



THE WHITE ROSE GRID e-Science Centre

Simulating Cardiac Arrest

Introduction

Cardiovascular disease remains an important cause of premature death in the industrialised world. It is the UK's biggest killer, and in 2004 was responsible for 37% of all deaths in England and Wales. Detailed analysis of data from the US indicates that about one half of these deaths will have been sudden and unexpected, and that the lethal event is most likely to have been ventricular fibrillation (VF), a sudden, unpredictable, yet reversible cardiac arrhythmia.

Despite the economic and social costs, the detailed mechanisms that initiate and sustain VF in the human heart remain poorly understood. As a result, there are few effective strategies for identifying individuals at risk, and the only effective treatment is prompt delivery of an electrical shock – defibrillation.

The heart is an electromechanical pump. During a normal heartbeat, contraction of cardiac muscle fibres is triggered and coordinated by an orderly and repetitive wave of electrical excitation that arises in the heart's natural pacemaker.

During ventricular fibrillation, this normal activity is overthrown by a state of electrical anarchy. Contraction of the heart is rapid, uncoordinated and highly ineffective, causing this condition to be lethal within minutes.

VF can be studied experimentally, where recordings of electrical activity are made from the surface of the heart, for example in patients who are undergoing heart surgery. However, these surface recordings are produced by 3-D electrical waves and computational models of VF are becoming an important tool for interpreting these experimental data. This situation is similar

to studies of the sun, where surface recordings are interpreted with knowledge and simulation of stellar nuclear reactions.

History of heart modelling

The electrical behaviour of heart cells results from the flow of ions through ion channels, pumps and exchangers embedded in the cell membrane.

Models of ion channel behaviour based on differential equations were developed for nerve cells by Hodgkin and Huxley in the 1940s, and these models were first adapted for cardiac cells in the early 1960s by Denis Noble.

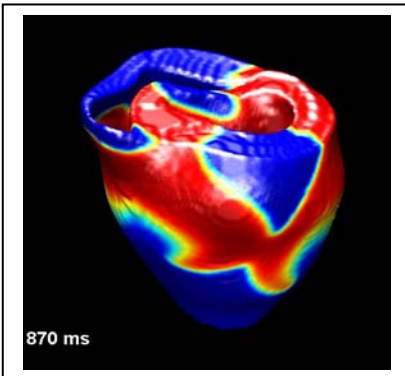
Since these early models, the relentless advances in computational power and experimental techniques have resulted in increasingly detailed models of both cardiac cells and the propagation of electrical activity in tissue.

Heart models and HPC

The present generation of cardiac cell and tissue models involve stiff systems of nonlinear differential equations, and are computationally intensive to solve. Although some simplified simulations can be run on a desktop machine, simulations in large 3D geometries require High Performance Machines.

The simulation code developed in Sheffield simulates electrical activity within a finite difference grid, using either detailed or simplified models of cellular electrical activity.

The Sheffield code is highly portable and can be run on machines with a single processor, machines with shared memory using OpenMP, or machines with distributed memory using MPI.



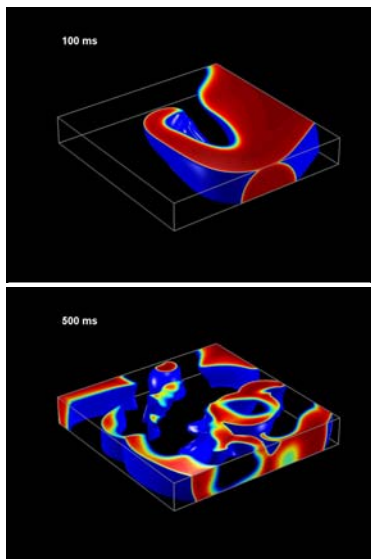
"Computational modelling is a powerful tool for probing the mechanisms that initiate and sustain dangerous cardiac arrhythmias."

Models of VF

Experimental studies have shown that the turbulent electrical activity typical of VF is produced by multiple rotating waves of electrical excitation. These re-entrant waves continuously re-enter regions of recovering tissue, and form spirals in 2D and scrolls in 3D. It is likely that VF starts as a single re-entrant scroll wave, and instabilities in the wave propagation then result in the breakdown of the initial wave into a turbulent regime with multiple re-entrant waves.

This instability is illustrated below, for a tissue slab that represents part of the heart wall.

Simulations of an unstable rotating electrical wave in a 3D tissue slab



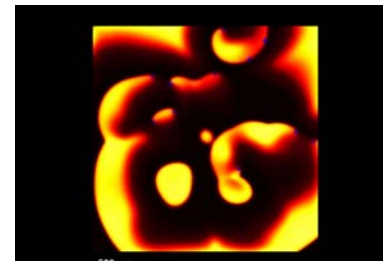
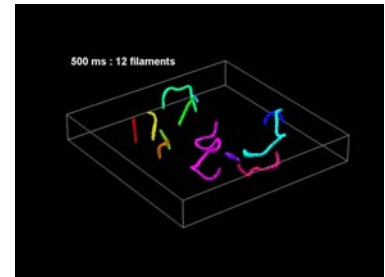
The turbulent activity can be analysed further by identifying and tracking the centres of rotation of each of the re-entrant waves. These features, called filaments, are analogous to vortices in fluid dynamics, and understanding their interactions and dynamics is a key to understanding the mechanisms that sustain VF.

An example of the filaments sustaining the VF shown in the previous example is shown below, together with the surface activation pattern that could be observed experimentally.

Future directions

Computational modelling is a powerful tool for probing the mechanisms that initiate and sustain dangerous cardiac arrhythmias. The work in Sheffield is part of a wider collaboration involving the Universities of Oxford and Auckland, and UCL Hospitals, where models are used to interpret experimental recordings from patients. This work has already shown that VF in the human heart has distinctive characteristics, and has indicated some new possibilities for identifying patients who are at risk of developing this lethal arrhythmia.

Filaments and simulated surface activity in a 3D tissue slab



Acknowledgements

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Further Information

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