Application of Quasi-Static Approximation Technique for Dipole Antenna Analysis to Bioelectromagnetic Problems

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Abstract

In this paper, a quasi-static approximation technique for improving the accuracy in the Finite Difference Time Domain (FDTD) analysis of dipole antenna is appied to the bioelectromagnetic problems. In the numerical simulation of bioelectromagnetic problems, the FDTD cell size is normally determined by the voxel size of the lossy dielectric bodies, such as the numerical human models. This limitation of cell size causes the difficulty in modelling a dipole antenna which is placed nearby the dielectric body. The calculations using different cell sizes which results in different dipole antenna length have confirmed the validity of the technique. Moreover, the modification of the FDTD cells to model the exact antenna length and overcome the difficulty when antenna radius is equal to half cell size is examined. In both cases, the quasi-static approximation technique can achieve good agreement results.

1. Introduction

In recent years, according to the rapid growth of the mobile communication system, many peopole are concerned about the possible effects of human health from the radio-frequency electromagnetic fields radiated by the mobile communication devices such as a mobile phone. Since it is difficult to evaluate the exposure characteristics directly in the living human, the numerical technique is needed. The Finite Difference Time Domain (FDTD) method [1], [2] is one of the currently widely used numerical dosimetry applied to the problem of the exposure of the human body to the radiation from mobile communication devices due to its simplicity and efficiency to model inhomogeneous structures of complex shapes such as a human body. However, it encounters difficulty in low accuracy results when applying the FDTD method to a thin-wire antenna.

In order to overcome this difficulty, authors have proposed a quasi-static approximation technique for improving the accuracy in the FDTD analysis of dipole, rectangular loop, and V-dipole antennas [3], [4], [5]. In this technique, the update equations in the FDTD method are modified by incorporating a quasi-static field behavior near antenna conductor into the Faraday's and Ampere's law contour-path integral formulations. The validity of the quasi-static approximation technique has been confirmed only for the simple antenna analysis. The calculation results of the proposed method agreed well with those of the Method of Moment (MoM) with higher accuracy than both conventional FDTD and $1/\rho$-subcell method [6].

We have introduced the application of the proposed quasi-static approximation of simple dipole antenna to the bioelectromagnetic problems [5]. The high accuracy antenna analysis results in the higher accuracy of the electromagnetic exposure evaluation of the Specific Absorption Rate (SAR) inside the lossy dielectric body. In this paper, we considered the limitation of the cell size. When the lossy dielectric bodies such as the numerical human-body models are used, the FDTD cell size is determined by the voxel size of the models. The limitation of the cell size results in the different antenna length in order to located the antenna ends on the FDTD cell edge. We show calculation results using various cell sizes and also introduce the modification of the FDTD calculation for modeling the exact length of dipole antenna even the antenna ends does not locate on the FDTD cell edge. The modification of the FDTD calculation when the radius of dipole antenna is larger than half cell size is also examined. The numerical results of spatial averaged SAR obtain using the quasi-static approximation technique are shown comparing with those of the $1/\rho$-subcell method.

2. Quasi-Static Approximation of Dipole Antenna

We consider a dipole antenna with geometry shown in Fig. 1. A dipole antenna consists of a hollow perfectly conducting cylinder fed by a delta gap voltage. The current distribution on the dipole antenna surface is assumed using the quasi-static field behavior as follow.

$$J_z(z) = \begin{cases} \dfrac{I}{2\pi a}\left(1 + \dfrac{z}{h_1}\right), & -h_1 \le z \le 0 \\ \dfrac{I}{2\pi a}\left(1 - \dfrac{z}{h_2}\right), & 0 \le z \le h_2 \end{cases} \tag{1}$$

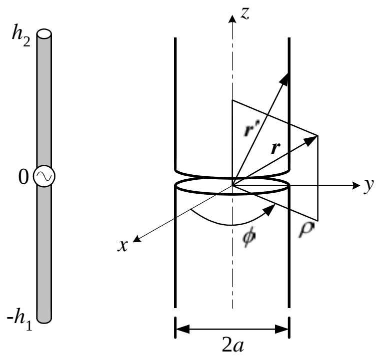


Fig. 1: Dipole antenna model.

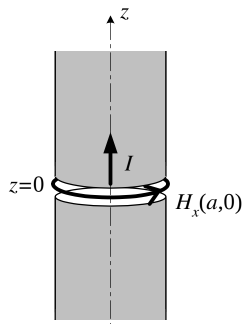


Fig. 3: Modified feeding current calculation.

