

Modelling and Simulation of Electromagnetic Radiation Effects of Mobile Phones on Teeth with an Amalgam Filling

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Abstract: Excessive everyday use of mobile phones and wireless communication systems has produced life in electromagnetic fields and growing public concern about possible effects on human health. All these devices operate close to the head and body and electromagnetic waves leave part of their energy in the matter through which they pass. There has been a lot of research on the toxic effects of amalgam fillings that are believed to be the main source of human total mercury body burden but there is not sufficient knowledge about the influence of electromagnetic radiation from mobile phone on amalgam filling and how that affects human health. Electrical engineering has the task to produce devices that improve the quality of human life without any negative effects, and to ensure the safety of new products and technologies. Using electromagnetic simulation to obtain electromagnetic quantities in the head and teeth and linking these results to physical and physical-chemical processes in the matter has led to advances in clarifying these issues. In general, the conclusion is that the use of mobile phones can lead to increased absorption of energy and other electromagnetic quantities in teeth and filling of teeth and cause increased release of mercury and toxicological effects to health associated with the intake of mercury in the human organism.

Keywords: amalgam filling; electromagnetic simulation; health impact; mercury release; mobile phone radiation

1 INTRODUCTION

A modern way of life will hardly find a person who has not a mobile phone and at least one amalgam filling. We are all concerned about the adverse effects on the health of using mobile phones and having amalgam fillings in particular.

The electromagnetic radiation produced by mobile phones is classified by the International Agency for Research on Cancer as possibly carcinogenic to humans and WHO (World Health Organization) tries in our long-time project to conduct a formal risk assessment of all studied health outcomes from exposure to radiofrequency fields.

Experimental research on the effects of radio-frequency radiation includes both studies of cell cultures and tissues (in vitro) and of laboratory animals (in vivo), as well as of human examinees (volunteers). The aim and focus of numerous studies range from functional changes in the brain and brain activity, reaction times, and sleep patterns, head cancers (glioma and acoustic neuroma), to secondary effects such as electromagnetic interference (medical device, pacemakers, implantable defibrillators, and certain hearing aids) and traffic accidents.

Over the past years, our laboratory has focused on studying the health effects of exposure to sources of electromagnetic fields ELF (high voltage cable, power plant, transformer station) and HF RF such as mobile phones, their base stations, and wireless communication [1-4].

All of these studies have indicated that electric, magnetic and electromagnetic fields, which vary from the natural field, have significant adverse agents acting on the material independently of that matter being living or inanimate. It is of interest to examine the effects of objects near the body or in the body when they are under the impact of electromagnetic radiation such as glasses, virtual reality glasses, pacemakers, dental implants, fillings, and especially amalgam fillings because of the significant content of mercury in them.

Mercury is the most toxic non-radioactive element. Mercury vapour is one of the most toxic forms of mercury along with some of the organic mercury compounds. Most human exposure to mercury is produced by outgassing of mercury from dental amalgam [5], ingestion of contaminated fish, or occupational exposure, according to the WHO [6]. Human exposure to mercury comes from mercury vapour from amalgam fillings at a rate of 2 to 28 micrograms per facet surface per day, of which about 80% is absorbed [6] through inhalation [7, 8], while only 7 to 10% is absorbed through ingestion [9].

New studies suggest that mercury from dental amalgam may lead to nephrotoxicity, neurobehavioral changes, oxidative stress, autism, skin and mucosa alterations or non-specific symptoms and complaints [22]. It is interesting to note that one filling per person in the USA population results in 75 - 100 tons of mercury placed in people's mouths of this country.

Amalgam is a mixture of metals and metallic mercury has the lowest evaporation temperature and easily turns into vapour. Although the use of amalgam has been decreasing, it remains major inorganic contaminant for people who are not occupationally exposed [11].

