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SAR Simulations in Wireless Communication and Safety Discussions in the Society

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Abstract

Numerical simulation in cellular phone - human tissue interaction is discussed in this paper. The powerful time domain (TD) techniques, the transmission line matrix (TLM) and the finite-difference time-domain (FDTD) methods, are used to model mutual effects. The purpose is to calculate specific absorption rate (SAR; defined as the power absorbed by the unit mass of the tissue), validate the codes and verify the results. Also, effectiveness of the SAR parameter in determination of the exposure limits for human health and environmental pollution is discussed.

Key Words: *Specific absorption rate, FDTD, TLM, wireless communications, safety discussions, precautionary principle, numerical simulation*

1. Introduction

The widespread use of mobile phones has escalated over the last few years. Nearly 20 million subscribers (out of 65 million population) use two GSM 900 MHz and two GSM 1800 MHz systems in Turkey. This number is more than 25 million in UK and 110 million in USA. It is projected that the worldwide subscribers will reach to 1.2 Billion by the year 2005. This very rapid development in mobile communication has drawn attention to possible health risks of electromagnetic (EM) energy emitted from the transmitters of mobile phones as well as from the base stations [1-19]. The debate on EM pollution has greatly focused on the question "*whether these two have adverse health effects in either short or long term periods*".

The non-governmental organization accepted as an independent expert body by the United Nations (UN), the World Health Organization (WHO), the International Labor Organization (ILO), the European Union (EU) and most of the developed countries is the *International Commission on Non-Ionizing Radiation Protection* (ICNIRP). The Commission is established for the purpose of advancing non-ionizing radiation

(NIR) protection for the benefit of people and the environment and in particular to provide guidance and recommendation on protection from NIR exposure. In 1998, the ICNIRP published its latest guidelines for exposure limits, which were based on the evaluation of all available and known analytical/numerical/experimental study results [20] (it should be noted that safety rules are stated by characteristic words such as *shall* - for mandatory rules, *should* - for recommendations, and *may* - for guidelines). In these guidelines as well as in others [21,22], for example, electrical field strength at 900 MHz and 1800 MHz (where major contribution arises from cellular systems) should not exceed 42 V/m and 59 V/m, respectively, anywhere in public residence. Inadequacy of the up to date scientific information has led to worldwide controversial and heated debate, which in turn forces many countries lower these levels as low as 4-6 V/m [1]. Moreover, ongoing research results have been transformed into standards and national guidelines in these countries.

A few-months repetitive field strength measurement has been conducted in different locations in Istanbul. To give an idea about the location of the equipment photographs of three base station antennas are given in Figure 1 and Figure 2. As shown in the photos, Istanbul has almost the worst case base station antenna locations, because (i) it has ancient small buildings and high modern towers located nearby along narrow streets built in Ottoman-Greek times, (ii) the population and number of mobile phone subscribers are very high in these regions. This may require to build base station antennas even at first or second floor levels (see the photographs). Most of these base stations have 5-6 W average output power and 13-15 dBi antenna gain (i.e., EIRP of 100-150 W). Although the antennas are a few meters above the street level, majority of these measured values vary between 1 V/m and 6 V/m, rarely reaches up to 13-15 V/m, which are all below the ICNIRP limits (these periodic and random measurements show that the reference levels in Turkey may easily be reduced to around 5 V/m without any extra equipment or labor). It should be noted that as much as 50 V/m - 60 V/m *near field* values may be measured within a few meter distance of base station antennas depending on antennas, emitted power and the frequency, therefore, electromagnetic power levels near the base station antenna like the ones in Figures 1 and 2 should continuously be monitored by the operators and/or official bureaus. Also near field EM values are of greater importance for the residents who live within a few meter distance of transmitting base station antennas.

On the other hand, at points 2.2 cm away from a handset antenna, maximum values of the electric field are measured to be about 400 V/m and 200 V/m for 2 W, 900 MHz and 1 W, 1800 MHz cellular phones, respectively [1]. Given the much lower exposures to radiation from base stations than from handsets, the greater public concern from the people in all around the world is paradoxical. It presumably arises because *individuals can choose whether or not to use a mobile phone*, whereas *they have little control over their exposures from base stations*. Furthermore, people derive a personal benefit from the use of a phone, but gain nothing directly from the presence of a base station close to their home or place of work. If anything they may suffer a loss of amenity and perhaps a reduction in the value of their property.

The concern related to health and safety issues in wireless communication persist because of the limited number and scope of scientific studies that have been undertaken. Scientific studies may be group into two categories; (i) in-vitro and in-vivo experimental studies, which may be named as fundamental research, and (ii) epidemiological studies. Majority of the fundamental research have been performed to test animal responses to exposure conditions and signals that are unique to a particular system and/or service. Since, wireless technology is one of the most rapidly evolving technologies, tests for one generation may totally be irrelevant to the next generation (this may be the case even for the same generation devices). For example, it has been found that the specific absorption rate (SAR) averaged over 1g human tissue may vary

Figure 1. Two base station antenna locations in Kadıköy (in Istanbul). Measured electric field strength on the ground varies between 2 V/m and 6 V/m.

Figure 2. Another base station antenna in Cengelköy (in Istanbul). Measured electric field strength on the ground varies between 3 V/m and 13 V/m.

widely; from 0.13 W/kg to 5.41 W/kg, for various cellular phones with different operational modes (such as, TDMA, CDMA, AMPS, etc.) and antenna structures [23]. This certainly necessitates undertaken a completely new series of studies to satisfy health and safety concerns. Moreover, fundamental research focuses on short and medium period effects that are mostly called thermal and do not include chemical, biological and psychological effects. Nevertheless, fundamental research is very important and will continue, because of the attainment of knowledge and learning about mutual interaction of electromagnetic fields and tissues in natural or under artificial environment, and also because of the repeatability of the tests and confirmation of the results.

