

Applied Mathematics and Computational Science

High Performance Approach to Cardiac Resynchronization Therapy

Background: Understanding Cardiac Resynchronization Therapy

Background

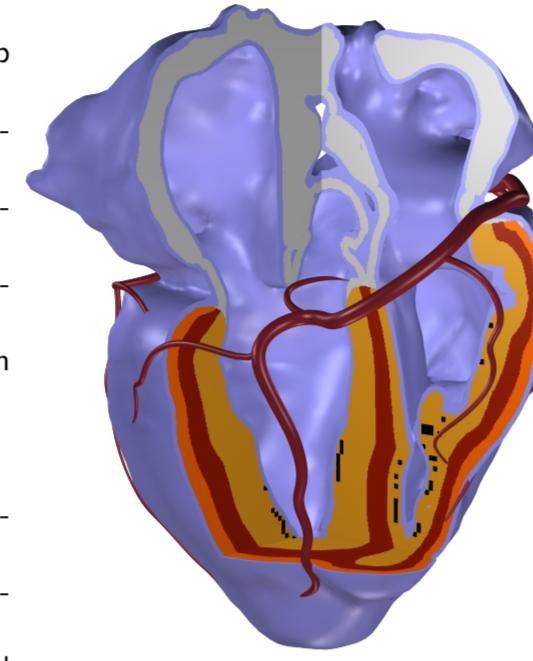
- Heart failure is a major health problem: ~ 5 million affected patients alone in Europe
- High direct and indirect treatment costs

Cardiac Resynchronization Therapy (CRT)

- Left bundle branch block: Failure in electrical activation system
- Leads to disorganized contraction and poor pump function
- CRT: Implantable pacemaker connected to a pacing electrode located in each of the main cardiac chambers
- Aim: Reduce total time of activation and improve synchrony
- Treatment effective for some patients: Reduces mortality and hospitalization rate
- Problem: Other patients show no change at all or even develop cardiac arrhythmia

Relevant Questions

- How to predict the success/failure of CRT using practical techniques like electrocardiograms (ECGs)
- Identify and separate anatomical and electrophysiological changes due to CRT
- Final Goal: Provide practical guidelines about optimal site, tailored device programming and easy-to-use follow-up criteria



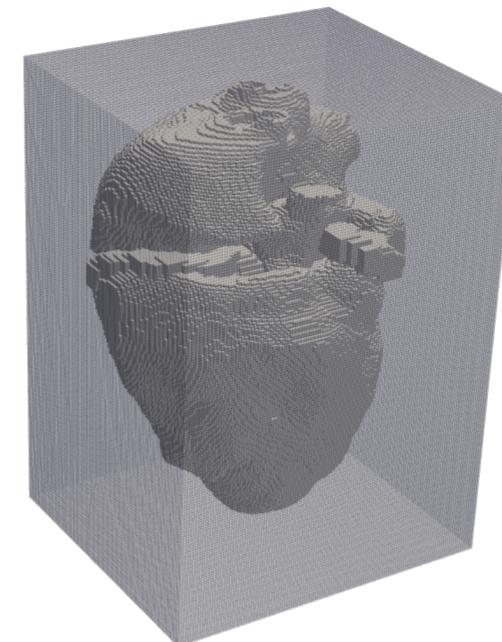
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Modeling Aspects

Bidomain Equation

$$\frac{\partial V_m}{\partial t} = \frac{1}{\beta C_m} \left\{ \nabla \cdot [G_i \nabla (V_m + \phi_e)] - \beta (I_{ion} + I_s) \right\} \text{ with } \nabla \cdot [(G_i + G_e) \nabla \phi_e] = -\nabla \cdot (G_i \nabla V_m)$$

- Reaction-diffusion model for the transmembrane potential $V_m = \phi_i - \phi_e$ with intracellular/extracellular potentials ϕ_i and ϕ_e
- Ionic part $I_{ion} = I_{ion}(V_m, t)$ of the transmembrane current density computed by a membrane model



Monodomain Equation

$$\frac{\partial V_m}{\partial t} = \frac{1}{\beta C_m} \left\{ \nabla \cdot (G \nabla V_m) - \beta (I_{ion} + I_s) \right\}$$

- Derived from bidomain model assuming scalar relation between intra- and extracellular conductivities and the "bulk conductivity tensor" G

