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Application of Huygens Subgridding to Study Defibrillation in Human Body

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Introduction

- Computational Electrodynamics methods allow to study wave propagation in human body.
- Finite-Difference Time-Domain (FDTD) method is a well-suited numerical algorithm.

Motivation

- In Europe 700,000 deaths per year are accredited to a sudden cardiac arrest.
- Only effective therapy for cardiac arrest is electric defibrillation.
- Success of defibrillation depends on
  - current level and waveform,
  - electrode size, shape and position,
  - body size and transthoracic impedance.

Research Objective and Focus

- Enable efficient simulation of defibrillation current propagating through human body.

Frequency-Dependent–Finite-Difference Time-Domain

- Regular FDTD [1] is based on a staggered calculation of Maxwell's equations:

$$\frac{\partial \boldsymbol{H}}{\partial t} = -\frac{1}{\mu}\nabla \times \boldsymbol{E}, \quad \frac{\partial \boldsymbol{E}}{\partial t} = \frac{1}{\varepsilon}\nabla \times \boldsymbol{H}, \quad \text{where}$$

$\boldsymbol{H}, \boldsymbol{E}$—magnetic, electric field vectors; μ—magnetic permeability; ε—electric permittivity.
- Space and time derivatives are approximated by centred difference and average operators.
- Debye relaxation model allows to incorporate material dielectric properties:

$$\boldsymbol{D} = \varepsilon \boldsymbol{E}, \quad \varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 \left(\varepsilon_s + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \jmath\omega\tau_1} - \jmath\frac{\sigma}{\omega\varepsilon_0} \right), \quad \text{where}$$

$\boldsymbol{D}$—electric flux density vector; $\varepsilon_0, \varepsilon_r, \varepsilon_s, \varepsilon_\infty$—free-space, relative, static and optical electric permittivities; σ—electric conductivity; τ_1—relaxation time; ω—angular frequency.

Huygens Subgridding Principles

- Subgridding—decomposition of simulation space into n subspaces with different spatial and temporal increments Δs and Δt.
- Huygens Subgridding (HSG) [2]:
  - Coarse (a) $\longleftrightarrow$ fine (b) grid influence is transferred via equivalent currents.
  - Arbitrary large subgridding ratio: $r = \frac{\Delta s_a}{\Delta s_b} = \frac{\Delta t_a}{\Delta t_b}$.
  - Synchronised multistep subgridding: $\Delta t_a = r\Delta t_b$.
  - Reduced spurious reflection from subgridding interface.
  - Drawback: late-time instability.