A good amount of fundamental research in this area suffer from reproducibility and different results may be obtained from the same experiments done by different groups. The major reason for that is basically using ill-established experimental set-up. It should be stated that, well-organized, large-scale and long-term epidemiological studies will be the best way to understand health effects of the wireless technology. Unfortunately, this may take years before getting trustable results.

This paper discusses various aspects of electromagnetic pollution in wireless communication. It also presents numerical simulations with characteristic comparisons. In Section 2, definition of the SAR is outlined. Numerical simulations with the two powerful time domain simulators are presented in Section 3. Risk Assessment and the Precautionary Principle are given in Section 4. Finally, the conclusions are given in Section 5.

2. SAR: Specific Absorption Rate

ICNIRP restrictions on the effects of EM exposure are based on established health effects and are termed *basic restrictions* [20]. Depending on the frequency, the physical quantities used to specify basic restrictions on EM exposure are *current density*, *SAR* and *power density*. In the frequency range of 10 MHz to a few GHz (including 900 MHz and 1800 MHz cellular phone frequencies), SAR is the main physical parameter. *Available experimental evidence indicates that human body can not regulate itself under a permanent temperature increase of more than 1 ° C*, which corresponds to a whole-body SAR value between 1-4 W/kg under 30 min EM exposure for resting humans. From this 4 W/kg value, a general public, continuous exposure limit of 0.08 W/kg is derived with a safety factor of 50.

Where appropriate, the derived limits called as *reference levels* are obtained from the basic restrictions by mathematical modeling and by extrapolation from the results of laboratory investigations at specific frequencies [20]. Reference levels are easy to measure and are applicable for base station controls. Unfortunately, basic restrictions should be taken into account for cellular phone EM exposure.

In tissues, SAR is proportional to the square of the internal electrical field caused by external device (e.g., cellular phone). It is given as

$$SAR = \tfrac{1}{2}\frac{\sigma}{\rho}|E|^2 \quad [W/kg], \tag{1}$$

where E [V/m], σ [S/m] and ρ [kg/m^3] are electric field strength, conductivity and density of the tissue, respectively.

Since electrical field strength inside tissues is required, SAR can be obtained via either laboratory studies [24] (where EM phantoms equivalent to human tissues are used) or with computer simulations [3-10]. In either case, standardization process has not been completed yet (see, for example [25]). In Figure

3, a typical head and hand phantom and measurement results for different hand positions are given [24]. In Figure 4, a typical discrete human head and hand model, which are used in numerical simulations, are pictured. Either measurement with phantoms or simulations with computers serve to understand short-term thermal effects and to obtain numerical values to control exposure levels.

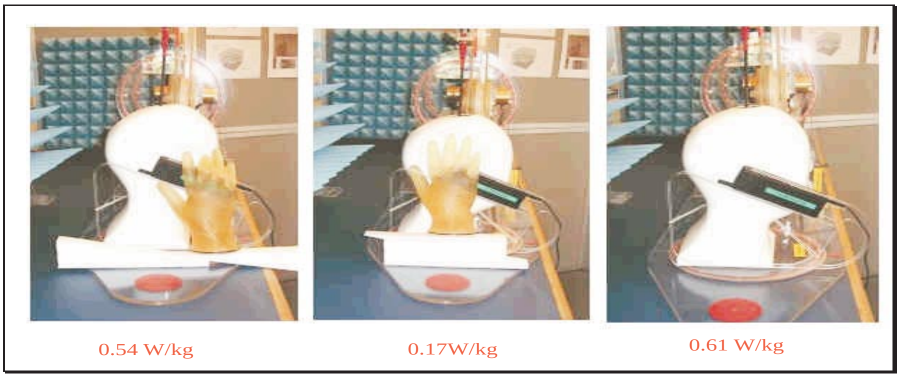


Figure 3. Head phantom and measured results for different hand positions

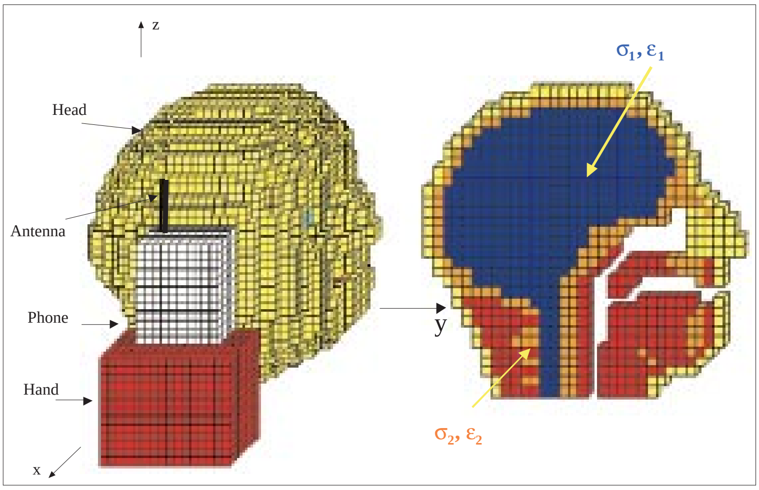


Figure 4. Discrete human head model used in computer simulations

Parallel to increase in computer speed and memory, EM problems have begun to be simulated directly in four-dimensional (i.e., in space and time) real world. The Transmission Line Matrix [26] (TLM) and the Finite-Difference Time-Domain [27] (FDTD) methods have become almost the most important time-domain simulation techniques used in broad range of EM problems. TLM is based on the *network theory* and each unit cell consists of 12 incident voltage pulses that are related by a scattering matrix to 12 reflected voltage pulses. But, FDTD uses the *field theory* and depends on the discretization of Maxwell equations directly in time domain. In addition, 6 EM field components are located at the same point in TLM, while they are located at different points in an FDTD cell. Therefore, the mesh structures of each method differ from each other requiring careful modeling of the objects under observation, as well as decision of the comparison criteria.