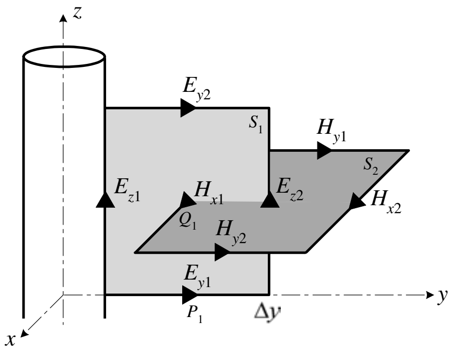


Fig. 2: FDTD cells near the antenna conductor.

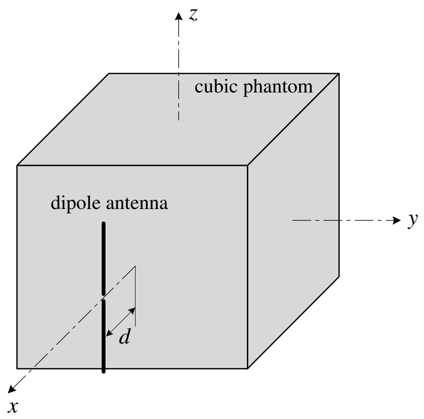


Fig. 4: Numerical simulation model.

We assumed that the FDTD cells near the antenna conductor as shown in Fig. 2 have the cell size considerably smaller than the wavelength, and the electric and magnetic fields in the FDTD cells should be dominated by the quasi-static field. With this assumption, the spatial dependence of electric and magnetic fields can be approximated as follows.

$$E_y(\boldsymbol{r},t) = E_y(P_1,t)\frac{\partial F(\boldsymbol{r})/\partial y}{\partial F(\boldsymbol{r})/\partial y|_{\boldsymbol{r}=P_1}} \tag{2}$$

$$H_x(\boldsymbol{r},t) = H_x(Q_1,t)\frac{\partial A_z(\boldsymbol{r})/\partial y}{\partial A_z(\boldsymbol{r})/\partial y|_{\boldsymbol{r}=Q_1}} \tag{3}$$

Where $E_y(P_1,t)$ and $H_x(Q_1,t)$ are the electric and magnetic fields located on the FDTD cell and $F(\boldsymbol{r}) = \partial A_z(\boldsymbol{r})/\partial z$. By substituting these field approximations into the integral form of the Faraday's and Ampere's laws, the modified FDTD update equations for the FDTD cells near the antenna conductor can be derived.

Furthermore, the feeding current calculation was also modified using the quasi-static approximation of magnetic field. The contour integral of magnetic fields is modified as shown in Fig. 3. The feeding current is then derived from the current density flowing in the conducting cylinder obtained from the difference between the magnetic fields at the outer surface (a_+) and the inner surface (a_-) as follow.

$$I(t) = 2\pi a\left\{H_x(0,a_+,0,t) - H_x(0,a_-,0,t)\right\}. \tag{4}$$

Both magnetic fields at the outer and inner surface of the dipole antenna can be derived using the quasi-static approximations.

3. Simulation Results

A dipole antenna and a homogeneous cubic phantom model from [7] as shown in Fig. 4 is used. The dimension of dipole antenna and the size and dielectric properties of cubic phantom are listed in Table. 1. The dipole antenna is placed at the distance $d = 1.5$ cm from the cubic phantom and the frequency used is 900 MHz. The input power is 1 W. The spatial averaged SARs obtained using the quasi-static approximation technique and the $1/\rho$-subcell method are compared.

In the bioelectromagnetic problems, when the anatomical model of the human body is used, the FDTD cell size is limited by the voxel size of the models. For example, the cell size of the Japanese adult male and female model is fixed to $2 \times 2 \times 2$ mm^3 [8]. When the half-wavelength dipole antenna ($h_1 + h_2 = 166.78$ mm) as listed in Table 1 is used, the length of dipole antenna does not fit into the FDTD

TABLE 1: DIMENSION OF DIPOLE ANTENNA AND DIELECTRIC PROPERTIES OF CUBIC PHANTOM.

Model	Property	
Dipole antenna	Length ($h_1 + h_2$):	0.5 λ
	Radius (a):	A 0.25 mm
		B 1.25 mm
Cubic phantom	Size:	$100 \times 100 \times 100$ mm^3
	Relative permittivity (ϵ):	55.81
	Conductivity (σ):	0.8 S/m
	Density (ρ):	930 kg/m^3

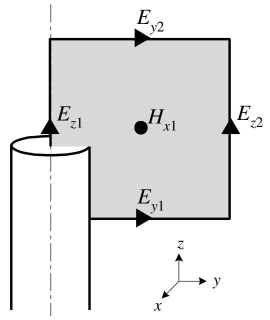
TABLE 2: COMPARISON OF SIMULATION RESULTS OF DIPOLE ANTENNA A.

