Modulation Influence on RF Fields Power Deposition
Inside Biological Objects:
A Dosimetric Analysis on Layered Planar and Spherical Models

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Abstract. A theoretical dosimetric approach is followed in the radiofrequency region of the electromagnetic spectrum. Analytical methods are applied in order to compute the absorbed electromagnetic field inside planar and spherical models of biological objects. Two algorithms are implemented in Mathcad environment: one is based on transmission line theory – for treating the planar layered models, and the other, based on Mie theory of electromagnetic scattering – for treating the spherical homogeneous and layered models. The excitations are microwaves in the UHF and SHF bands, either continuous or modulated. Features of absorbed fields are targeted, and differences underlined. Generally, modulated fields have different deposition features in the models, depending on both the target geometry and dielectric characteristics, and on the incident signal spectral content. The functionality of the algorithms for modulated signals is proved here, and partial conclusions extracted. For the near future our focus is the generalization of conclusions and finding of the rule of thumb regarding field deposition of modulated fields.

1. Introduction

Biological effects due to radiofrequency (RF) field exposure are numerous and well represented in literature. Special attention was attracted when experimental work showed that modulation parameters may influence the biological response, and “window effects” were observable (both frequency and amplitude windows) [1], [2]. Even the total amount of delivered energy to the absorber was the same for a continuous wave (CW) and for a modulated field, at the same frequency, and the two signals had the same average power, it was observed that the time course of energy deposition and dissipation was different.

Origin of differences was mostly analyzed from the biological point of view, in the light of direct experimental observations [1]. However the physical interaction between a signal and a heterogeneous dielectric object may imply a specific response component, even that it is clear that the role of biological structure as a live system is very important. In a first approach, pure physical reasons are to be analyzed, to partially explain such differences, if any. Conclusion of such analysis may offer a prediction of location of the “windows” with a high degree of confidence and may firmly establish the nature of response. Lack of theoretical analysis dealing also with modulated RF field’s excitation of layered models is notable [3].

On this background, the aim of present paper is a comparative analysis of RF power absorption features in depth of layered biological models, when excitatory signals are continuous and digital modulated ones, and their carrier frequency is in the UHF and SHF range. Local specific absorption rate (SAR) is calculated inside planar and spherical models and its variation along depth in the model is represented, so as a view of differences due to modulation characteristics to be outlined.

2. Materials and method

For 300 MHz - 6 GHz band, the relevant measure of power deposition in the biological matter is the specific absorption rate (SAR – in W/kg). For stationary sinusoidal waves, the temporal average SAR in one spatial point (local SAR) is given by:
\[ \text{SAR} = \frac{P_v}{\rho_m} = \sigma \cdot \frac{|E_{\text{int}}|^2}{\rho_m} = \omega \varepsilon_0 \varepsilon \cdot \frac{|E_{\text{int}}|^2}{\rho_m} \]  

(1)

where \( \sigma \) is the electrical conductivity of the material, \( \omega \) is the pulsation of the wave, \( \varepsilon_0 \) is free space permittivity, \( \varepsilon \) is the loss factor of the material and \( |E_{\text{int}}| \) is the root-mean-square magnitude of the electric component of the field in the point of interest.

The methods used here for calculation of the internal field and SAR respectively, are analytical methods. In the case of planar layered model, the transmission line equations are used [4], while for the spherical model the Mie theory is the fundament [5], [6], [7].

The incident field is a continuous or a digital modulated RF field (harmonic plane wave, linearly polarized) that penetrates into the layered model. The considered modulation types for present calculations are amplitude shift keying (ASK) and frequency shift keying (FSK). The form of an incident ASK signal is:

\[ E_{i}(t) = \begin{cases} E_0 \cdot e^{j \omega_c t} & 0 \leq t \leq \tau \\ 0 & \tau < t \leq T_0 \end{cases} \]  