3. Numerical SAR Simulations

The most recognized EM exposure standards, including ICNIRP, adopt the SAR, averaged over the whole body (SAR_{WB}), as the basic parameter to establish the safety of an exposure [20-22]. The value of 4 W/kg is accepted worldwide as the threshold for the induction of biological thermal effects and introducing a safety factor of 50 for general public exposure gives rise to a basic limit on SAR_{WB} equal to 0.08 W/kg.

Sometimes, although SAR_{WB} becomes below the basic limit, the local SAR values can be rather high in a confined body region, where the power absorption takes place, such as a human head near an antenna of a mobile phone. For such conditions, limits on local SAR averaged over tissue masses of 1 or 10 g have been introduced in the standards, as 1.6 W/kg over 1 g or 2 W/kg over 10 g.

In this study, besides the local SAR evaluation with TLM and FDTD methods, the SAR values at a single cell (i.e., only for one FDTD or TLM mesh size) are calculated to show the computation differences between two methods, as well as the instant behavior of the SAR at a chosen point. As is shown further, it is observed that peak SAR values for only one cell may be higher than the local SAR values averaged over tissue masses of 1 or 10g.

3.1. SAR_F and SAR_T algorithms

Two packages are prepared and used in SAR simulations; FDTD based SAR_F and TLM based SAR_T. They are tailored with exactly same peripheral units except the main FDTD and TLM routines. These are:

- **Main Routines:** FDTD and TLM computation space is a $N_x \times N_y \times N_z$ cubical volume (typically $100 \times 100 \times 100$), where geometry under investigation is located at the center and TD simulation is performed.

- **PML Routine:** A 5 to 8 cell perfectly matched layer (PML) blocks surround the computation space to simulate free space (open region) with minimum unwanted reflections.

- **NTFF Routine:** A standalone routine to extrapolate near fields simulated around the geometry under investigation directly in time domain that uses Huygen's principle. In this routine, surface electric and magnetic currents over a virtual closed surface between the geometry and PML termination are calculated in rectangular coordinates, and then far zone electric fields in spherical coordinates. Actually, it may be summarized as to accumulate far zone TD vector potentials due to the tangential electric and magnetic fields on this virtual closed surface at each time step. A gap of 6 to 10 cells between both the geometry and virtual surface and the PML termination and virtual surface is practically adequate for this purpose. This routine is required to obtain antenna patterns with and/or without human head.

- **Power Routines:** Two routines are prepared to calculate radiated power and absorbed power. Radiated power is calculated by using Poynting vector over the virtual closed surface enclosing the geometry. By using the tangential electric and magnetic field components at the virtual surface, radiated power is calculated from

$$P = \oiint_S (\mathbf{E} \times \mathbf{H}) \cdot \mathbf{dS} \tag{2}$$

where **E**, **H** and **dS** are electric field, magnetic field and, surface element vectors, respectively. Here, **dS** is defined as $\mathbf{dS} = dS \cdot \mathbf{n}$ where **n** is the normal vector outwards the surface.

Absorbed power at each cell is calculated from $\sigma|\mathrm{E}|^2$ and total absorbed power in a medium or a tissue is derived by volume integration.

Both FDTD and TLM techniques are based on exact analytical formulations. Major error sources are geometric approximations (staircase discretization), imperfectness of the PML termination and the numerical dispersion. Although all may be dominant depending on the case we are interested in, the numerical dispersion is the most annoying one.

Numerical dispersion is a kind of relation among the wave component, the frequency and the spatial discretization step, and mentioned by the ratio of minimum wavelength λ_{min} (i.e., maximum frequency) component to spatial mesh size ($\Delta\ell$). In practical applications (e.g., in EM problems from RCS and antenna analysis to microstrip network simulations), depending on the topology of the problem ratios of 10 to 150 is used. A ratio of 10 is roughly acceptable in most of the simulation techniques both in time and frequency domain, such as FDTD, TLM and also Method of Moments (MoM). As will be shown, a generally applicable strict threshold number for this ratio shall not be given. Depending on the complexity of the problem, it sometimes may be sufficient to use ratio of 10-20, but sometimes that of 100-150. Therefore, the modeler should experience the optimum ratio before doing physical analysis, in order to reduce computation time.

To test SAR_F and SAR_T packages against numerical dispersion, structures in Figure 5 are taken into account. A perfectly electrical conductor (PEC) resonator is used to eliminate errors introduced by PML blocks. The size of the resonator is taken as 26cm×26cm×26cm. Once differentiated Gaussian point pulse source (having 2.5GHz bandwidth) is used to excite E_y component of the electric field at mid-height near (3cm in front of) the left wall and same component is observed at the same height near right wall (see the figure). The simulation is repeated with different $\lambda_{min}/\Delta\ell$ ratios and an example is presented in Figure 6. Here, time variations of normalized E_y at the observation point is plotted for the ratio of minimum wavelength (λ_{min}=12cm) to the mesh size ($\Delta\ell$=0.5cm), $\lambda_{min}/\Delta\ell$=24. Almost excellent agreement is clearly observed in the figure for this highly oscillatory behavior. Very good agreement is obtained also for $\lambda_{min}/\Delta\ell$=12 (which is not shown here). Tests performed with $\lambda_{min}/\Delta\ell$=36 are assumed to be reference for this case and others are checked against the reference solution and it is concluded that $\lambda_{min}/\Delta\ell$ ratio of 15 to 20 is quite acceptable for this test case.

