Fraunhofer Institute for Digital Medicine MEVIS

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Patient Specific Modelling of Microwave Ablation

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Challenges of Computing Microwave Ablation

Is it possible to integrate into clinical workflow?

Aim to develop **patient-specific**, **computationally tractable** simulations of dose, thermal and electromagnetic fields for **needle-based** microwave ablations.

Computation of the electromagnetic field is far more complicated than the thermal and the dose fields.

Patient specific means:

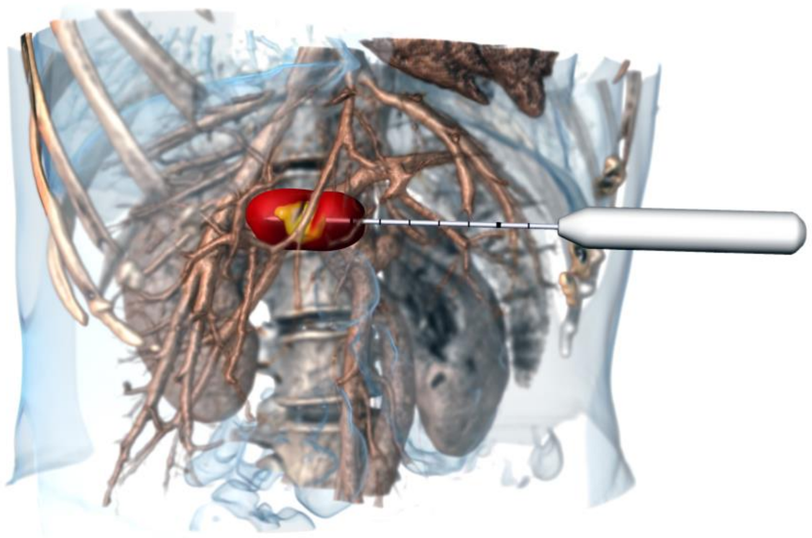
- Three-dimensional domain
- Clinically relevant domain sizes and resolutions
- Clinically relevant material properties, demarcating different tissue types, identifying vascular structures, OAR etc
- Realistic characterisation of applicator

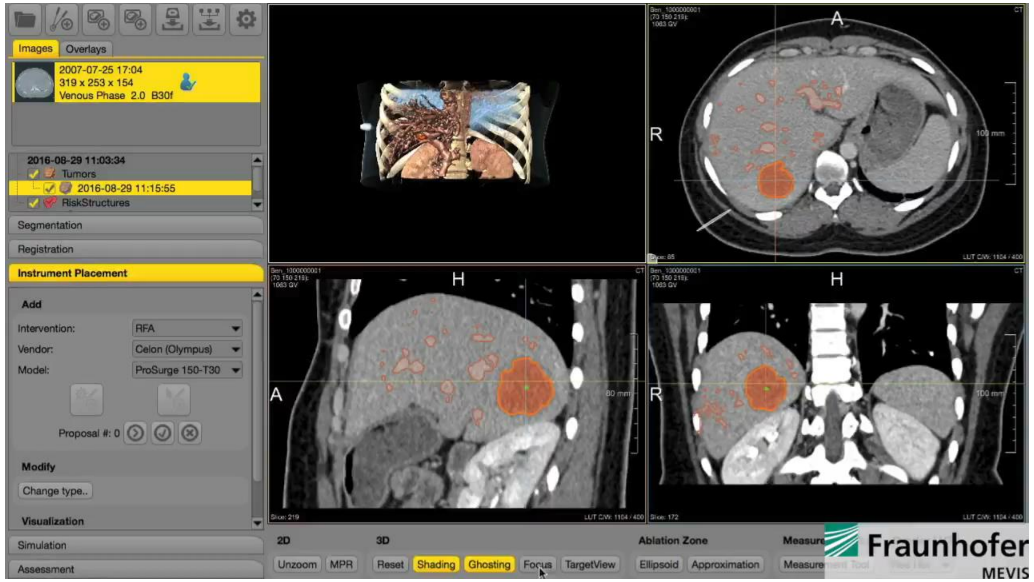
Computationally tractable means

- Fast
- Accurate

Modelling Needle-based Ablations

- Knowledge of the electromagnetic field is dependent on the position of the needle in the patient.
- Needle identified from imaging and registered against a planning image or segmented to derive a computational domain.
- Fraunhofer MEVIS has platform **SAFIR**: software assistant for interventional radiology. Has existing capability for RFA.





