosimetry

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INTRODUCTION



- **Bluetooth technology** – enables low-power wireless communications in the 2.4–2.4835 GHz range
- **Where is it used?**
 - Medical devices
 - PCs and printers
 - Smartphones and **headsets/earbuds**
- **Power classes** – higher power = higher operating range:
 - High (100 mW)
 - **Med-high (10 mW)** → Bluetooth headset
 - Medium (2.5 mW)
 - Low (1 mW)

Radiation type?

- **Non-ionizing** radiation in the RF spectrum (**non-hazardous below certain power thresholds**)

Issue?

- Increasing number of devices operating at the same frequency (**higher cumulative exposure**)
- **Long term exposure** (e.g. Bluetooth headsets)

EMF EXPOSURE CLASSIFICATION

- **What factors influence electromagnetic field (EMF) exposure?** – frequency, field intensity, exposure interval, field polarization and dielectric properties of the absorbing material (e.g. tissues' dielectric properties) [1]
- **2 main effect groups – thermal effects** (principally) and **non-thermal effects** (more subtle biochemical and bioelectrical consequences)
- **Thermal effects :**
 - Considered hazardous in case tissue's temp. rises by $>1^{\circ}\text{C}$ (conservative measure)
 - Used to classify the exposure as they are direct, measurable, well-documented and predictable
 - Expressed by specific absorption rate (SAR)
- **Non-thermal effects:**
 - Research results vary – often inconsistent and contradictory
 - Usually after long-term exposure – development of atypical symptoms (e.g. headaches, weakness, skin tingling etc.)

Bluetooth headsets overview

FREQUENCY

2.4-2.4835 GHz

LONG TERM EXPOSURE

- **Hot topic** due to prolonged exposure times
- Indicators of **direct link between prolonged exposure and thyroid nodule** occurrence [1]
- ~5 % of the emitted power is absorbed in the head glands [2]

LEVEL OF RESEARCH

No systematic overview of Bluetooth's near field influence on the standardized human head model in controlled experimental or computational environments

Possibly outdated guidelines that neglect certain effects [3]



[1] N. Zhou *et al.*, *Sci. Rep.*, vol. 14, no. 1, p. 14354, Jun. 2024.

[2] A. Gravina *et al.*, in *Proc. EMC Europe*, Rome, Italy, Sep. 2020.

[3] ICBE-EMF, *et al. Environ Health*. 2022;21:92.

OBJECTIVE



Computational study

of the Bluetooth earbud's radiation into the IEEE Specific Anthropomorphic Mannequin (SAM) head model



Why?

- **Systematic overview** of the Bluetooth's near field influence **on a standardized model**
- **Reference for future experimental studies** with the physical head phantom

BLUEPRINT FOR THE COMPUTATIONAL STUDY

- Blueprint for the computational study – SAR evaluation report for Apple Bluetooth earbud from 2019 [1]
- Measurement setup:
 - **Physical SAM head model** – contains plastic shell in which the head simulating liquid is poured
 - **Bluetooth earbuds (dipole antenna)**– mounted on small tripod so that the dipole feed point was positioned below the center marking of the flat phantom section
 - **Isotropic field probe** – area and zoom scanning; area scanning finds the area with high field values, followed by a fine measurement around the hotspot; zoom scan measures points within a specified grid that forms a 1 or 10 g cube enabling averaged 1 or 10 g SAR values
- Phantom – antenna distance – 10 and 15 mm

Example of SAM head phantom:



[1] UL SAR report, Bluetooth earbud, 12458150-S1V1 (2019).

NUMERICAL MODELING

- **FEKO 2024** (Altair Engineering Inc., Troy, Michigan) software for **high-frequency electromagnetic simulations**
- **Software capabilities:**
 - Variety of numerical techniques and hybridizations for different electromagnetic problems
 - Finite element method (**FEM**),
 - Method of moments (**MoM**),
 - MLFMM,
 - Finite Difference Time Domain (FDTD), etc.
- **FEM** – solves partial differential equations:
 - problem domain volume is discretized – tetrahedrons
 - Each element is assigned with a simpler eq. Approximating the original eq.
 - All eq. are assembled into a larger system to describe the full field behavior of the problem
- **MoM** – solves integral equations:
 - Problem domain is discretized – segments /patches (usually used for antennas)
 - Unknown quantity (e.g.. Current density) is approximated by a basis function for each element
 - All eq. are assembled in a larger system to describe the problem's behavior