Then, a five-facet PEC cube of 10cm×10cm×10cm is located inside this PEC resonator (as shown in Figure 5) and same procedure is repeated. The results are plotted in Figure 7. Here, normalized E_y vs. time are given for three different $\lambda_{min}/\Delta\ell$ ratios (12, 24 and 36, respectively). Although, quite good agreement is obtained between the results of the packages SAR_F and SAR_T, there are still major discrepancies at certain time instants (see, for example, around 8ns-9ns).

The simulation of short pulse propagation inside a PEC resonator requires tracing short pulse bouncing back and forth at six walls, where multi-reflection and high interference occur. These are mostly first order scattering mechanisms. On the other hand, when another PEC structure is located inside, with one facet open, beside the first order scattering mechanisms (i.e., specular reflections) additional complex wave phenomena also occur. For example, second order scattering mechanisms, such as edge and tip diffraction, surface waves, etc. may well be excited inside the second structure.

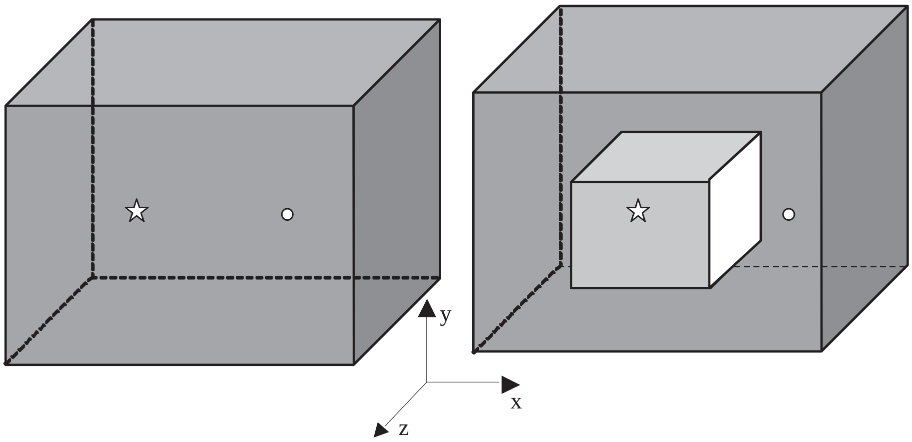


Figure 5. Two structures used in numerical dispersion tests. (left) a PEC resonator, (right) a PEC resonator with a five facet-PEC cube inside

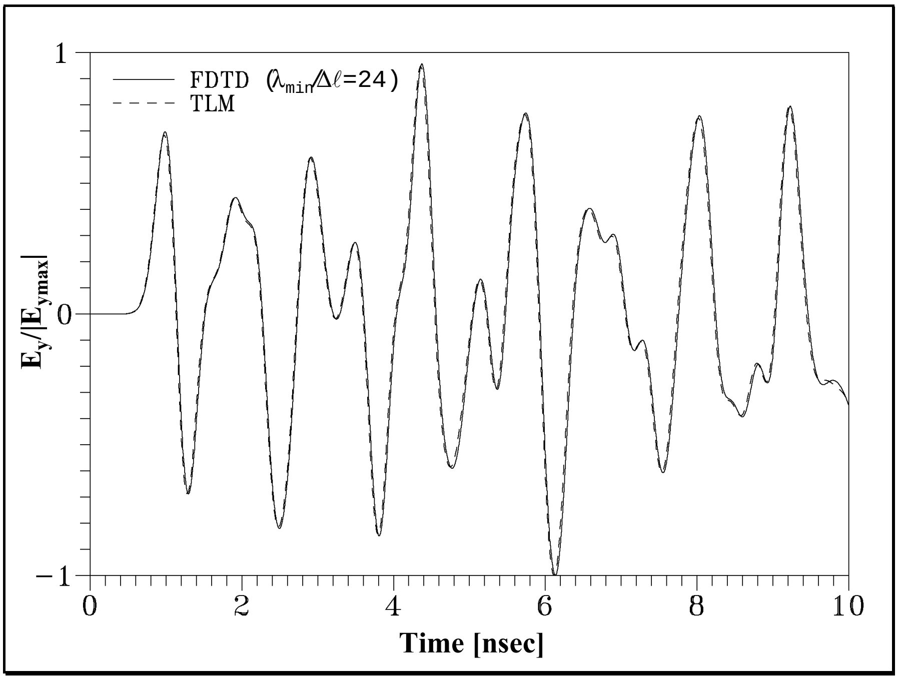


Figure 6. Normalized E_y vs. time for the test case given in Figure 5 (a PEC resonator on the left) SAR_T and SAR_F are made up $52\times52\times52$ and $53\times53\times53$ cells, respectively. Mesh size is $\Delta\ell$=0.5 cm.

Numerical dispersion is related to discretization (i.e., mesh size) and depends on the geometry of the problem at hand and the physical wave phenomena occur in that geometry. The geometry may be simple, but second order diffraction effects may be dominant, which may require higher minimum wavelength, mesh size ratios. On the other hand, the geometry at hand may be complex, but there may be only first order reflections, which can be handled with the ratios of 10 to 20. Moreover, the simulators may also cause some non-physical components (e.g., ghost modes, etc.). The packages may have quite different responses to those phenomena. Therefore, the modeler must determine the mesh size depending on the complexity of problem (either geometry or wave phenomena) at hand.