In summary, both mercury vapour from dental amalgam and methylmercury derived from amalgam have the full toxic potential [10, 12]. There are various factors depending on the rate of mercury release as filling size, tooth, and surface placement, chewing, food texture, tooth grinding, and brushing teeth, as well as the surface area, composition, and age of the amalgam [16]. One new factor has appeared as a release factor, it is the electromagnetic radiation of mobile phones. Mortazavi et al, [17], conclude that MRI and microwave radiation emitted from mobile phones significantly release mercury from dental amalgam restoration. The test group students were exposed to electromagnetic radiation by mobile phone value of $SAR = 0.96 \text{ W/kg}$ that was operated in talk mode for 15 min every day at days 1 - 4 after tooth amalgam restoration. The increase in mercury release is observed in the urine of examinees that had amalgam fillings two days after using the phone or after 45 minutes of using the phone.

2 ELECTROMAGNETIC SIMULATION AS RESEARCH METHOD

This research aims to prove the presumption that EM radiation of mobile phones leads to an increased level of release of mercury from the amalgam filling and how this process occurs and find mechanisms of action in the process. For this purpose, a good tool is computational electromagnetics because with its use we obtain physical quantities that describe the fields, forces and thermal effects in the material.

Computational electromagnetic or electromagnetic simulation is the process of setup models of sources of electromagnetic wave and objects that are influenced by the energy of radiation and the calculation of electromagnetic quantities in the object. [1, 2, 19]. The electrical and magnetic field, conduction current, absorbed energy, *SAR* (Specific absorption rate) are usually calculated. All of these quantities can be used to evaluate physical effects on the object through which waves pass and lead to the assessment of biological and health effects of electromagnetic radiation.

SAR is a measure of the rate at which energy is absorbed by the human body when exposed to a radio frequency (RF) electromagnetic field. *SAR* is averaged either over the whole body or over a small sample volume (typically 1 g or 10 g of tissue). In essence, *SAR* is the dose, from Eq. (1), that represents the rate of energy Q received per unit mass body, but by connecting electromagnetic quantities it can be expressed over the strength of the electric field and the induced current and the rate of temperature change Eq. (2).

$$SAR = \frac{d}{dt} \left(\frac{Q}{m} \right) = \frac{P_j}{m} \quad (1)$$

where P_j is absorbed energy or power of Joule losses. Then point *SAR* is:

$$SAR = \frac{P_j}{m} = \frac{\sigma E^2}{\rho_m} = \frac{J^2}{\rho_m \sigma} = c_p \frac{dT}{dt} \quad (2)$$

where are: ρ_m is the mass density of the body, σ is electrical conductivity, J is induced current density and c_p is specific heat capacity. Total *SAR* is power loss density of a biological material divided by its mass density, where maximum point *SAR* is the maximum point *SAR* of all grid cells.

For the practical calculation of *SAR*, the formula is:

$$SAR = \frac{1}{V} \int_V \frac{\sigma(r) |E(r)|^2}{\rho(r)} \quad (3)$$

where V is the volume of an averaged part of the body. Eq. (2) shows that *SAR* value is proportional to the rate of temperature change, which means that there will be heating at a certain point in the material in which the arrival of the wave leads to the changes in the magnitude of the electric field.

In this research, the model of the source is the smart mobile phone-smartphone (monoblock, modern phone with integrated antennas). As the antenna is planar inverted F antenna-PIFA, (Fig. 1), which is increasingly used in the modern mobiles because it reduces the required space needed on the phone. The antenna is resonant at a quarter-wavelength. The model of the exposed object is human head with all internal parts (Tab. 2) and especially the part of interest: jaw and teeth. The head should be as similar as possible to anatomical models, and there is always a certain degree of approximation within the model and averaging of the real structure. In this case, models obtained by Computer-Aided Design (CAD) were used.

The model of head, jaw, and tooth with fillings and mobile phone is shown in Fig. 1.