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Maxwell's Equations

Physics and Imaging

For wavelengths in tissue and length scales from dicom, waves can be resolved.

As the device operates at a single frequency, and the length of exposure durations is far greater than the period of the wave, assume **continuous-wave** simulations – these can be may be quicker (Oskooi 2010) but can be notorious difficult to solve for large systems or high frequencies (Ernst and Gander 2012).

The length scales also effect the characterisation of the device:

- The electromagnetic field in the patient is in the **near-field**
- The probe is a **short antenna**

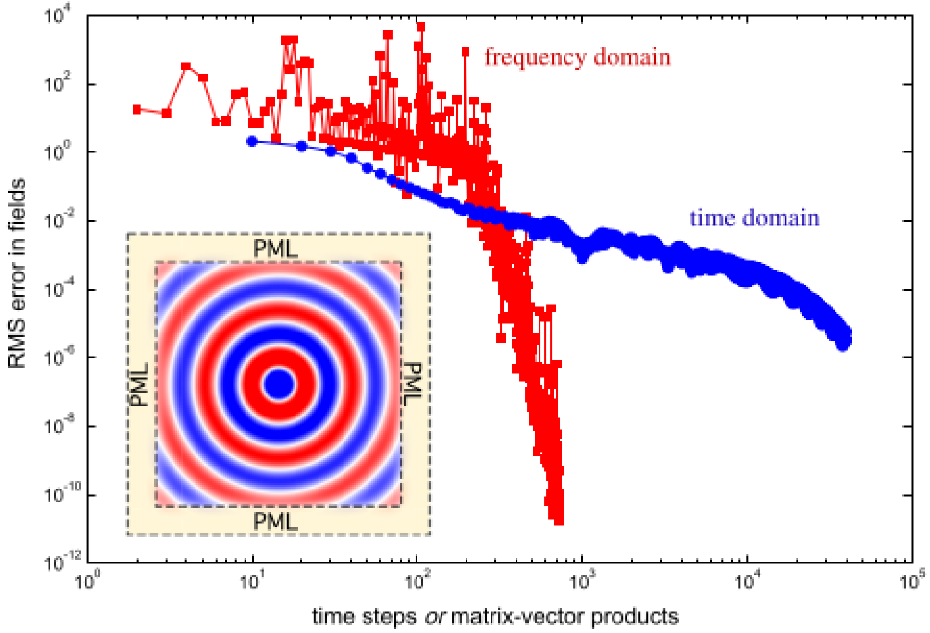

Figure 1: Converge of frequency domain and time domain solvers. Image taken from (Oskooi 2010, Fig 10)

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Solving Maxwell's Equations on Patient Data

Divergence-free

We must ensure the electric field is **divergence-free** in the tissue, i.e. $\nabla \cdot E = 0$

A way of ensuring that this is satisfied is to perform computations of the **Yee-cell** (Yee 1996).

This means that for each voxel the components of the electric and magnetic field must be evaluated at voxel edges and faces respectively.

Thus the material properties: σ (the electrical conductivity), ε (the complex permittivity) and μ (the magnetic permeability) must be interpolated.