COMPUTATIONAL MODEL COMPOSITION

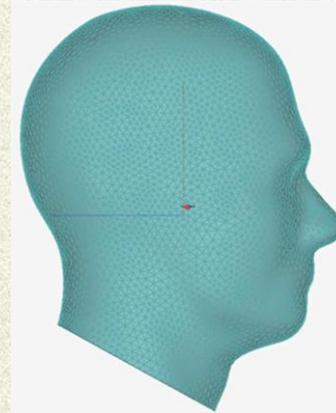
HEAD MODEL

- SAM head model [1]
- Designed according to the 90th - percentile anthropometric data corresponding to the adult male head (US Army)
- Homogenous model with the following properties at 2.45 GHz: $\epsilon_r = 39.2$, $\sigma = 1.8 \text{ S/m}$, $\rho = 1000 \text{ kg/m}^3$
- FEM method

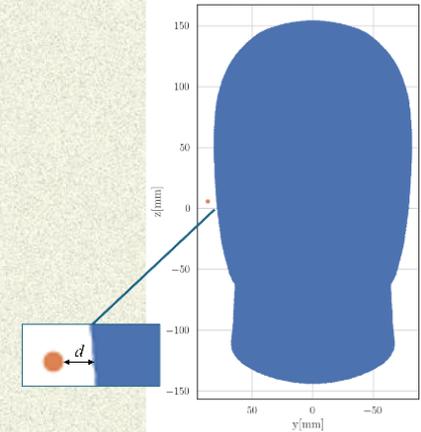
BLUETOOTH EARBUD

- Modelled as a 2.45 GHz dipole antenna (10 mm; PEC)
- MoM method
- 10 & 15 mm distances from the model [2]
- Total radiated power of the antenna – 12.5 dBm

Head model in FEKO::



Antenna's position relevant to the head's surface:



[1] IEEE 1528-2013 (SAR head).

[2] UL SAR report, Bluetooth earbud, 12458150-S1V1 (2019).

EXPOSURE GUIDELINES

- **Exposure guidelines** – expressed in form of specific absorption rate (SAR) averaged over 1 or 10 g of tissue (depending on the reference)
- SAR – quantification of **electromagnetic dosimetry at frequencies below 6 GHz**
- Guideline differentiation:
 - general public and occupational exposure; both are conservative
 - Head, limbs and whole body exposure
- **Our scope – general public**
- **RF/EMF exposure standards bodies and regulators:**
 - IEEE (ICES/TC95)
 - International Commission on Non-Ionizing Radiation Protection (ICNIRP)
 - Federal Communications Commission (FCC)

Head exposure guidelines:

$$SAR_{10g} = 2 \text{ W/kg}$$

$$SAR_{1g} = 1.6 \text{ W/kg}$$

SAR COMPUTATION (1)

Pointwise SAR [1,2]

$$SAR = \frac{\sigma}{2\rho} |\vec{E}|$$

- σ – tissue conductivity
- ρ – tissue density
- $|\vec{E}|$ – electric field magnitude at a specific coordinate in the model

SAR averaged over 1 /10 g

General expression:

$$SAR_{av} = \frac{1}{V} \int_V SAR dV$$

- V – tissue volume encompassing either 1 or 10 g of tissue
- SAR – point-wise SAR value calculated in the points encompassed by the volume; or function that describes the SAR's distribution in the volume

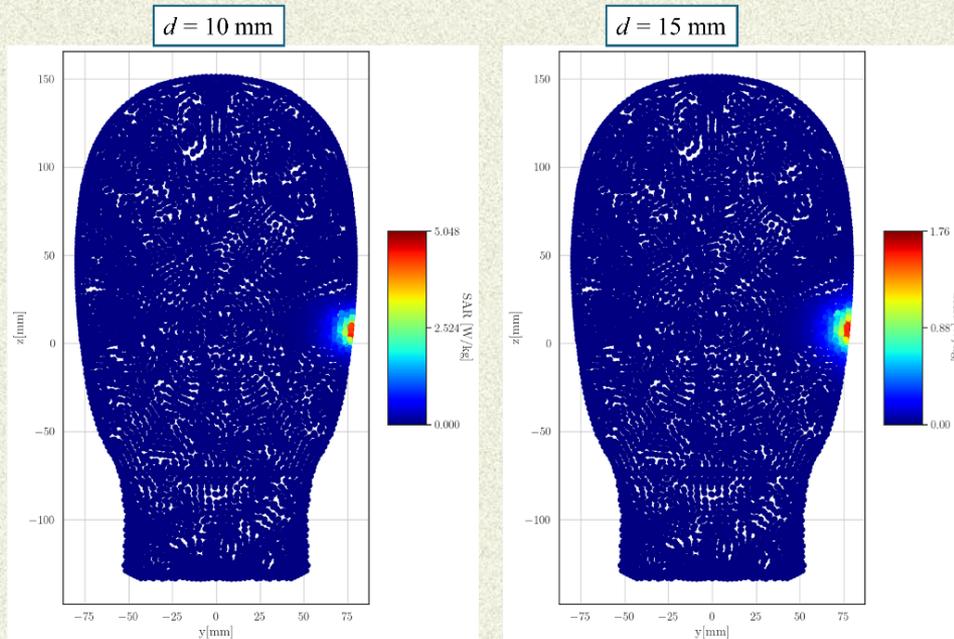
Illustrative implementation:

$$SAR_{av} = \frac{\sum_i^N SAR_i V_i}{\sum_i^N V_i}$$

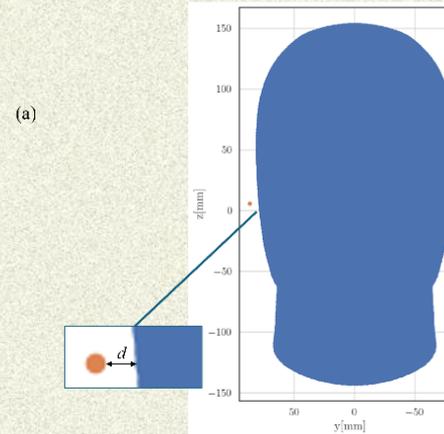
- Used in FEM-based software
- SAR_i – average SAR of a specific finite element (V_i to scale it)
- V_i – volume of each finite element
- Summation – SAR contributions from all relevant elements
- Total volume – encompasses 1/10 g of tissue

RESULTS (1)

- **Point-wise SAR** across the coronal head section (cut directly below the antenna position above the head's surface)



Pointwise SAR – values are the greatest around the head's surface, as expected



RESULTS (2)

- SAR_{1g}/SAR_{10g} – calculated using a build-in feature in FEKO
- **Target points:**
 - **1st point – 5 mm below the maximum E – field value** (it was on the surface and hence averaging would be performed over air)
 - **Subsequent points** – 3 points along the direction of the positive y axis (inside the head; 5 mm apart)

Ant. Dist.	Points (x,y,z)	SAR 1g [W/kg]	SAR 1g [W/kg]	SAR 10g [W/kg]	SAR 10g [W/kg]
10 mm	-6.98047, 72.1139 ,7.49393	1.78	1.62	/	/
	-6.98047, 67.1139 ,7.49393	0.90	0.82	0.69	0.63
	-6.98047, 62.1139 ,7.49393	0.45	0.41	0.42	0.38
	-6.98047, 57.1139 ,7.49393	0.22	0.20	0.22	0.20
15 mm	-0.414664, 71.7052, 8.35908	0.72	0.67	/	/
	-0.414664, 66.7052, 8.35908	0.38	0.36	0.31	0.31
	-0.414664, 61.7052, 8.35908	0.20	0.18	0.20	0.18
	-0.414664, 56.7052, 8.35908	0.10	0.10	0.11	0.10

Guidelines	SAR 1g [W/kg]	SAR 10g [W/kg]
ICNIRP & IEEE	/	2
FCC	1.6	/

SAR_{1g} value in case of the 10 mm antenna distance is slightly above the FCC guideline, but at present it is not alarming as the guidelines are conservative, and homogenous models tend to overestimate exposure [1]

SAR COMPUTATION (2)

Commercial software (e.g. FEKO)

- Exact numerical algorithm is not specified
- Generally accepted practice for electromagnetic FEM – edge basis functions are used (ensure tangential E-field component travels continuously)
- SAR calculation – when computing the SAR over each tetrahedron, **edge basis functions** were used

In-house computation

- Python code
- E-field values at all nodes of the model were exported from FEKO and an in-house tetrahedron mesh was created
- SAR calculation – when computing the SAR over each tetrahedron, **vertex/node basis functions** were used

DISCUSSION AND CONCLUSION

- A SAM head model was placed in the near field of a 2.45 GHz PEC dipole placed at 2x different distances and the electromagnetic dosimetry was evaluated through SAR
- **The achieved SAR values never exceeded ICNIRP/IEEE guidelines**
- The achieved SAR values were compared to a report on Apple earbuds [1] where SAR was physically measured within the SAM head phantom – they reported significantly lower SAR
- Possible discrepancies are due to difference between a computational and experimental environment (e.g. antenna mismatch; human head phantom shell thickness and different dielectric properties of the filling)
- Additionally, usage of homogenous head model for the frequency range 1.5 –2.5 GHz could potentially overstate the exposure
- **Successive step** – computational studies on more complex head models (additional tissues and accurate ear model) and realistic antenna

Thank You for Your attention!

Do you have any questions?
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