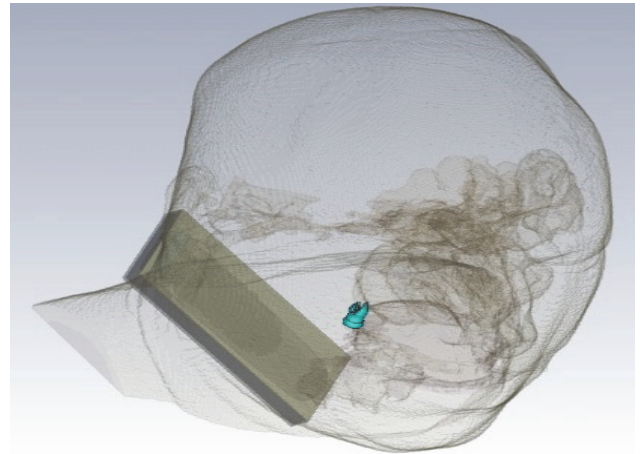


Figure 1 Full anatomic model of a head with mobile phone monoblock with integrated antenna (PIFA)

The shape of the individual filling will depend on the shape and extent of the caries infection [13], and one of the forms with a significant fill mass is selected and modelled for simulation.

The tooth with and without amalgam filling is specially modelled and is shown in Fig. 2.

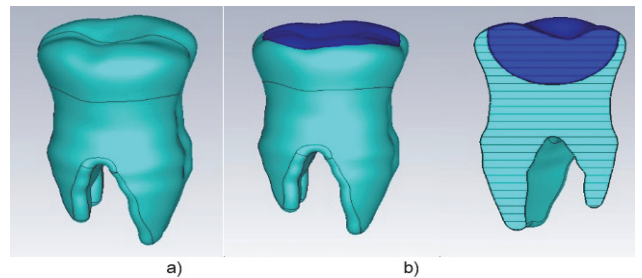


Figure 2 Models of the tooth a) without filling b) with an amalgam filling face view and cross-section view

In the process of simulation AustinMan Electromagnetic Voxels model [20] was used as the adult head model. It is estimated that the greatest effects are expected on those teeth that are closest to the source when the teeth are in the upper jaw. The tooth model with and without amalgam filling is positioned in the upper jaw model of the head, Fig. 1.

In dentistry, amalgam is an alloy of mercury with various metals used for dental fillings. It commonly consists of mercury (50%), silver (~22 - 32%) tin (~14%), copper (~8%), and other trace metals. In simulation

procedure amalgams fillings consisting of mercury (50%), silver (28%), tin (14%) and copper (8%) were used.

Usually, telephones work on two frequency bands at 900 MHz and 1800 MHz and therefore it is important to know the electromagnetic characteristics of biological materials on these two frequencies. In the simulation process, the filling with electromagnetic characteristics: $\sigma = 2.414 \times 10^{-7} \text{ S/m}$, $\rho = 12170 \text{ kg/m}^3$ is used.

Table 1 Filling properties

Components	El. Cond. / S/m	Density / kg/m ³	Thermal cond. / W/K/m
Mercury	1.04e+006	13590	8.30
Silver	6.30e+007	10490	429
Tin	8.70e+006	7280	66.6
Copper annealed	5.80e+007	8930	401
Copper pure	5.96e+007	8930	401

Numerical values of electromagnetic characteristics (permittivity, electrical conductivity, density, thermal conductivity) of biological tissue at 900 MHz and 1800 MHz are shown in Tab. 2.

Table 2 Electromagnetic characteristic [32]

Biological tissue	900 MHz		1800 MHz		$\rho / \text{kg/m}^3$
	ϵ_r	$\sigma / \text{S/m}$	ϵ_r	$\sigma / \text{S/m}$	
Brain	49.4	1.26	46.1	1.71	1046
Tooth	16.5	0.260	11.8	0.275	1850
Cortical bones	12.5	0.143	11.8	0.275	1908
Muscle	55.0	0.943	53.5	1.34	1090
Fat	11.3	0.109	11.0	0.19	911
Skin	41.4	0.867	38.9	1.18	1109
Eye-aq. humor	72.3	1.85	67.2	2.92	1010
Eye-lens	35.8	0.485	34.6	0.787	1076

2.1 Calculation Process

For calculating the electromagnetic field presented in this paper, the Finite Integration Technique (FIT) was used. The Finite Integration Technique [1, 2, 24] is a consistent geometric discretization method which turns Maxwell's equations into a set of algebraic matrix equations. The spatial discretization of Maxwell's equations is finally executed on these two orthogonal grid systems. The following electromagnetic quantities are calculated: the intensity of the electrical field, power loss density, Specific Absorption Rate (SAR), conduction current density and surface current on the tooth.

