Project title: Predictive Modelling of Cardiovascular Disease Using Physics-Informed Neural Networks

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Aim of the project

Cardiovascular disease (CVD) is a leading cause of morbidity and mortality. It often disrupts electrophysiological mechanisms in the heart leading to cardiac arrhythmias, affecting the blood supply to vital organs, and greatly increasing risks of thrombus formation and stroke. However, the underlying mechanisms are incompletely understood, resulting in suboptimal treatments. Mechanistic and statistical models emerged as powerful tools for dissecting such mechanisms and predicting treatments, but application of the former is hindered by high computational costs, while the latter don't account for the underlying (Bio)Physics.

This project aims to:
1)develop Physics-Informed Neural Networks (PINNs)that combine advantages of the mechanistic and statistical models,
2) apply the novel PINNs for efficient simulation of 3D atrial electrophysiology models and prediction of treatments, and
3) apply PINNs to simulate3D atrial blood flow models and predict the associated risks of stroke.

Project description

Cardiovascular diseases (CVD) are a leading cause of morbidity and mortality, accounting for over 30% of all deaths in recent decades. Mechanisms of such diseases are often linked to the occurrence of cardiac arrhythmias –common pathologies caused by disruptions in electrical activity in the heart. Several mechanisms contribute to arrhythmogenesis, such as disruptions in the propagation of cardiac action potentials (APs) by re-entry. However, the precise spatio-temporal mechanisms of most arrhythmias are still poorly understood, and the success rate of their treatments remains suboptimal. Computational models of cardiac electrophysiology emerged as a quantitative framework that can integrate clinical and experimental data, dissect complex mechanisms of arrhythmias and improve therapy.

AP generation and conduction can be mathematically described using ordinary (ODEs) and partial (PDEs) differential equations that are solved numerically. However, the application of such, generally nonlinear and complex models is hindered by the high computational costs, with simulations of large-scale 3D cardiac models running for many hours and days. Hence, the models are generally incompatible with the clinical timescale and impractical to use in the clinic. Statistical deep learning (DL) models have been used as an efficient way to solve ODEs/PDEs and overcome

the drawbacks of traditional mechanistic models and numerical methods. In particular, Physics-Informed Neural Networks (PINNs) can combine precise formalisms of the biophysical equations with computational efficiency of the DL. This project will develop PINNs as a novel DL tool for simulating cardiac electrophysiology.

CVD also greatly increases risks of thrombus formation in the heart and stroke. Thus, the most common arrhythmia, atrial fibrillation (AF), accounts for a third of ischaemic strokes. Clinical approaches to stroke risk assessment are empirical, based on patient characteristics (such as age, weight) and comorbidities, and are only effective for high-risk AF patients. This warrants the development of novel, reliable approaches that account for anatomical and functional mechanisms underlying thrombogenesis. One of the main mechanisms is AF-induced stasis of blood in the left atrium (LA), which promotes thrombus formation, but the exact haemodynamics facilitating ro-thrombotic conditions in the LA remain unclear. Computational fluid dynamics (CFD) modelling has proven to be successful in predicting patient-specific flow characteristics, but it suffers from the same issues of computational inefficient as EP models. Hence, another PINN tool will be created for modelling LA flow.

Thus, this project will facilitate creation on fast and computationally-inexpensive tools for simulating complex CVD conditions, leading to the development of a robust, reliable and rapid framework for patient-specific cardiac simulations. This will be achieved through the development and application of PINNs: this advanced approach enables integration of the underlying laws of (Bio)Physics into DL models that can predict outcomes for CVD patients. The project will focus on two linked problems: 1) arrhythmias in 3D atrial electrophysiology models and prediction of efficient treatments, and 2) blood stasis in 3D atrial blood flow models and prediction of associated risks of stroke. As an exploratory step, the developed PINNs will also be tested on their ability to simulate models of ventricular arrhythmias.

References

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Illustration of the Physics-informed AI framework for 3D atrial modelling, with the PINNs receiving patient imaging data and electrophysiology or flow equations (PDEs) as inputs, and predicting the respective 3D patterns of electrical activity or flow velocity in the LA.