(2)

where: \( E_0 \) is amplitude of the incident field, \( T_0 \) is the repetition period of the pulses, \( \tau \) is the duration of a pulse and \( \omega_c \) is the carrier pulsation. The FSK signal can be expressed as:

\[ E_{i}(t) = \begin{cases} E_0 \cdot e^{j(\omega_c - \Delta \omega) t} & 0 \leq t \leq \tau \\ E_0 \cdot e^{j(\omega_c + \Delta \omega) t} & \tau < t \leq T_0 \end{cases} \]  

(3)

2.1. Computation algorithm for the planar models

For planar model computations, we took the case of a TM-polarized wave (H component along the separation interfaces) that propagates in the Oz direction of the model. For the calculations we choosed a three-layered model and a seven layered model respectively. The first (i=1) and the last layer (i=5 and i=9 respectively) are considered semi-infinite air layers, while the interior biological layers are human tissues. We hypothesize that they are homogeneous, isotropic and linear media.

Considering an incident CW (a single spectral component), the transmitted field in i-th layer, at depth \( z \) (origin is considered each time at the i/(i+1) interface, and \( z \in (0,d_i) \)), can be calculated using the relation:

\[ E_i(z) = E_{i-1}^0 \frac{\cos \theta_i}{\cos \theta_{i-1}} \left( e^{-k_i z} + R_{i+1} e^{-k_{i+1} z} \right) \prod_{j=2}^{i} \left( 1 + R_j \right) e^{-k_j z} \]

(4)

where \( E_{i-1}^0 \) is the amplitude of the electric component in the air layer (i=1), at the separation surface, \( \theta_i \) is the incidence angle on the model (at air-2nd layer interface), \( \theta_{i-1} \) is the incidence angle on the i/(i+1) interface, \( R_{i+1} \) is the reflexion coefficient at the same interface, \( k_i \) is the complex propagation constant in i-th layer and \( d_i \) is the thickness of the j-th layer.

In the case of modulated signals that penetrate the planar layered model, each spectral component propagates in a different manner. Relation (4) must be rewritten for each n Fourier component, and gives the \( E_{i,n}(z) \) internal field value. Calculation of the transmitted field of the n-th harmonic in the i-th layer, \( E_{i,n}(z) \), at one specific depth \( z \), allows then the total field calculation in one layer, as the sum of the spectral transmitted components. The dependence of \( \varepsilon_{ri,n} \) (complex relative permittivity of the n-component in the i-th layer) of each harmonic was extracted from the parametric model of the dielectric properties of human tissues [8].

The local SAR for a modulated signal in the i-th layer, will be:
\[ SAR_i(z) = \frac{2}{\rho_i} \sum_{n=1}^{\infty} n \omega_0^2 \varepsilon_{\text{air}} \text{Im}(\varepsilon_{\text{air},n}) \left| E_{i,n}(z) \right|^2 \]  

(5)

where \( \rho_i \) is the mass density of the tissue layer \( i \), and \( \omega_0 \) is the repetition pulsation.

For calculations presented below we used the planar layered model. The incidence angle can be varied from 0 to \( \pi/2 \) rad, and the amplitude of the incident field is considered \( E_0=19.41 \text{V/m} \) (corresponding to an incident power density of \( 1 \text{W/m}^2 \)). The mass density values for human tissues are extracted from [9].

A number of graphs showing SAR variation along the depth in the model (layers) were represented and analysed, for different modulation parameters of the signals. Three excitations were applied for comparison, and are shown as they penetrate in the layers: ASK, FSK and CW case. Relative SARs were also represented, by dividing SAR(\( z \)) to its value at the entrance in the layer, SAR(0), to show amplification features inside each layer. We also followed the behaviour of power deposition in the case when different thicknesses of the layers were considered. For all representations given in graphs below, \( \theta_1 = 0 \), since variation of the incidence angle was observed to have little influence on the absorption features.