Reference power of the phones is $P = 1 \text{ W}$ (according to the Standard IEEE C.95.3) at $f = 900 \text{ MHz}$ and $f = 1800 \text{ MHz}$ and port impedance $Z = 50 \Omega$.

Generally, SAR is being averaged on 1 g or 10 g of body mass. Due to the small amount of tooth mass, in this case, SAR averaging was performed on 0.1 g of tooth mass. For SAR ($SAR_{0.1g}$), the efficient averaging algorithm was used based on IEEE C95.3 standard [25], which was included in the CST (Computer Simulation Technology) package [26]. CST Microwave Studio is the software of choice for these calculations.

The distance from the tooth to the port of the mobile phone was 1.5 cm, corresponding to real conditions of mobile phone use when the tooth is in the upper jaw.

For the appropriate use of the CST software package, the crucial step before the computation is to create the mesh of elements. A better quality mesh with a greater number

of elements leads to more accurate results. Of course, finer mesh requires more powerful hardware and longer computational time and for some applications, the calculation time can last for days. For that reason, the calculation should be made with as low the calculation time as possible while maintaining the accuracy of the results (convergence of results). The convergence test and its conversion on the convergence curve show the stability of the obtained results in the function of the number of mesh elements. Fig. 3 shows the curve of the convergence process in the calculation process for the electrical field and SAR for the 3 G frequency (1800 MHz) for smartphone and model of the tooth. Of course, the test of convergence was performed for each frequency. The graph in Fig. 3 shows that a sufficient number of mesh cells is about 12 million for this example. It can be assumed that with this number of elements the accuracy of the numerical results is independent on the number of mesh elements. It should be noted that the number of mesh cells is different for different frequencies due to the wavelength.

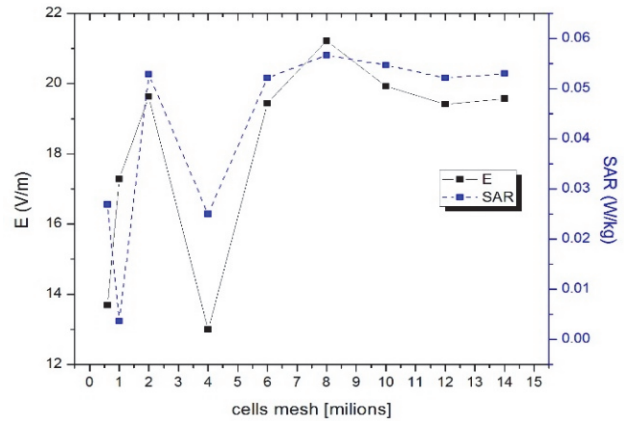


Figure 3 Convergence results according to the number of grid cells.

3 RESULTS OF SIMULATION

After simulation with the smartphone as a source of radiation, electromagnetic values were calculated. Maximum calculated values in the area of interest are presented in Tab. 3.

Table 3 Results of simulation for 900 MHz (maximum value)

Parameter	Model without filling	Model with filling
$E / \text{V/m}$	32.7	62.9
Power loss density / W/m^3	21.8	724
$SAR_{0.1g} / \text{W/kg}$	0.096	0.129
Conduction current density / A/m^2	2.57	25.6
Surface current on filling / A/m	-	43.5

Table 4 Results of simulation for 1800 MHz (maximum value)

Parameter	Model without filling	Model with filling
$E / \text{V/m}$	31.5	37.9
Power loss density / W/m^3	175	183
$SAR_{0.1g} / \text{W/kg}$	0.090	0.091
Conduction current density / A/m^2	9.04	8.99
Surface current on filling / A/m	-	0.83

The simulation of the electric field and related dimensions is done for the head with all parts, including the tooth with and without filling. For clarity, only the source of radiation and the tooth are presented in the

results. In Fig. 4 only phones and tooth as an object of interest in real position are shown. Tab. 3 and Tab. 4 show the maximum value of electromagnetic quantities of interest in tooth exposed to electromagnetic radiation of smartphone for two frequencies.

