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# Computational modeling of non-linear diffusion in cardiac electrophysiology: A novel porous-medium approach

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## Abstract

The electrophysiological behavior of excitable biological media has been traditionally modeled using a nonlinear reaction-diffusion equation commonly known as the cable equation. To account for the propagating nature of electrical waves, virtually all cardiac electrophysiology formulations proposed to date consider a linear diffusion flux, a constitutive relation known in biology as Fick's law. In this work, motivated by the porous nature of intercalated discs in cardiac muscle cells that mediate intercellular communication and ultimately tissue conductivity, we propose a novel formulation of cardiac electrophysiology that incorporates a nonlinear diffusion term of the porous-media kind. To solve the resulting system of non-linear partial differential equations we develop a non-linear implicit finite-element scheme that is suitable to simulations of large-scale cardiac problems. We show that the proposed porous-medium electrophysiology model results in propagating action potentials that have well-defined wavefronts and travel with finite speed. We also show that the proposed model captures the restitution properties of cardiac tissue similar to the cable model. We demonstrate the capabilities of our method by simulating the activation sequence of a three-dimensional human biventricular heart model, where important microstructural features like cardiomyocyte fiber orientation and the His-Purkinje activation network are successfully incorporated into the simulation.

*Keywords:* Nonlinear Diffusion, Nonlinear Finite Element Method, Cardiac Electrophysiology, Computational Cardiology, Porous Medium Equation

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## 1. Introduction

Computational modeling of the heart is an active research field, with important contributions being provided by the computational science community. The development of advanced mathematical models of the electrical activity of the heart, along with the computational power currently available, have been key to understand the onset and development of heart disease at the organ level, as arrhythmias [1]. Remarkable advances have been also conducted at the tissue level by means of phenomenological models able to reproduce several spatio-temporal experimental observations [2, 3]. These advances notwithstanding, the complexity of biological tissue with newly discovered cellular mechanisms call for more complex computational models that result in computationally intensive simulations [4, 5, 6]. Thus, excitable tissue modeling continues to pose great challenges at both the theoretical and computational levels [7].

Virtually all mathematical models of excitable media derive from the seminal work of Hodgkin & Huxley on the squid giant axon [8] and are typically formulated in terms of the cable equations, either in their monodomain [9] or bidomain [10] version. The resulting set of equations constitute a nonlinear reaction-diffusion system [11] in which spatial propagation of electrical potentials are coupled to evolution equations describing

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