Subcell Modelling of the Digital Human Phantom (DHP) in the Finite-Difference Time-Domain (FDTD) Method

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Basics of the FDTD Method

- The standard FDTD method [1] solves space and time derivatives of Maxwell's curl equations in the time domain using the central difference approximations.
- The method is powerful and robust for solving electromagnetic problems in broadband simulations; it provides a solution for a large number of scattering and interaction electromagnetic problems for wide range of frequencies in a single simulation run.
- However, the uniform rectangular grid structure of the FDTD method demands excessively high computational resources to resolve electrically-fine geometrical features in the problem space.

Subcell Technique

- The standard FDTD method, the entire problem space must be sampled at a scale equal to or smaller than the thickness of the layer. This spatial constraint typically causes very fine meshing of the entire problem space of interest.
- The fine spatial sampling results in excessively large memory consumption due to a dramatic increase of the total number of cells. The small size usage leads to a small time step under stability the condition, therefore an unreasonable computational time is required even for a simple engineering problem containing an electrically-fine geometrical features.

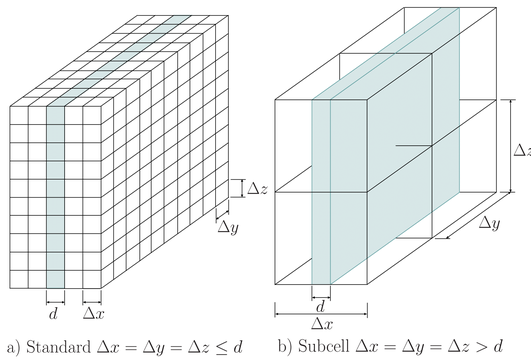

Figure 1: *Meshing of the problem space.*

- The subcell model permits the user to choose an FDTD cell size greater than the object thickness .
- The model relies on the application of the integral form of Ampere's law to the cell that contains the thin layer [2] .

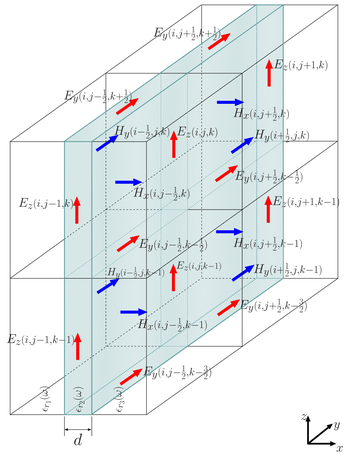

Figure 2: *Thin layer and the electric and magnetic field components in the three-dimensional grid.*

The Digital Human Phantom (DHP)

- To test human body's response to electromagnetic radiation without exposing a human volunteer at any risk.
- To perform any number of tests at far lower cost than actual clinical trials.

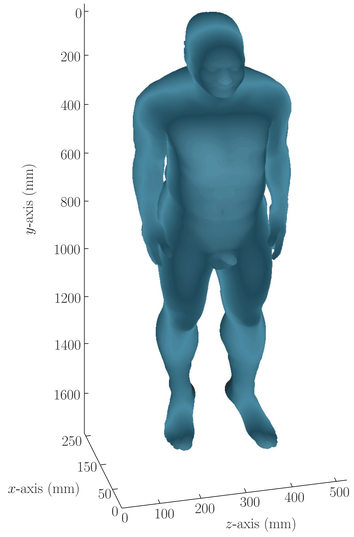

Figure 3: *Three-dimensional Digital Human Phantom (DHP) created by combining 1654 cross-sectional MRI scans, taken at 1 mm intervals from the head to feet, of the healthy subject.*

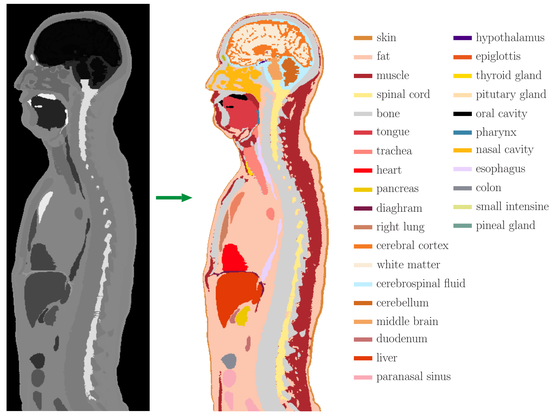

Figure 4: *A slice of the digital human phantom showing the location of the tissues*