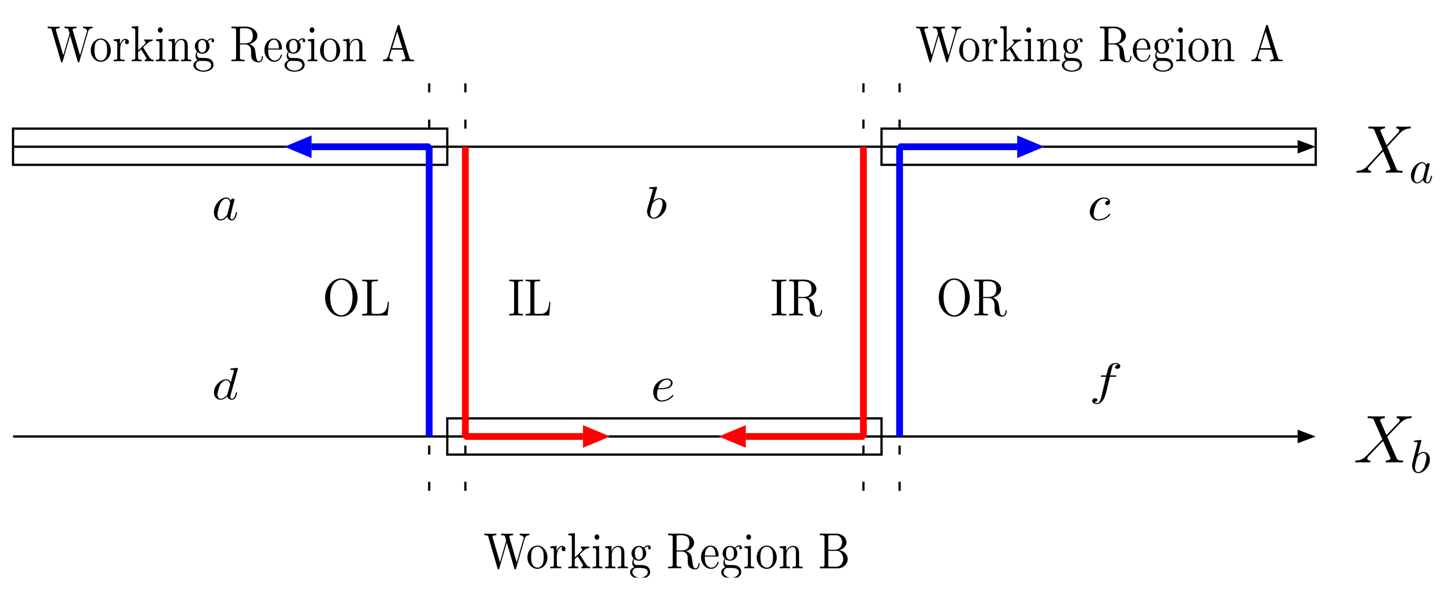


Figure 1: HSG principle in one dimension (1D). *X_a and X_b denote coarse and fine grid regions. Simulation is performed for subspaces a, e and c. Equivalent current from coarse to fine grid is transferred via the Inner Surface (red arrows) and from fine to coarse via the Outer Surface (blue arrows).*