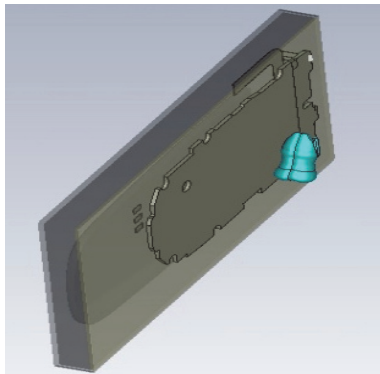


Figure 4 Model of the smartphone with the PIFA antenna with the tooth in the real position

3.1 Result of the Simulation Process at 900 MHz

The electric field in the tooth with the filling on frequency 900 MHz is about 2 times greater in the entire volume (Fig. 5).

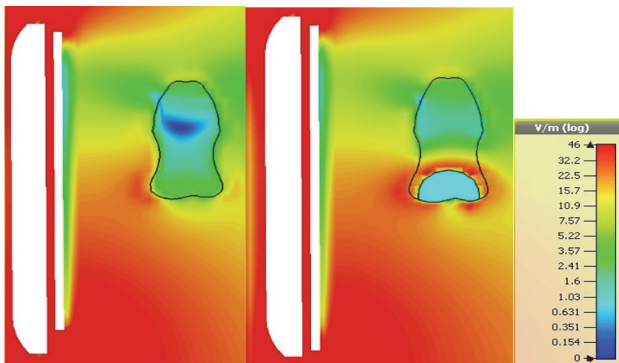


Figure 5 E field (V/m) for the smartphone at 900 MHz: a) tooth model without filling, b) tooth model with filling

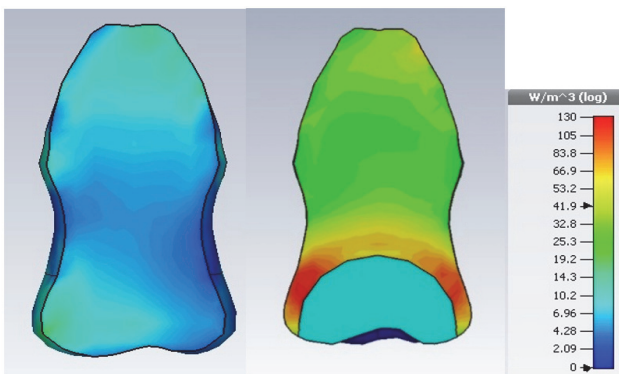


Figure 6 Power loss density in the tooth for the smartphone at 900 MHz: a) without filling, b) with filling

Fig. 6 shows intensive power loss density in the tooth with filling in the area above the filling in comparison with tooth without filling.

The result for SAR when the tooth is exposed to electromagnetic radiation by smartphone on frequency 900 MHz is shown in Fig. 7 and Fig. 8 for the different cross-section of the tooth with a filling.

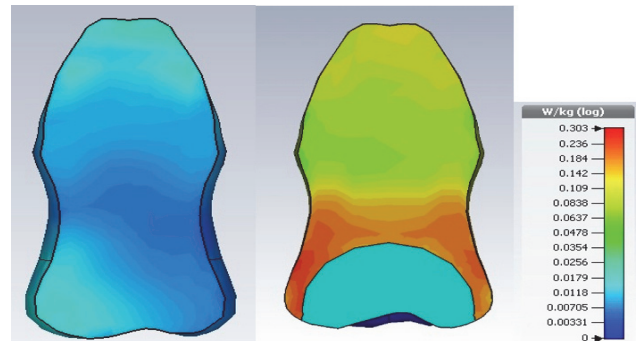


Figure 7 SAR_{0.1g} in the tooth for the smartphone at 900 MHz: a) without filling, b) with filling