- We used the Debye model to describe the electrical properties of the human tissues

$$\epsilon_r(\omega) = \epsilon_\infty + \frac{\epsilon_S - \epsilon_\infty}{1 + j\omega\tau} + \frac{\sigma_S}{j\omega\epsilon_0}.$$

- Each tissue is identified with a unique ID number - 49 (Muscle), 48 (Fat) - and calls its own parameters, ϵ_∞, ϵ_S, τ and σ_S to solve the subcell equation in each coarse cell

$$E_z^{n+1} = \gamma_1 \left[\Psi_z^{n+1} + \gamma_2 E_z^n - \gamma_3 E_z^{n-1} - \sum_{m=1}^{M} \left(s_m \zeta_{1_m} D_{z_m}^n - s_m \zeta_{2_m} D_{z_m}^{n-1} \right) \right]$$

where $\gamma_1 = \left(\sum_{m=1}^{M} \xi_{1_m} s_m \right)^{-1}, \quad \gamma_2 = \sum_{m=1}^{M} \xi_{2_m} s_m, \quad \gamma_3 = \sum_{m=1}^{M} \xi_{3_m} s_m$

and $\xi_{1_m} = \dfrac{2\epsilon_0\epsilon_{\infty_m}\tau_m + 2(\epsilon_0\epsilon_{S_m} + \sigma_{S_m}\tau_m)\Delta t + \sigma_{S_m}(\Delta t)^2}{2(\Delta t + \tau_m)},$

$$\xi_{2_m} = \frac{4\epsilon_0\epsilon_{\infty_m}\tau_m + 2(\epsilon_0\epsilon_{S_m} + \sigma_{S_m}\tau_m)\Delta t - \sigma_{S_m}(\Delta t)^2}{2(\Delta t + \tau_m)},$$

$$\xi_{3_m} = \frac{\epsilon_0\epsilon_{\infty_m}\tau_m}{\Delta t + \tau_m}, \quad \zeta_{1_m} = \frac{\Delta t + 2\tau_m}{\Delta t + \tau_m}, \quad \zeta_{2_m} = \frac{\tau_m}{\Delta t + \tau_m}.$$

Figure 5: *The coarse sampling of the DHP by 8x8, then identification of tissue types and volumes in each coarse cell.*

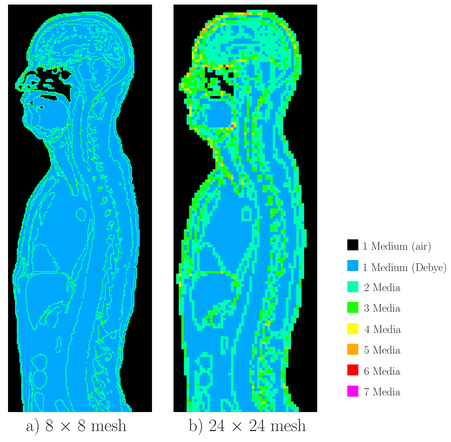

Figure 6: *The media mapping of the DHP after coarse meshing*

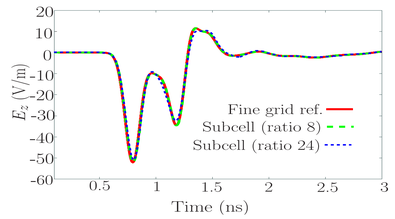

Figure 7: *The observation of E_z. The source excitation was a Gaussian pulse and the frequency range was set up to 5.0 GHz.*

Subcell Ratio	Total Grid	Memory	Speed up	Relative Error
8	300×600	×14	×37	2.03%
24	100×200	×85	×1342	6.34%

Conclusion

The subcell technique has the potential to be used in numerical applications of bioelectromagnetism, providing dramatic reductions in the computational requirements.

Future Works

- To apply the proposed subcell technique for the simulation of moving, expanding, or contracting frequency-dependent objects.
- To achieve higher computational performance by parallelization of the subcell algorithm in MPI.

Bibliography

[1] A. Taflove and S.C. Hagness. *Computational Electrodynamics.* Artech House, Norwood, MA, 2005.

[2] K. Tekbas, F. Costen, J. P. Berenger, R. Himeno, and H. Yokota. Subcell modeling of frequency-dependent thin layers in the FDTD method. *IEEE Transactions on Antennas and Propagation*, 65(1):278–286, Jan 2017.