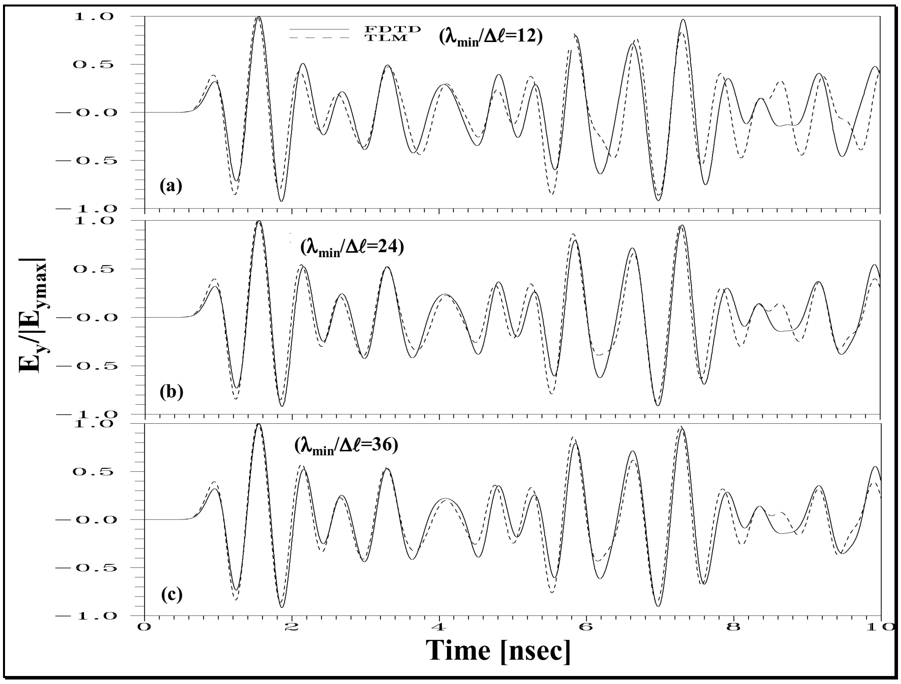
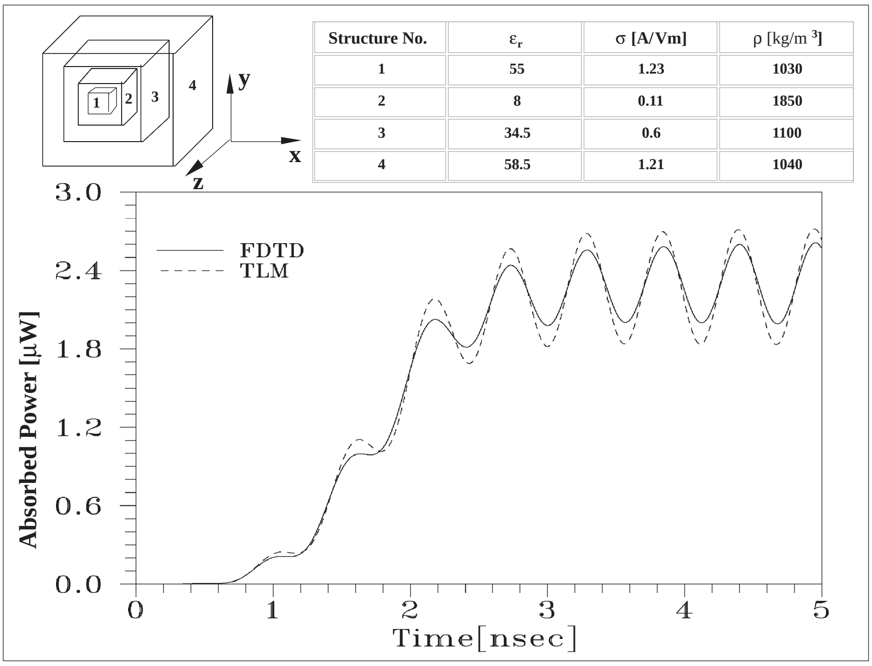


Figure 7. Normalized E_y vs. time for the test case given in Figure 5 (for the structure on the right) for three different $\lambda_{min}/\Delta\ell$ ratios (12, 24 and 36, respectively).

3.2. Canonical tests

The routines in SAR_F and SAR_T packages are also tested against canonical structures. For a comparison, first a cubicle structure is chosen as seen in Figure 8, of which electrical parameters are approximately equal to those in a human head. Here, a 5-cell PML is used for both packages. Since no discretization errors occur in cubical structures, it is possible to compare the results of TLM and FDTD techniques in terms of stability, numerical dispersion and accuracy. The instant absorbed power in this structure is plotted in the same figure to show the calibration of the TLM and FDTD codes and comparisons of the results. A $\lambda/3$ antenna is fed with sinusoidal wave whose frequency is 900 MHz (with 2 mm cell size), located near the structure. The dimension of the whole structure is 9.2 cm. The average of the absorbed power is equal for both methods, while the peak power differs slightly because of numerical dispersion.

Another example is given in Figure 9, where SAR values averaged over a tissue mass of 1 g (SAR_{1g}) at the center of the structure is calculated and the results of TLM and FDTD are compared. The slight divergence in the results for SAR_{1g} can be reduced by decreasing the cell size (i.e., reducing the effect of numerical dispersion). The instant SAR values calculated at each cell in the horizontal slices are seen in Figure 10 for the steady state time case. The scale at the left hand side of the figure changes from zero to its maximum SAR value for each slice individually. The maximum SAR values for each slice are written in the same figure. As it is clear, the SAR values at the regions close to the antenna are higher, and the results of FDTD and TLM are almost identical. The similar comparison is repeated for the vertical slices of the same structure and the results are given in Figure 11. Note that, at some slice positions, the maximum values for both methods are different.