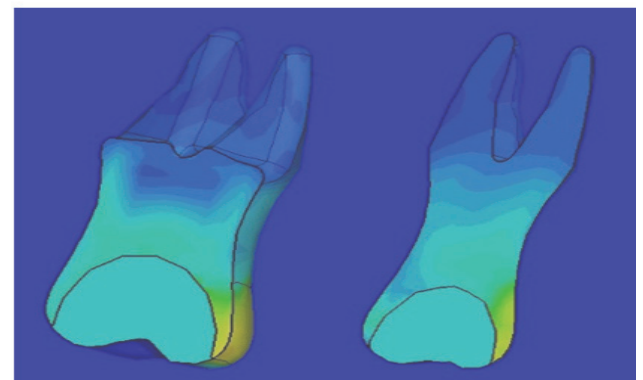
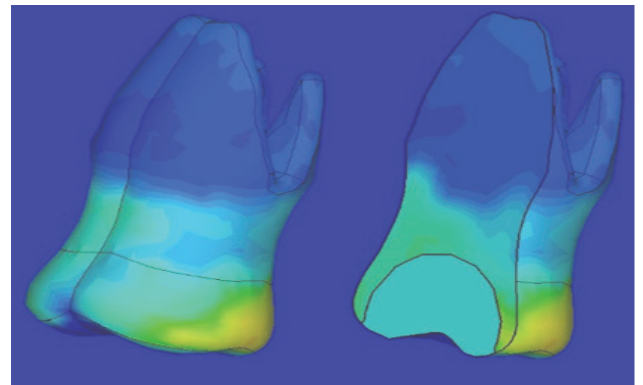


Figure 8 SAR_{0.1g} in the tooth with filling for the smartphone at 900 MHz: different cross-section

The results for conduction currents (Fig. 9) show currents on the separation surface between tooth and filling. Fig. 10 shows surface currents on filling also, which may indicate the processes of corrosion on the filling surface.

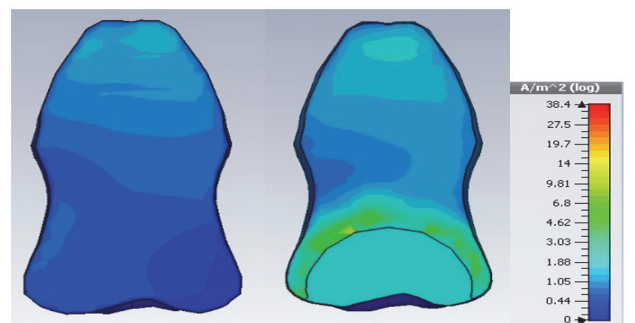


Figure 9 Current density in the tooth for the smartphone at 900 MHz: a) without filling, b) with filling

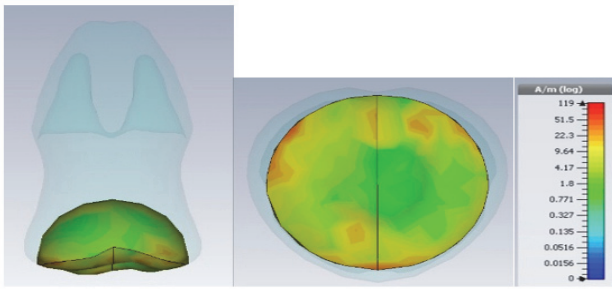


Figure 10 Surface current on the tooth with filling for the smartphone at 900 MHz

3.2 Result of the Simulation Process at 1800 MHz

Distribution value of the electrical field in the cross-section of a tooth with and without fillings exposed to electromagnetic radiation of smartphone at 1800 MHz is shown in Fig. 11. There is a slight increase in the electric field in the tooth model with fillings.

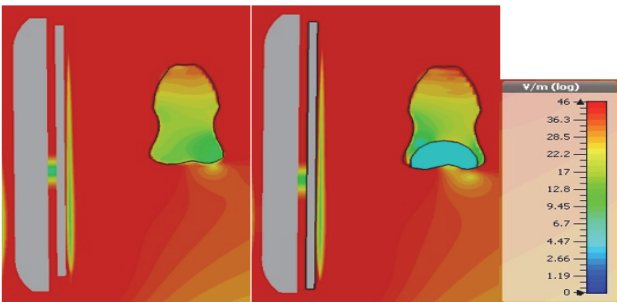


Figure 11 E field (V/m) for the smartphone at 1800 MHz: a) without filling, b) tooth with the filling

Fig. 12 shows power loss density in two models of a tooth at 1800 MHz, which corresponds to the absorbed energy of the field in the tooth.