2.2. Computation algorithm for the spherical models

In this case Mie theory equations were used. A sphere composed of three layers of human tissues was used in present calculations (\( p=1..3 \) - starting from the center of the sphere), while \( p=4 \) is the exterior air layer (fig.1). For an incident CW, that is linearly polarized (\( E || x \)) and propagates in the \( z \) direction, the transmitted field at one point of a layer, in spherical coordinates, is given by:

\[ E_p(r, \Theta, \Phi) = E_0 e^{j \omega_0 t} \sum_{n=1}^{\infty} (-j)^n \frac{2n+1}{n(n+1)} \left[ a_{np} \cdot M^{(4)}_{np}(k) + j \cdot b_{np} \cdot N^{(4)}_{np}(k) + c_{np} \cdot M^{(4)}_{np}(k_p) + j \cdot d_{np} \cdot N^{(4)}_{np}(k_p) \right] \]  

(6)

where the form of Mie coefficients \( a_{np}, b_{np}, c_{np}, d_{np} \) and the vectorial spherical functions \( M \) and \( N \) are given in [4]. In this case \( n \) denotes the number of components in the Mie series, and not the spectral component of the field, as in the above case. For practical reasons, in the calculation algorithm, summing after \( n \) is stopped for \( n_{\text{max}} = N \), where \( N \) is given by Wiscombe’s criteria [6].

If the incident signal is modulated, the transmitted field is calculated for each Fourier \( v \) component - \( E_{pv}(r, \Theta, \Phi) \) and finally all the transmitted components are summed to give total local SAR of the modulated signal:
SAR for CW case is calculated as in (5) or (7), but considering n and v respectively equal to 1. In the calculations on spherical model the same tissues as in the planar model were considered. All the calculations were performed in Mathcad environment.

3. Results and discussion

3.1. Planar model

The representations in figures 2 and 3 are for the three-layered model: (i=2=skin, i=3=fat, i=4=muscle). The layers thickness were: \( d_2=2.5 \text{ mm} \), \( d_3=10.0 \text{ mm} \), \( d_4=50.0 \text{ mm} \). The dependence of relative SAR on depth \( z \) in the model is shown, for next signal parameters: a) fig. 2 - the carrier frequency, \( f_c=3 \text{ GHz} \), the repetition frequency \( f_0=5 \text{ MHz} \); for the ASK signal, the duty cycle= 1/10; for the FSK signal, the duty cycle=9/10 and \( \Delta f=100 \text{ MHz} \); b) fig. 3 - the carrier frequency, \( f_c=400 \text{ MHz} \), the repetition frequency \( f_0=200 \text{ kHz} \); for the ASK signal, the duty cycle= 1/100; for the FSK signal, the duty cycle=1/2 and \( \Delta f=100 \text{ MHz} \).

The calculations of the Fourier coefficients of the incident signals were made using FFT in 2048 points (fig.2) and in 8192 points (fig.3). If we modify the number of points for FFT calculation, we obtain different absolute values of SAR. This is due to the effect of signal sampling process. However the curves allure of SAR is independent on the number of points for FFT calculation.

In fig. 4, the seven-layered model is used, (i=2=skin, i=3=fat, i=4=muscle, i=5=bone, i=6=muscle, i=7=fat, i=8=skin). The thickness of the layers were: \( d_2=2.5 \text{ mm} \), \( d_3=3.0 \text{ mm} \), \( d_4=21.0 \text{ mm} \), \( d_5=22.0 \text{ mm} \), \( d_6=21.0 \text{ mm} \), \( d_7=3.0 \text{ mm} \), \( d_8=2.5 \text{ mm} \). The CW has a carrier frequency, \( f_c=3 \text{ GHz} \), while for the ASK signal, the repetition frequency \( f_0=5 \text{ MHz} \) and the duty cycle= 1/10.

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FIG. 2. Power deposition in the skin-fat-muscle planar model, for an ASK signal (continuous line), for the CW (dot line) and for FSK signal (dash line) – SHF carrier (3GHz).
FIG. 3. Power deposition in the skin-fat-muscle planar model, for an ASK signal (continuous line), for the CW (dot line) and for FSK signal (dash line) – UHF carrier (400 MHz).

FIG. 4. Absorption pattern for ASK signal (solid line) and CW (dot line) in the seven-layered model – SHF carrier (3GHz).
In the case of a monolayer model, it has been shown that the steady-state transmitted field at a specific depth in a layer can be expressed as a function of a transmission function of the layer, which depends on the dielectric dispersive characteristics, on the wave characteristics and on the depth in the layer [10]. By using such a representation, a better understanding of the mechanism by which the modulated signal propagates is gained, because superimposing of the transfer function on the spectral density of the Fourier coefficients of the incident signal decisively influence the features of the absorbed power. Practically, the incident signal spectrum is filtered by the transfer function.