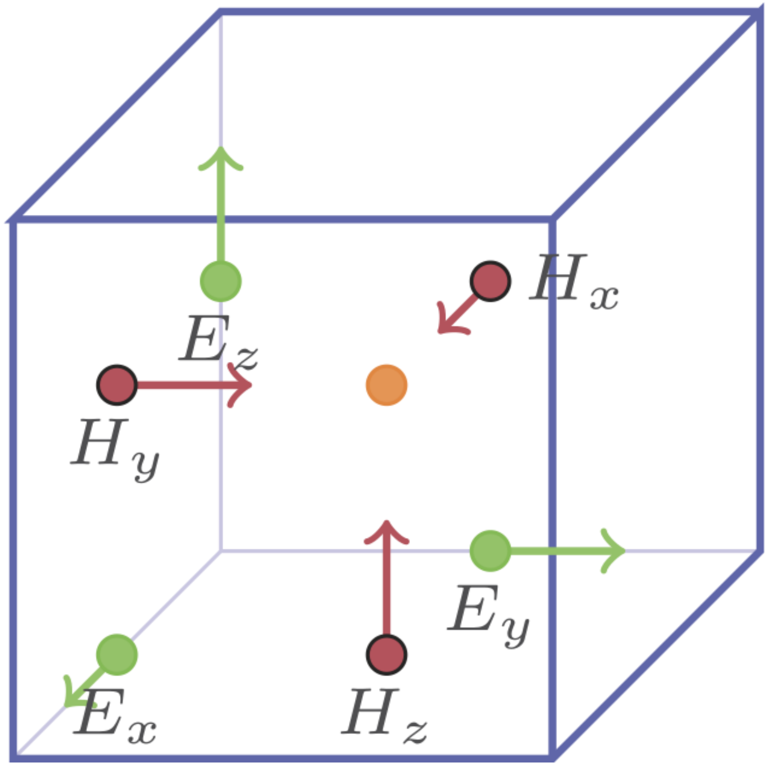

Figure: The Yee cell, with locations of electric and magnetic field components relative to centre of voxel.

Solving Maxwell's Equations on Patient Data

All values of the material properties need to be averaged

Let the material properties be defined by the tissue label and temperature which are located at the centre of the voxel.

- For the evaluation of quantities on the grids for the magnetic field we average between adjacent values.
- For values of the electric field, it is necessary to average between four values, i.e for E_x the permittivity is given by

$$\frac{1}{4}\left(\varepsilon^{i,j,k} + \varepsilon^{i,j+1,k} + \varepsilon^{i,j,k-1} + \varepsilon^{i,j+1,k-1}\right)$$

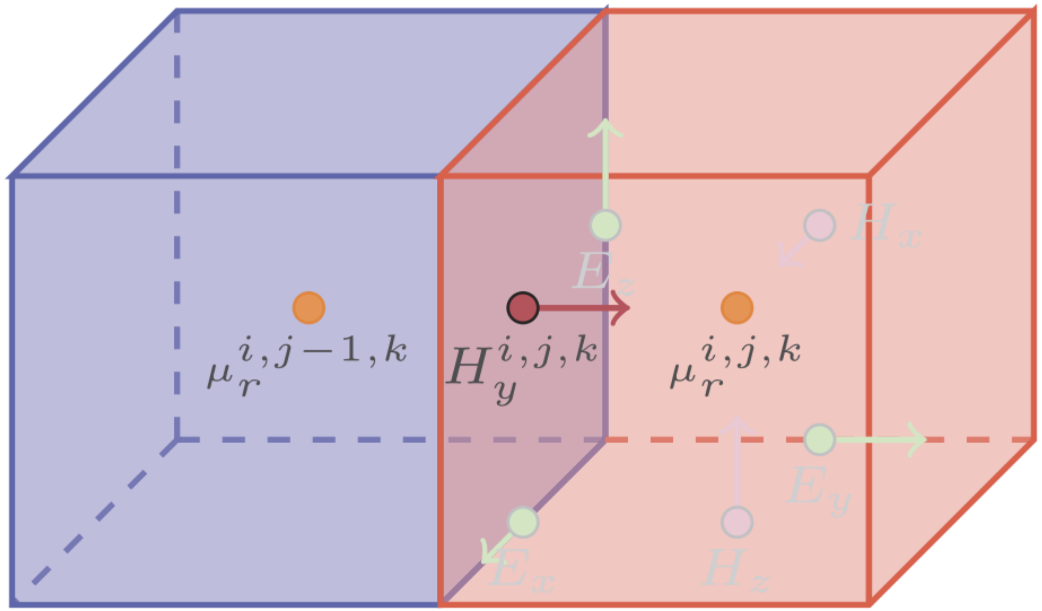

Figure: Interpolating material properties for staggered gird for H_y

Big Data?