Method	Δz [mm]	Antenna length [λ]	10-g SAR [W/kg]	Difference [%]
Quasi-static approximation	4.76	0.500	4.79	-
	5.00	0.495	4.76	-0.626
	2.48	0.500	5.28	-
	2.50	0.502	5.37	1.70
1/ρ-subcell	4.76	0.500	4.82	-
	5.00	0.495	4.96	2.90
	2.48	0.500	5.10	-
	2.50	0.502	5.36	5.09

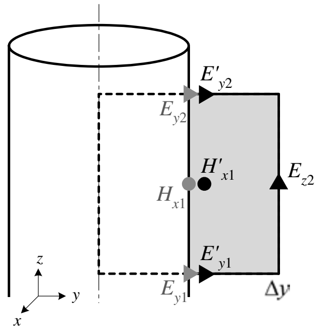
cell. The simulations of dipole antenna A ($a = 0.25$ mm) using 4 different cell sizes are performed. The cell size in x and y direction ($\Delta x = \Delta y = \Delta$) is set to 5.00 mm for $\Delta z = 4.76$, 5.00 mm, and 2.50 mm for $\Delta z = 2.48$, 2.50 mm. The difference of cell size result in different dipole antenna length in order to place the antenna ends on the FDTD cell edge. Table 2 shows the comparison of the local SAR average over 10-g region and its difference from that of the exact half-wavelength dipole antenna using the closest cell size. We can see that, the quasi-static approximation technique gives less difference of the results for slightly different cell size and dipole antenna length.

In addition, the numerical simulations of the larger radius dipole antenna B ($a = 1.25$ mm) are examined. In order to obtain the same dipole antenna length in the calculation using different cell size, the exact length of the dipole antenna is modelled and the calculation of the FDTD cells of electric fields at both ends of dipole antenna are modified as shown in Fig. 5 (a). Moreover, when the cell size is equal to half of the cell size, the location of electric and magnetic fields considered in the calculation is slightly shifted as shown in Fig. 5 (b). The cell size in x and y direction (Δ) is set similarly to the previous calculations.

Table 3 shows the comparison of 10-g SAR and Fig. 6 shows the SAR distribution inside the cubic phantom on x axis comparing with the measured results in [9]. These results illustrate that the quasi-static approximation technique can efficiently model both ends of the dipole antenna. Moreover, the quasi-static approximation technique can also give good agreement results when the antenna radius is equal to half cell size and the calculation of the FDTD cells near the antenna conductor are modified.



(a) In case antenna length does not fit to FDTD cell.



(b) In case antenna radius is equal to half cell size.

Fig. 5: Modification FDTD cells of electric fields in the calculation of dipole antenna B.

TABLE 3: COMPARISON OF SIMULATION RESULTS OF DIPOLE ANTENNA B.

Method	Δz [mm]	a/Δ	10-g SAR [W/kg]	Difference [%]
Quasi-static approximation	4.76	0.250	4.78	-
	5.00	0.250	4.82	0.837
	2.50	0.500	4.58	-4.18
1/ρ-subcell	4.76	0.250	4.76	-
	5.00	0.250	4.88	2.52
	2.50	0.500	3.46	-27.3

4. CONCLUSIONS

This paper has introduced the application of the quasi-static approximation technique for improving the accuracy in exposure evaluation of dipole antenna in case the FDTD cell size is fixed. The validity of the quasi-static approximation technique to the bioelectromagnetic application is confirmed for 3 different cases. First, in the case that antenna length does not fit into the FDTD cell which results in the difference of antenna length, the quasi-static approximation technique can achieve lower difference of the 10-g SAR results. Secondly, the modification of FDTD calculation at the antenna ends to model the exact antenna length is also efficient. Finally, in the case that the antenna radius is equal to half of cell size, the location of electric and magnetic fields is slightly shifted and the quasi-static approximation technique can achieve good agreement results comparing with the measured results.

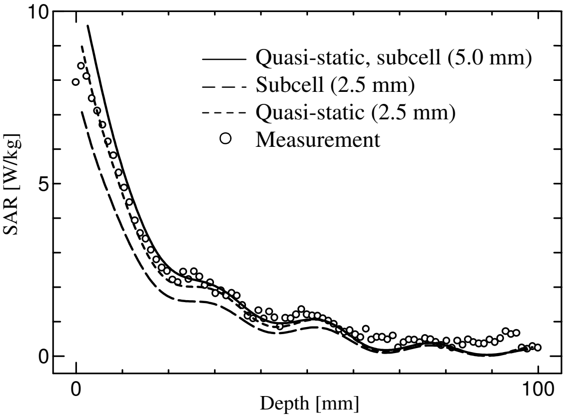


Fig. 6: SAR distribution on x axis.

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