Structure No.	ε_r	σ [A/Vm]	ρ [kg/m ^{3}]
1	55	1.23	1030
2	8	0.11	1850
3	34.5	0.6	1100
4	58.5	1.21	1040

Figure 8. Absorbed power in a cubical test structure

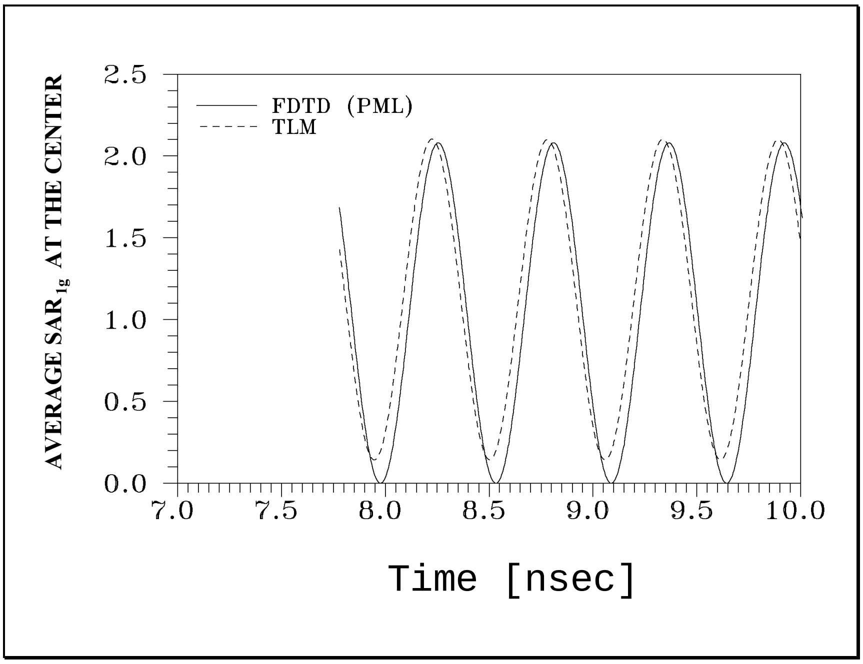


Figure 9. Instant SAR$_{1g}$ at the centre cell

3.3. Human head model

In order to compute SAR values, the chosen human head model derived from numerical magnetic resonance (NMR) image by semi-automatic algorithm is located within computation volume together with an EM source such as antenna [5]. In this model, seven different tissue types are used with their electrical parameters (ε_r, σ) and densities (ρ) at the frequencies of interest. It should be noted that, the dimension of the head is factorized by 0.5 (i.e., the numerically implemented head is half size of a mature human head), in order to meet the memory requirements.