The locations of relative SAR extreme values inside the layer depend on the incident signal characteristics in connection to the dimension of the layer and its dielectric properties: they may be the same (as in fig. 2 and fig. 3) or may differ (as in fig. 4). Following SAR values distribution along one layer for the same signal, one observes that they vary and this behavior depends on the dielectric characteristics and the thickness of the layer: the thicker the layer, the more variations of SAR are to appear.

Any modification of the signal parameters affects the SAR distribution, and its absolute values at the same depth in the model. The signal’s spectrum is centered on the carrier frequency and the modulation parameters influence the bandwidth and the magnitude of the spectral components. Remarkable modifications of SAR distribution in depth can be observed only if the significant spectral components are covered by the transfer function of the layer. For example, in the case of the ASK modulation, the duty cycle decreasing conduct to differentiation of SAR distribution comparing to the CW case.

The attenuation slope of SAR is lowest in the case when the carrier frequencies are low and these signals penetrate deeper in the model, no matter of the modulation characteristics.

SAR values, as one goes from one layer to another, are amplified or attenuated, as a function of the relative refraction index of two adjacent layers.

3.2. Spherical model

The heat distribution mechanism inside a homogeneous sphere irradiated by CW was comprehensively described by Kritikos and Schwan [11] and by Ho and Guy [7]. In [11] authors defined a useful a-f diagram for separating the two possible types of maximum power deposition (superficial and internal distribution) - where a is the radius of the sphere, and f is the frequency of the CW illumination. Following their findings, the case when the wavelength inside the sphere ($\lambda_i$) is of the same order of magnitude as the radius a, is of most interest. For $\lambda_i < a$, they showed that the energy is focused just beyond the centre of the sphere, while for $\lambda_i > a$ resonant energy distribution with peaks inside the volume of the sphere is encountered. The latest case seems to pose the biggest concern. They also found equivalence relationships between relative variation of radius and relative variation of the dielectric parameters (conductivity and dielectric constant) that influence the peak absorbed power positioning in the two cases. Later, the study of RF power deposition inside a homogeneous sphere irradiated by a spectrum of electromagnetic plane waves concluded that the power distribution is not easily predictable from the summation of the power density of the incident plane waves composing the spectrum [12].

On the basis of these findings, a first approach of ours was set to follow the internal E-field distribution inside a homogeneous muscle sphere (with radius a=10cm) irradiated by either a CW, a modulated FSK signal or a modulated ASK signal (fig.5). The signals characteristics are: for CW - f=910MHz, for FSK - the carrier $f_c=910$ MHz, repetition frequency $f_0=91$ MHz, $\Delta f=50$ MHz and duty factor=1/2 and for ASK - the carrier $f_c=910$ MHz, repetition frequency $f_0=91$ MHz and duty factor=1/2. Differences between CW deposition and modulated waves deposition are observable in depth of the sphere. At this moment no extent calculations were done yet, but they need to be done on a wide range of size-frequency combinations so as the rule of thumb to be extracted.
In fig. 6 the homogeneous muscular sphere is illuminated by the same frequencies as the CW applied to the planar stratified model, \( f=400\text{MHz} \) (fig. 6a) and \( f=3\text{GHz} \) (fig. 6b). The sphere has the same radius as the total thickness of the first investigated planar model, \( a=6.25\text{cm} \). One notes the important modification of field deposition with frequency.