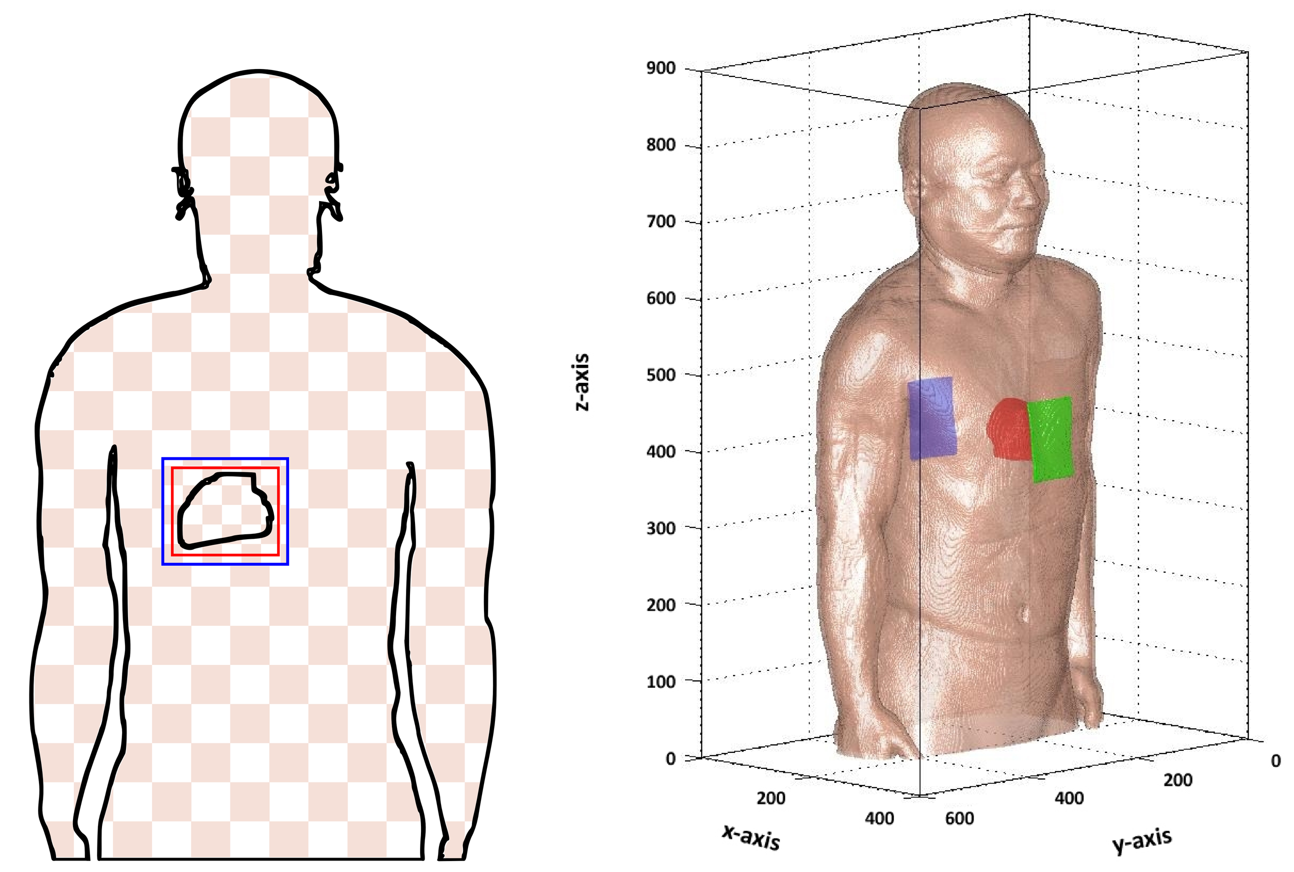
Propagation Environment Setting

- Three codes used for verification: HSG, FDTD (a), FDTD (b).
- Subgridding ratio $r = 5, \Delta s_a = 5\ \mathrm{mm}, \Delta t_a = 8.95\ \mathrm{psec}$.
- Human torso (a) $61 \times 106 \times 182$ points (pts) and heart (b) $162 \times 173 \times 151\ \mathrm{pts}$.
- Two defibrillator pads: anterior $84\ \mathrm{pts}$ and posterior $72\ \mathrm{pts}$.
- Excitation source $\longrightarrow$ unmodulated Gaussian pulse:

$$f(t) = \exp\left[-\left(\frac{t - 3T}{T} \right)^2 \right], \quad \text{where} \quad T = \frac{1}{2f_{max}}, \quad f_{max} = 6 \cdot 10^9\ \mathrm{Hz}.$$

Parameter	$\sigma, \left[\frac{\mathrm{S}}{\mathrm{m}}\right]$	ε_s	ε_∞	$\tau_1, [\mathrm{sec}]$
Air	0.000	1.000	1.000	0.000
Bone	0.104	14.169	7.363	$3.411 \cdot 10^{-11}$
Heart	1.019	63.549	34.910	$2.886 \cdot 10^{-11}$
Fat	0.037	5.531	3.998	$2.363 \cdot 10^{-11}$
Muscle	0.747	56.931	28.001	$1.867 \cdot 10^{-11}$
Skin	0.541	47.930	29.851	$4.363 \cdot 10^{-11}$

Table 1: Debye relaxation media parameters, RIKEN



(i) Coarse, fine grid locations **(ii) Defibrillator pads locations**

Figure 2: Propagation environment
(i) Human torso in coarse grid (large squares) with heart in fine grid (small squares). Outer surface (blue) and inner surface (red) bound the fine grid region.
(ii) Human torso with heart (red) and two defibrillator pads (green, purple) placed anteroposteriorly.