Approaches are needed to reduce memory footprint

Following (Rumpf 2012), via Ampère's law, Maxwell's equations can be written in the curl-curl form:

$$\nabla_H \times \bar{\mu}^{-1} \nabla_E \times E \; - \omega^2 \bar{\varepsilon} E = -i\omega J$$

For a system of size (10 cm, 10 cm, 10 cm) with resolution (1 mm, 1 mm, 1.25 mm) we have a complex-valued matrix with around a **trillion** entries.

But it is very **sparse** – each row of the matrix typically only contains **13 non-zero entries**. Sparsity drastically reduces memory requirements and accelerates computations

Use a **perfectly-matched layer** (Berenger 1994) to truncate the domain by suppressing artefacts, such as reflections, from the boundaries.

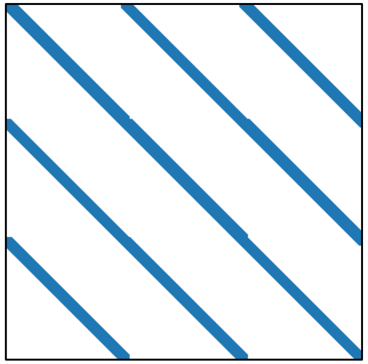

Figure: Sparsity pattern for matrix. Note matrix is very large and distances between bands can not be seen well.

Solving the Linear System

Details

The curl-curl form of Maxwell's equation yields the linear system

$$A\boldsymbol{x} = \boldsymbol{b}$$

- inverse of A describes the propagation of the electromagnetic field in the patient
- position and power of the probe is contained the vector $\boldsymbol{b}$. Typically use **dipole antenna** as approximation for the electric field on the surface of the probe.

Solve for electric field $\boldsymbol{x} = A^{-1}\boldsymbol{b}$, to get the heat source.

The inverse of the matrix A is far too large to compute directly, so employ a **modified stabilized biconjugate gradient solver** (Sleijpen 1994).

However, the system is ill-conditioned but left and right preconditioners, called **stretched-coordinate preconditioners** (Shin and Fan 2012) render the linear system tractable.

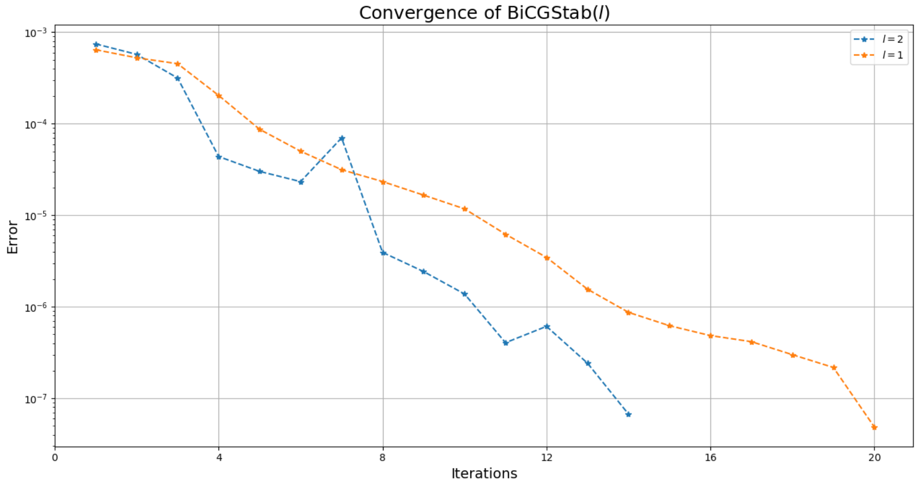

Figure: Convergence of BiCGStab(l) scheme with stretch-coordinate preconditioners on 64x64x64 domain size.

Simulation Times for Solver

Hardware	Size	Preconditioner	Solver	Time
CPU	100x100x100	None	BiCGStab(1)	-
		Jacobi	BiCGStab(1)	~2.5 hours
		Stretch-coordinates	BiCGStab(1)	~2 hours
CPU	64x64x64	Jacobi	BiCGStab(1)	~45 min
		Stretch-coordinates	BiCGStab(1)	~15 min
GPU	64x64x64	Jacobi	BiCGStab(1)	~10 min
		Stretch-coordinates	BiCGStab(1)	~4 min
GPU	64x64x64	Stretch-coordinates	BiCGStab(2)	~2 min