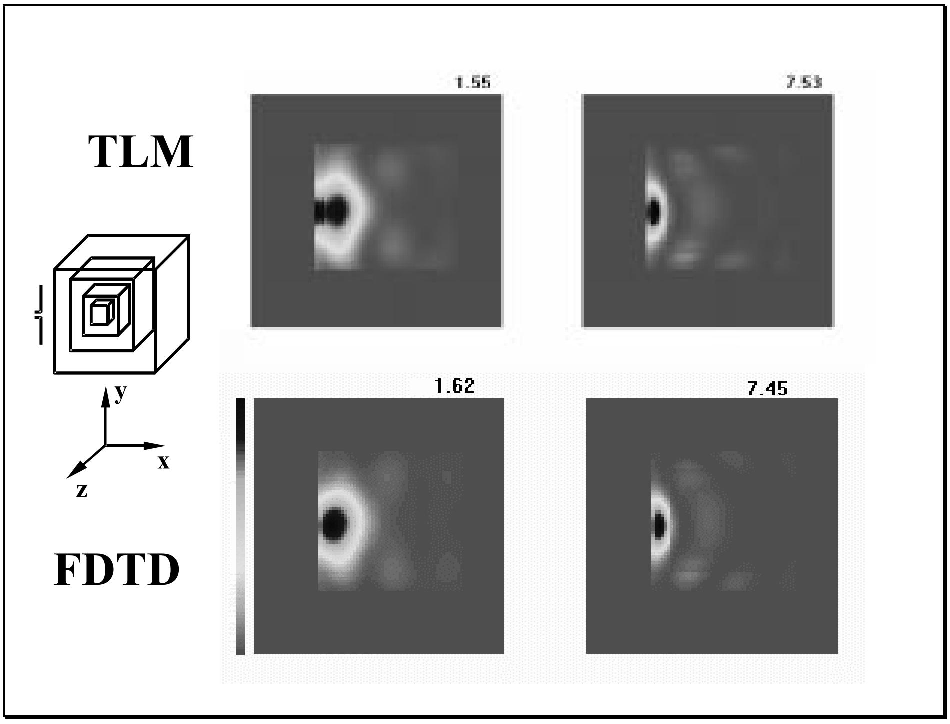


Figure 10. SAR values at horizantal slices

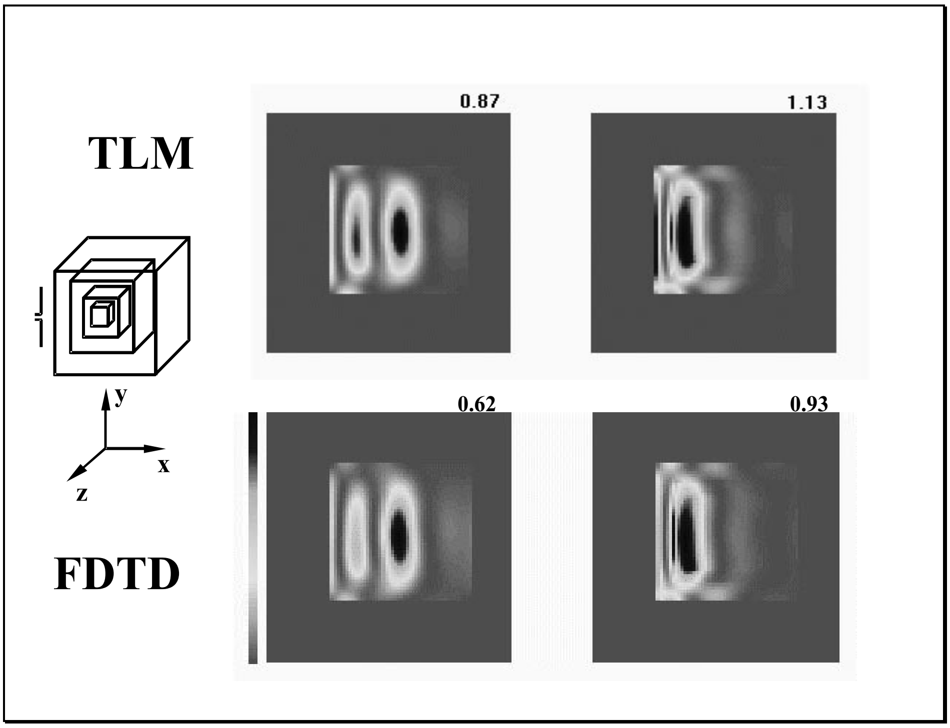


Figure 11. SAR values at vertical slices

The instant SAR values calculated via SAR_T at each cell in the vertical slices of head model are seen in Figure 12 for the steady state time case. The maximum SAR values for each slice are written in the same figure. The SAR values in the brain, of which conductivity is more effective, are high. Also if the tissue is closer to the antenna, it results in obviously high SAR values. The same calculations are repeated with the SAR_F simulator and the results are given in Figure 13.

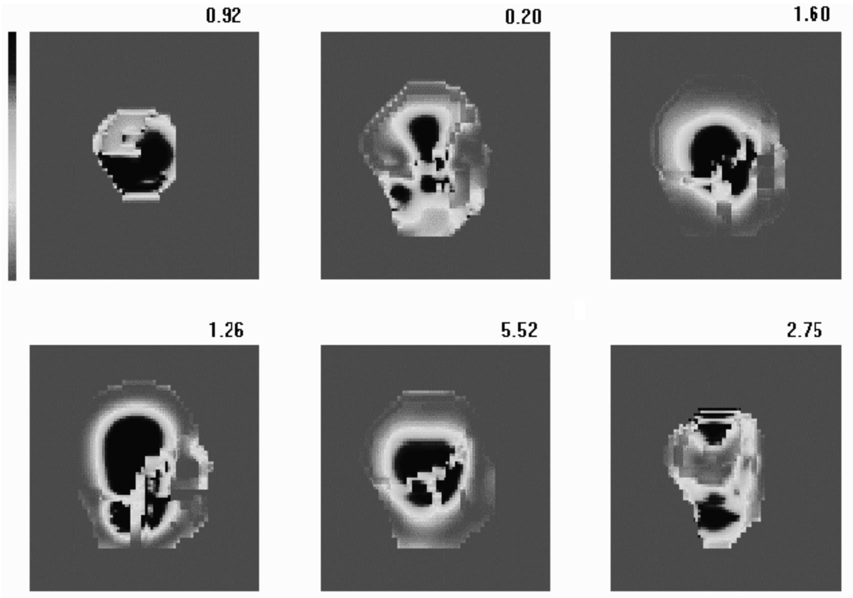


Figure 12. SAR values at vertical slices of the head obtained via SAR_T package (Computation space: $100 \times 100 \times 100$, head size: $64 \times 48 \times 48$, cell size:2mm)

Comparisons of the simulation results of different groups are very important. On the other hand it is difficult to show a one-to-one correspondance between our data and the results in the literature, because (i) different human head models are used, (ii) the handset and the antennas as well as their position have significant effects on the EM exposure. The results of local SAR values which agree from different calculations (SAR_T and $SART_F$) at different cells may be in the order of the values presented in the literature.

4. Risk Assessment and the Precautionary Principle

A new discussion -EM pollution- has been raised in the public all around the world parallel to exponential increase in cellular phone users. Because of the lack of information and long-term experimental and epidemiological studies, there exist contradictory opinions on EM exposure safety levels in societies. Different governmental offices, universities, media and non-profit organizations may have different approaches for this problem, since available scientific knowledge is far from ending these discussions. Believes may totally be different from one group to another. It is the obligation of the scientists not to confuse believes with scientific studies. Because of the lack of information enough to end these discussions, scientific society has recently focused on the risk assessment and the precautionary principle.

Risk assessment is the process whereby the potential adverse consequences (hazards) associated with a technology or developments are identified, and the probability (risk) of their occurrence is estimated. The hazards may be to human health or to the environment, or may be economic, but here the focus is on hazards to human health. Since our knowledge of physical world is never complete, there is always the possibility of yet to be discovered hazards, especially related to long-term, low level exposures. Moreover, risk perception varies with the situation. For example,

⇒ risks that are familiar are more acceptable than unfamiliar ones,

⇒ risks that are taken unwillingly (e.g., base stations) are less acceptable than those taken willingly (e.g., mobile phones),

⇒ risks that are controlled by others are less acceptable than those controlled by us, etc.