The result for SAR when the tooth is exposed to electromagnetic radiation by smartphone on frequency 1800 MHz is shown in Fig. 13 and Fig. 14 for the different cross-section of the tooth with a filling.

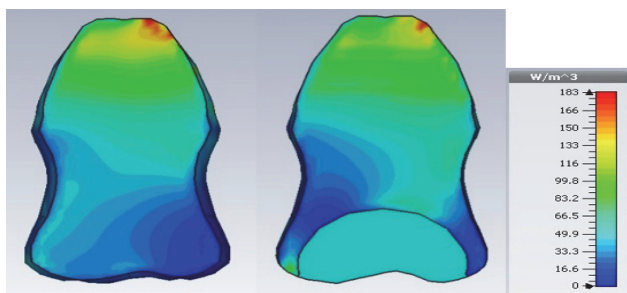


Figure 12 Power loss density in the tooth for the smartphone at 1800 MHz: a) without filling b) with filling

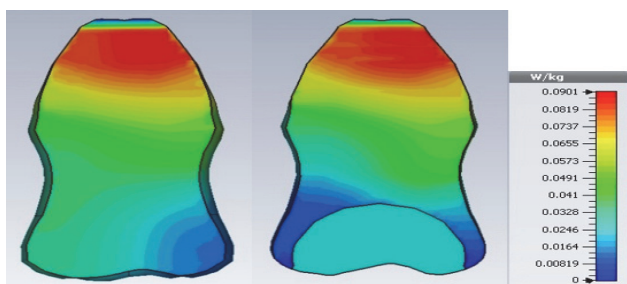


Figure 13 SAR_{0.1g} in the tooth for the smartphone at 1800 MHz: a) without filling, b) with filling

In Fig. 14 it should be noticed that the maximum value of SAR is distributed in the tooth roots closer to the source.

The results for current density (Fig. 15) show currents in the tooth for both models. Fig. 16 shows surface currents on the filling of the tooth.

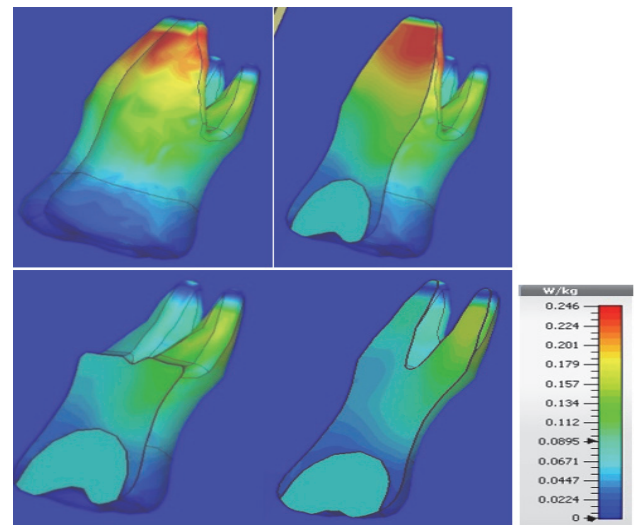


Figure 14 SAR_{0.1g} in the tooth with filling for the smartphone at 1800 MHz, cross-section

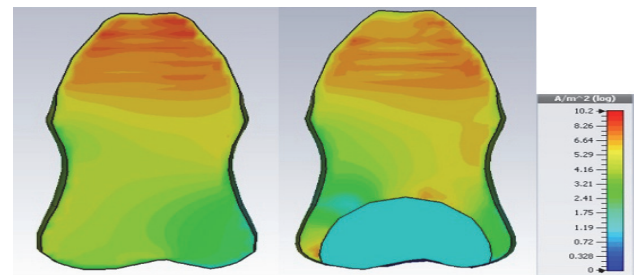


Figure 15 The current density for the smartphone at 1800 MHz: a) without filling, b) with filling