CPU: Intel i7-9750H

GPU: Nvidia GeForce GTX 1650

(C++ and OpenCL v2.2)

Results

Simulations are possible

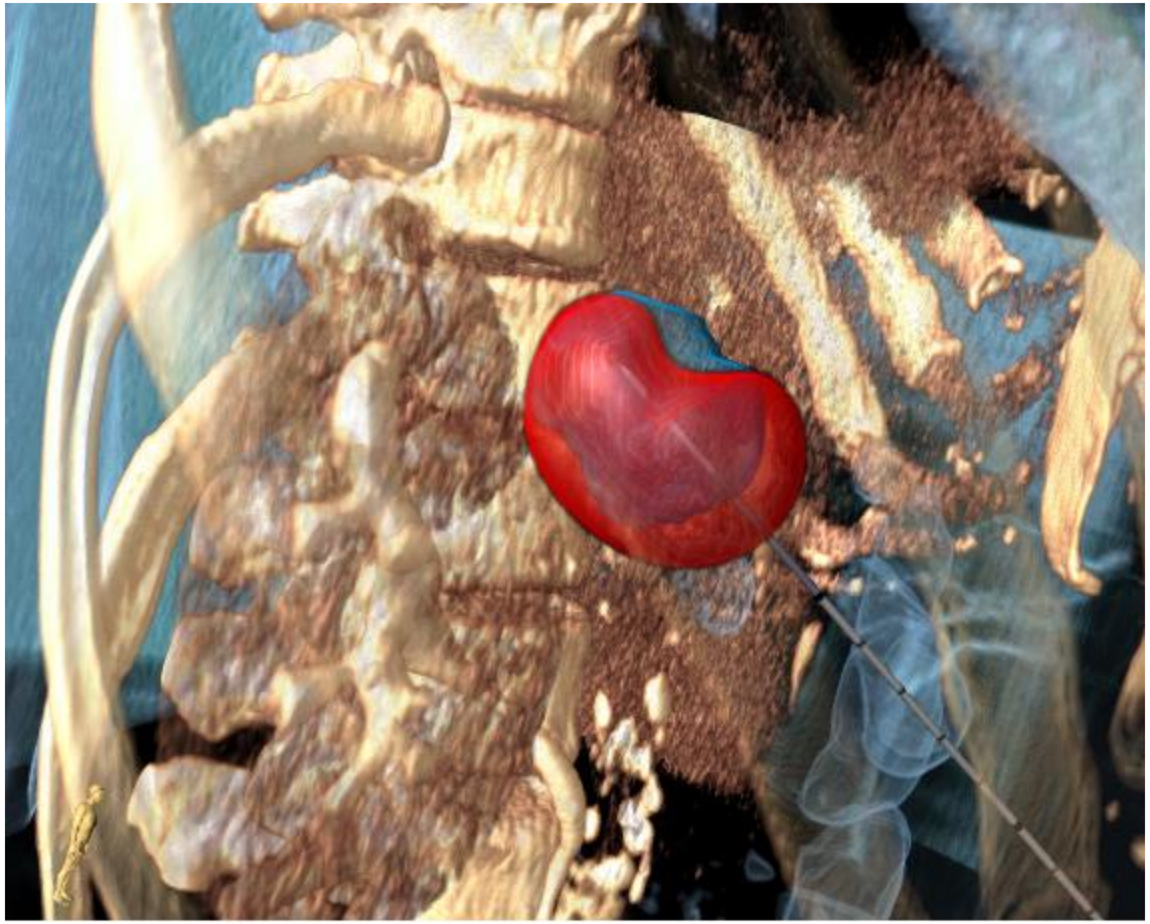

Figure: Electromagnetic field simulations, from segmented images, coupled to thermal and dose fields showing potential treatment outcomes against planned treatment volume.

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Conclusions & Outlook

Overview:

- Using a bespoke sparse iterative solver with left and right preconditioners, patient-specific simulation of microwave ablation can be performed.
- Clinically relevant, three-dimensional, continuous-wave simulations of microwave ablation which can include changes in material properties and multiple probes.
- On a GPU simulations may be integrated into clinical workflow.

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Thank you for your attention

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