The layered spherical model is under analysis at present. This approach has, at its turn, taken into account previous results presented in [13], [14], [15]. Interesting aspects were recently revealed also in [16], but still only the CW case is treated. Generally, it was demonstrated that multilayered model shows an extra resonant absorption than homogeneous model, situated in the higher frequencies range, where \( k_0a=1.3\ldots5 \) (where \( k_0 \) is the propagation constant in free space). The additional resonance of the layered model at higher frequencies is due to impedance matching effects of the layers. This “layering resonance” [15] is present both in planar and in spherical layered models. It may be independent of

*FIG. 5. The distribution of the normalized E-field intensity in the meridian plane \( \Phi=\pi/3 \) of the homogeneous spherical model for a CW with \( f=910\text{MHz} \) (a), for a FSK-modulated signal (b) and for an ASK-modulated signal (c), on the same carrier frequency as CW.*
the geometrical resonance (revealed in the homogeneous sphere treatment) if the layering resonant frequency is well above the geometrical resonance (i.e. the surface layers responsible for the layering resonance represent a small fraction of the overall size of the object). The planar model can well predict the layering resonance in the sphere, both in absorption efficiency and in the location of the resonant peaks, if the geometrical resonance is independent from the layering resonance.

![Image of normalized E-field intensity](image)

**FIG. 6.** The distribution of the normalized E-field intensity in the meridian plane $\Phi=\pi/3$ inside the homogeneous muscular sphere for a CW with: a) $f=400$ MHz; b) $f=3$ GHz.

Following these findings, next step is modelling a muscle-fat-skin sphere. This is done so that the layers in the sphere to have the same thickness as in the first chosen planar model, i.e. the radius of the layers are: $a_1=50\text{mm}$, $a_2=60\text{mm}$, $a_3=62.5\text{mm}$. The external layers represent 25 % of the total sphere radius. We are in the case when layering resonances may be predicted by the planar layered model, and we’ll look after this feature. The incident CW applied to the sphere should have the same frequencies as in the case of planar models: $f=400$ MHz and $f=3$ GHz respectively. The internal field distribution in the meridian semi-plane for $\Phi=\pi/3$ is to be represented for the layered sphere and will be compared to the results obtained for the homogeneous spherical model composed by muscle ($a=62.5\text{mm}$), as it appears in fig. 6 (a and b). This methodology should allow verification of the prediction of planar layered model absorption resonances, and is prepared for near future.

Second step in our next computational approach is the assessment of modulation implications upon field deposition in the layered spherical model. As seen in the planar layered model and in the homogeneous spherical model, differences in field deposition are notable when CW or modulated fields are applied.

4. Conclusion

The computational technique presented here, even relatively restricted due to analytical approach usage, is suitable for in-depth analysis of RF signal’s absorption inside simple models of biological objects. Various types of digital modulated RF field can be solved by using the proposed algorithms, allowing a primary view of differences in power deposition due to different modulations.

Using planar models and solving the propagation problem by the means of a transmission line method algorithm offer a basic energetic explanation of the pure physical reason for possible different responses of biological targets to various RF electromagnetic stimuli. The phenomena observed in the
case of planar model excitation may be explained in terms of transmitted spectral content of the signal, if one takes into account the selective role of the transmission function of the layer. In order to get the value of the internal electric field or finally SAR, one needs to convolve the spectral content with the transmission function. When running the algorithm, care must be taken in order to get accurate values of SAR: the computation capabilities must satisfy the need that the signal sampling process to allow a sufficient number of points for FFT calculation.

The spherical models present more complex distribution of the absorbed energy, due to both geometry and to layering. By applying Mie theory of electromagnetic scattering, one can solve the internal field distribution in either homogeneous or stratified models. Calculations were done in the past, but mostly using CW. We were interested in the problem of modulation influence assessment. When excited by modulated fields, the homogeneous model responds different, at the same location, for different signals. In the spherical case, differences are more obvious than in the planar model case, proving that the geometry of the target is very important. Sitting of SAR resonances may differ from the case when a planar model is exposed. Refining the model by layering it may conduct to higher complexity of the field deposition. A future approach will follow the predictive power of the planar model to the absorption features of the spherical model, in the case when modulated signals are applied.

Even if a gross theoretical assessment on simplified models is not of great value to conclude when one deals with real cases, it sustains the differentiation that may appear in responses of non-alive dielectric structures to various modulations of RF fields. Present computations will be extended to a wider range of size-dielectric parameters-frequency combinations for a better understanding of the physics behind the phenomena.

REFERENCES