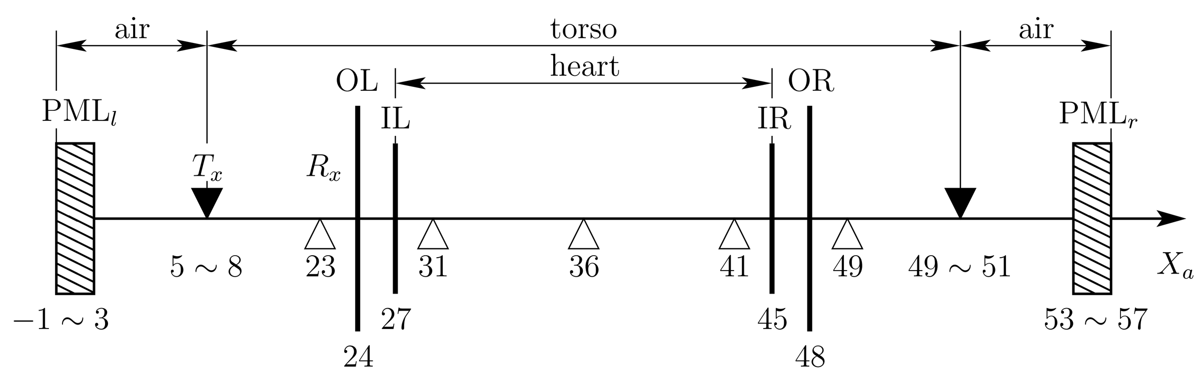
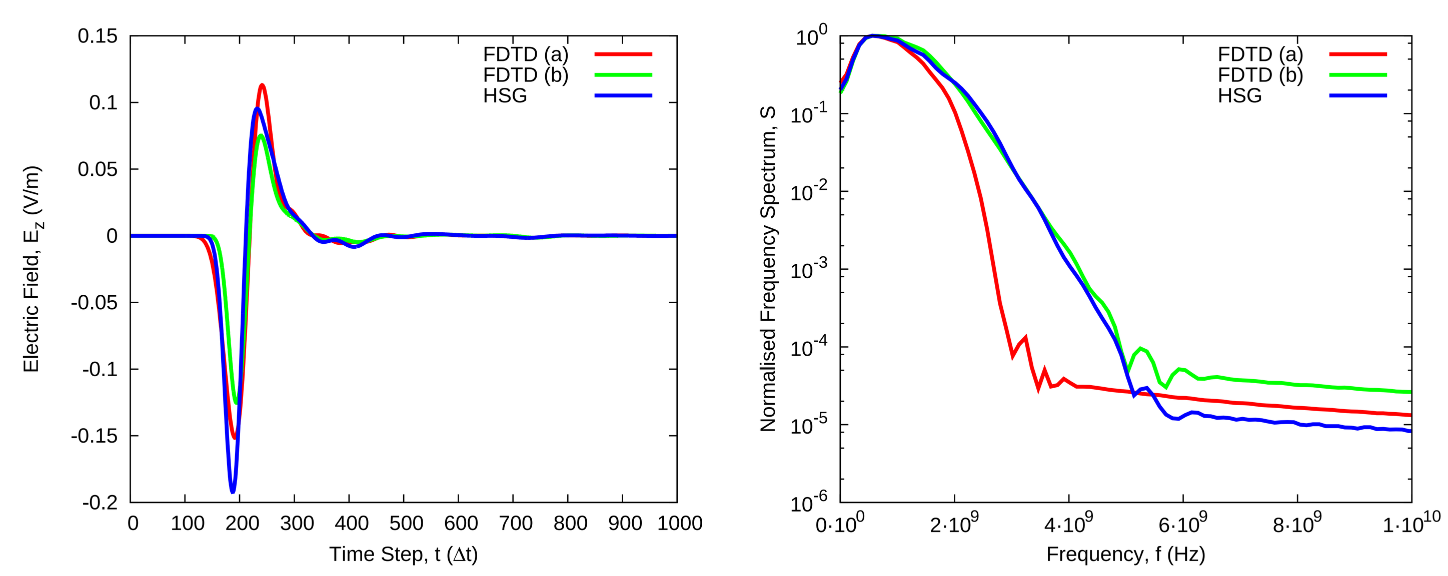


Figure 3: Scenario setting in 1D, $\mathbf{X_a}$. *OL, OR and IL, IR stand for outer and inner Huygens Surfaces; T_x, R_x for excitation and observation locations; PML$_l$, PML$_r$ for left and right Perfectly Matched Layers. Heart is situated in the fine grid region, between IL and IR. Coarse grid region occupies the rest of simulation space.*

Simulation Results



(i) Time domain **(ii) Frequency domain**

Figure 4: *Observation point in the middle of fine grid region. HSG signal curve is average of FDTD coarse and fine grid signals. Total amount of time steps is equal for all algorithms.*

Algorithm	Time, [HH:MM]
FDTD (a)	0:06
FDTD (b)	41:12
HSG	5:42

Table 2: Simulation time. *HSG and two reference codes FDTD (a) and FDTD (b).*

Summary

- Highly efficient Maxwell's equations solver developed $\longrightarrow$ perfect tool to study defibrillation.
- Huygens Subgridding provides a dramatic decrease of simulation time by 84%.
- Debye relaxation model enables simulation of human tissues's frequency response.

Future Work

- Include Biphasic Truncated Exponential (BTE) waveform into the model.
- Conduct a comparative study of various defibrillator pads settings.

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[1] Kane S. Yee. Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media. *IEEE Transactions on Antennas and Propagation*, 1966.

[2] Jean-Pierre Bérenger. A Huygens Subgridding for the FDTD Method. *IEEE Antennas and Propagation*, November 2005.

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