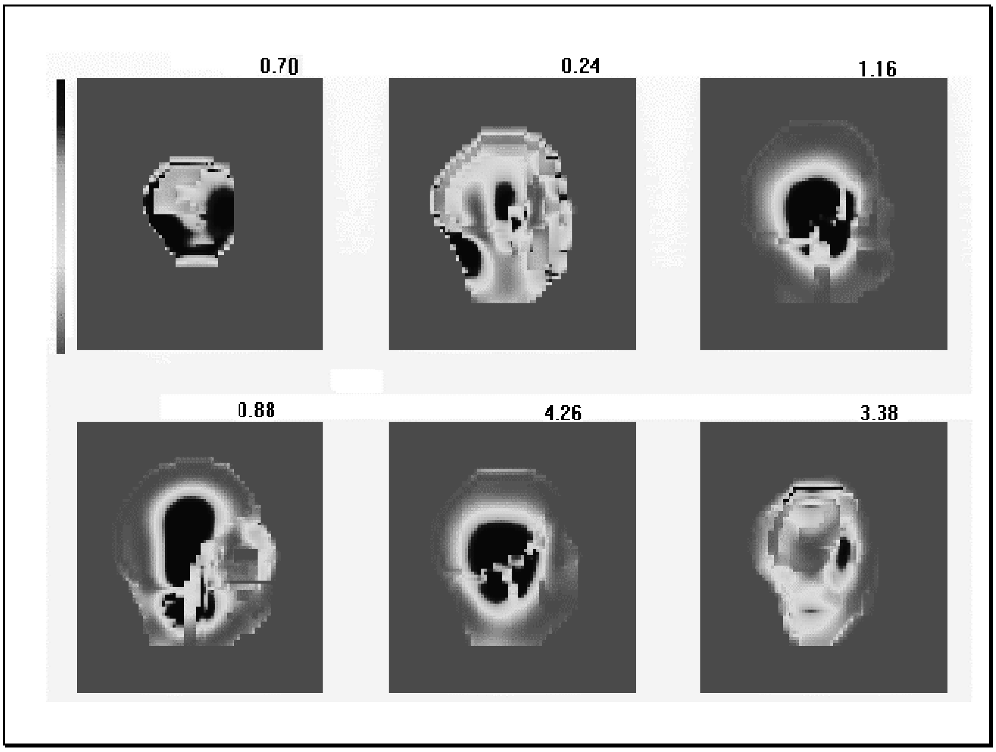


Figure 13. SAR values at vertical slices of the head obtained via SAR_F package (Computation space: $100 \times 100 \times 100$, head size: $64 \times 48 \times 48$, cell size:2mm)

A common approach in risk management is to identify a critical adverse health effect, (usually that which occurs at the lowest level of exposure). The lowest exposure at which this effect has been shown to occur is then multiplied by an "assessment" factor, also known as a "safety" or "uncertainty" factor, to derive an exposure limit or guideline. The aim is that, below this limit, exposures will not cause the adverse effect in any individual [28]. The policy by which a precautionary approach is applied to risk management in situations of scientific uncertainty has been termed the precautionary principle [29].

The precautionary principle should be considered within a structured approach to the analysis of risk, which comprises three elements: risk assessment, risk management, risk communication. It is essentially used by decision-makers in the management of risk, and should not be confused with the element of caution that scientists apply in their assessment of scientific data. The decision-making procedure should be transparent and should involve as early as possible and to the extent reasonably possible all interested parties. It is discussed in [29] that, where action is deemed necessary, measures based on the precautionary principle should be;

- *proportional* to the chosen level of protection,
- *non-discriminatory* in their application,
- *consistent* with similar measures already taken,
- *based on an examination of the potential benefits and costs of action or lack of action* (including, where appropriate and feasible, an economic cost/benefit analysis),
- *subject to review,* in the light of new scientific data, and
- *capable of assigning responsibility for producing the scientific evidence* necessary for a more comprehensive risk assessment.

Finally, it should be noted that epidemiological studies provide the most direct information on risks of adverse effects in human beings. Although, these studies have severe limitations (especially when low relative risks are found) long-term, large-scale studies should be carried out to fill in the knowledge gaps in this area. Fundamental research should be thought as of complementary to epidemiology in this subject.

5. Conclusions

Two powerful numerical simulation packages are tested against each other in this study. Since they are based on well-established models (Field and Network theories) validation reduces to "*debugging*" only, which is done at the very beginning. Verification is quite complicated for these packages, since characteristic scenarios should be prepared, and the results of the obtained via simulators must be compared with available reference data. It should be noted that, although comparisons between the two packages are done and very good agreement are obtained, they may still be incorrect and it may not be understood because of the lack of reference data. Moreover, it should be remembered that numerical simulation is a kind of intelligent game and their results should be verified against reliable solutions. In these kind of complex problems, reliable measurement data may best serve as reference results, since analytical exact solutions are rarely available. Standardization efforts of laboratory SAR measurement have not concluded yet and discussion on the suitability of SAR parameter in determining EM exposure levels has still continued. Nevertheless, SAR is still the only measurable, engineering parameter at hand.

Ongoing electromagnetic pollution debate seems to continue in the near future and the problems will not be resolved in a short period. The trend is towards the understanding of risk assesment and the precautionary principle. Although, scientific research based on SAR simulations/measurement is essential, reliable solution can not be obtained without long-term, large-scale epidemiological studies, therefore these studies should be carried out with international cooperative labor.

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