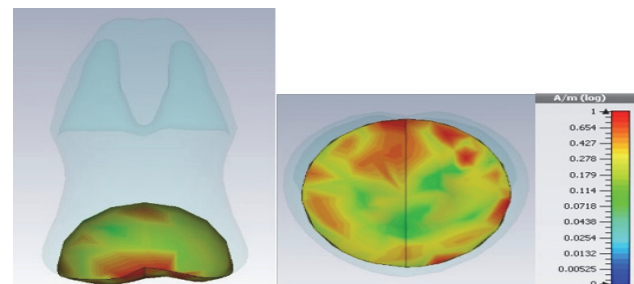


Figure 16 Surface current on the tooth with filling for the smartphone at 1800 MHz

4 DISCUSSION

The results of the simulation show the increased values of the electric field in a model with filling compared to a model without filling at all frequencies. These values show that the presence of filling leads to the increase of electric field intensity in the space above the fillings for teeth in the upper jaw.

The difference in the electric field in the tooth filling with respect to the tooth without filling is greater when the phone operates at a lower frequency (900 MHz). This fact can be explained by the lower penetration depth of waves at a higher frequency and reversion, that is, the greater part of the energy remains absorbed in the structure of the face,

so a smaller part of the energy comes to the teeth at a higher frequency, so the difference is smaller.

The values for power loss density show that intensive energy absorption occurs in tooth tissue of the model with filling and absorption in the tooth area is on average five times greater in comparison with the model without filling at 900 MHz (Fig. 6). It was observed that there are areas near filling where this relationship was 15 times greater, and even 34 times greater at one point (Tab. 3).

It is logical to assume that this intense absorption will lead to a local increase in temperature and possibly accelerate the evaporation of the mercury from filling.

In the case of smartphone exposition at 1800 MHz, values for power loss density in tooth tissue with filling are slightly higher than in tooth without filling.

Calculated values for *SAR* are similar to power loss density with a slight variation.

Mercury has the lowest freezing and boiling point compared to all stable metals. We assume that local warming in the vicinity of amalgams and mercury atoms will lead to an increase in the kinetic energy of the atom and to slight evaporation, i.e. the release of mercury from amalgams.

The hypothesis, which resulted from the simulation results that the increase in the electric field and *SAR* in the tooth model can lead to an increase in mercury release, is confirmed by other experimental studies [17].

The simulation shows the existence of induced current in the tooth, which is increased in the model with filling as compared to the model without filling. The process of corrosion is detectable on amalgam filling [27] and it can be explained by the induced current in the tooth, especially in fillings where saliva has a role as electrolytes in electrolysis. Surface currents on the filling may cause chemical reactions in the filling itself, or between the filling and saliva ingredients [17].

By using BDORT (Bi-Digital O-Ring Test) [28-30] it is possible to determine the relative value of BDORT units of mercury in the whole body or every specific organ.

When summarizing all results of calculation and comparing with facts from the literature it is evident that the increased values of E field in a model with filling implicate higher power absorption and *SAR* and it provokes local temperature rise and probable higher mercury evaporation. In addition, currents near and on the fillings may lead to electrical processes in the transport of ion of metallic mercury.

5 CONCLUSION

The absorbed energy in tooth tissue due to exposition to the electromagnetic field from the mobile phone is mostly transformed into heat energy and may lead to temperature increase inside the tooth.

The absorbed energy in tooth tissue due to exposition to the electromagnetic field from the mobile phone is greater in the tooth with filling in comparison with the tooth without filling. The same conclusion is valid for the electric field, *SAR* and currents in the area of teeth.

The absorbed energy in the tooth with filling is greater for the smartphone which operates at 900 MHz when compared to the same model operating at 1800 MHz.

The increased absorption near filling leads to the increased temperature of this area and the increase in mercury vaporization.

Finally, this leads to an increased release of mercury from filling and toxicological effects that endanger human health.

Presented results can be applied to numerous statistical studies of amalgam fillings to make quantitative estimates for future research.

Acknowledgements

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