Discretization

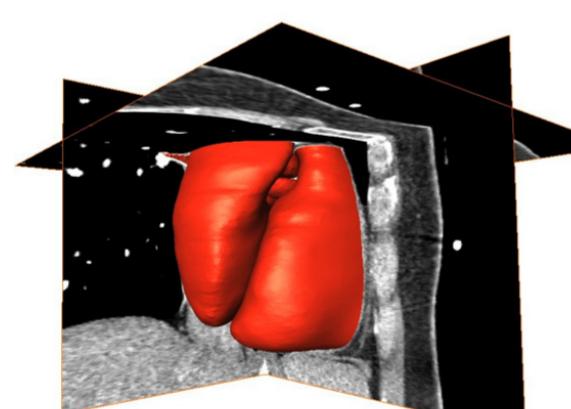
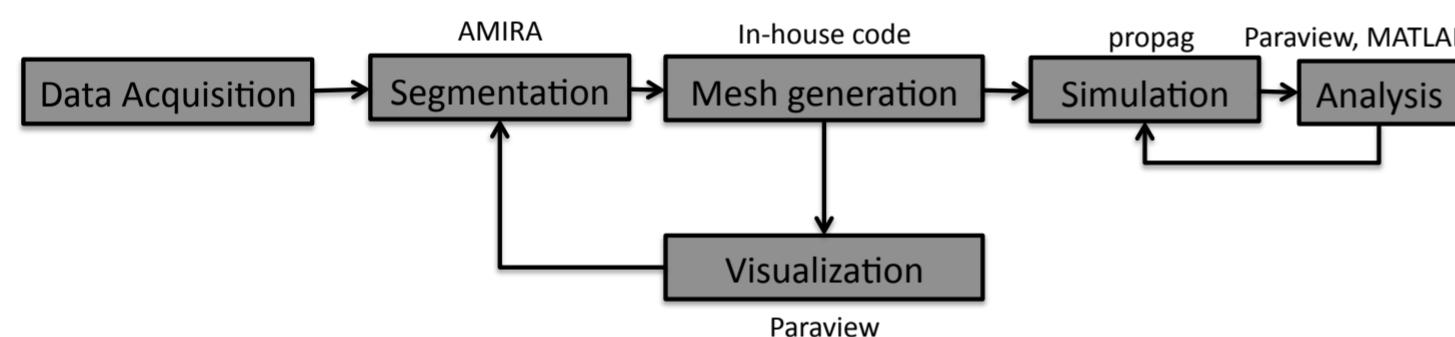
- Voxel geometry, $O(\text{mm})$ resolution
- Second-order finite difference approximation of anisotropic Laplacian
- Explicit or implicit time integration

End-to-End Workflow

Project Partners

- Prof. A. Aurichio, Fondazione Cardiocentro Ticino
- Prof. F. Prinzen, Dr. M. Potse, Maastricht University
- Prof. R. Krause, Dr. T. Dickopf, D. Krause, J. Steiner, L. Blondel, Institute of Computational Science, USI

Workflow Diagram



Description

- Data Acquisition by clinical partners: MRI, CT images, ECG
- Segmentation: Create high-quality surface representation from medical images, requires manual detection of anatomical structure
- Mesh generation: Create voxel approximation based on surface data
- Visualization: Required for steering of process and quality assurance, challenging due to high data volume

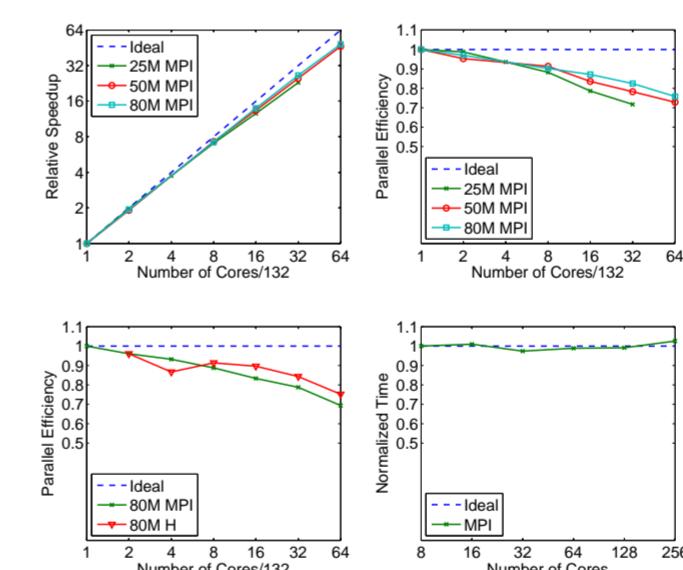
A Case for High Performance Computing

Challenge

- Simulate large amount of patient-specific geometries with various parameters: requires fast execution of forward model
- Patient-specific geometries require high number of voxels: $\sim 80M$ nodes
- Need to scale-out code on high number of cores
- Utilize massively parallel supercomputers such as Rosa at CSCS (Swiss National Supercomputing Centre in Manno) with 22k cores

Achievements

- We have scaled-out our production code `propag` on up to 16k cores on Rosa allowing us to reduce the compute time by orders of magnitudes
- Best scaling is achieved by combining two parallel programming models: MPI between compute nodes and OpenMP inside nodes



Simulation of a Heartbeat

Description

- Monodomain simulation of a full heartbeat
- Stimulation current applied at end of Purkinje fibers
- Performed on 132 cores of Rosa with ~ 40 min wallclock time
- The visualization shows the steep rise of the transmembrane potential and the smooth decay

Visualization

- Visualization is an essential tool for analysis of simulation data but can be a challenge in itself
- Visualization (performed by Jean Favre from CSCS) required four visualization nodes to allow for handling the massive data volume produced by the time-dependent simulation

