



Design of Artificial Heart with EMP Protection

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Abstract

This paper presents a computational framework for modeling electrical signal propagation in cardiac tissue using two complementary mathematical models implemented within a multiphysics simulation environment. The FitzHugh-Nagumo equations are employed to describe the excitable nature of cardiac tissue and to simulate the propagation of action potentials, while the complex Ginzburg-Landau equations capture the chaotic dynamics associated with arrhythmic conditions. A simplified three-dimensional heart geometry, comprising a hollow, two-chambered shell with a septal wall, is constructed through a sequence of Boolean operations on primitive geometric objects. Both models are solved independently on the same geometry using a General Form PDE interface with transient studies. The results demonstrate characteristic spiral wave patterns in both models: the FitzHugh-Nagumo system produces persistent re-entrant waves that remain stable over extended simulation times, whereas the Ginzburg-Landau system exhibits increasingly complex spatiotemporal patterns with multiple interacting spiral cores, resembling the transition from organized re-entry to turbulent fibrillation. Additionally, the design of an Electromagnetic Pulse (EMP) - protected electronic circuit for an artificial heart is presented to illustrate the practical implementation of EMP protection in cardiac assist devices. The methodology provides insight into the transition from normal rhythmic activity to arrhythmic states in cardiac tissue and offers a foundation for future patient-specific modeling and therapeutic development.

Keywords: Cardiac Electrophysiology; FitzHugh-Nagumo; Ginzburg-Landau; Spiral Waves; Arrhythmia; Multiphysics Modeling

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Introduction

The heart generates rhythmic electrical pulses that initiate mechanical contractions, enabling the pumping of blood throughout the body. These electrical signals originate from the sinoatrial node and propagate through specialized conduction pathways before depolarizing the ventricular myocardium. In a healthy heart, electrical pulses are appropriately damped and coordinated. However, various pathological conditions increase the risk of signal re-entry, disrupting normal rhythm and potentially leading to life-threatening arrhythmias. Understanding the mechanisms underlying cardiac electrical activity is essential for diagnosing and treating arrhythmic disorders. Computational modeling provides a powerful tool for investigating these phenomena, allowing researchers to study the spatiotemporal dynamics of electrical wave propagation in silico. Figure 1 illustrates the conceptual design of a soft total artificial heart, providing a visual representation of the simplified cardiac geometry that serves as the computational domain for the electrophysiological simulations.

The study of cardiac electrical activity and its pathological disturbances have been profoundly shaped by the integration of experimental physiology, nonlinear dynamics, and computational modeling. The references cited in the accompanying work represent a rich intellectual heritage spanning foundational mathematical models, seminal experimental discoveries, and contemporary computational frameworks that together illuminate the mechanisms underlying cardiac arrhythmias. This review synthesizes these contributions, organizing them around three thematic pillars: the development and application of reduced mathematical models of excitable media, the discovery and characterization of spiral wave dynamics as a mechanism of arrhythmia, and the evolution of computational modeling toward clinical translation and broader interdisciplinary applications [1-10]. Figure 2 (a) presents a three-dimensional finite element model of the aorta and its major branches embedded within surrounding tissue, with panel (b) showing the displacement magnitude distribution throughout the vessel wall under applied axial stretch and inner pressure. Figure 3 (a) presents a three-dimensional finite element model of the aorta and its major branches embedded within surrounding tissue, with panel (b) showing the displacement magnitude distribution



Figure 1: Soft total artificial heart.

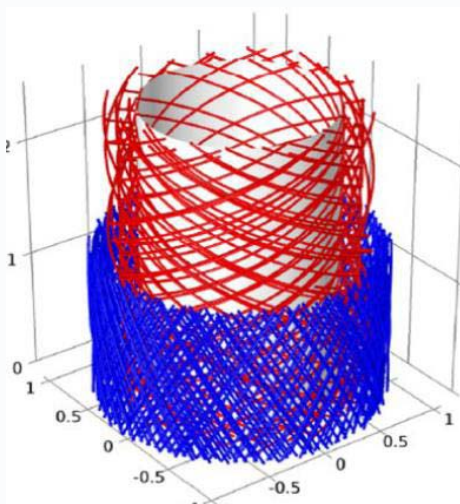


Figure 2: Axial stretch and inner pressure are applied to the artery.

throughout the vessel wall under applied axial stretch and inner pressure.

The development of reduced mathematical models for excitable media constitutes one of the most significant advances in theoretical biology, providing a framework for understanding how electrical signals propagate through cardiac tissue. The FitzHugh-Nagumo (FHN) equations represent the most influential reduction of the Hodgkin-Huxley formalism, capturing the essential dynamics of excitable media through a two-variable system. FitzHugh introduced a phase-plane description of nerve impulse generation that reduced the complex ionic dynamics of the Hodgkin-Huxley model to a tractable system of two ordinary differential equations [6]. Independently, Nagumo, Arimoto, and Yoshizawa implemented an active pulse transmission line simulating the nerve axon, providing a physical realization of these mathematical principles [9]. The FHN equations describe a fast activator variable, representing membrane potential, coupled to a slow inhibitor variable, representing recovery dynamics, producing the cubic nonlinearity and threshold behavior characteristic of excitable systems. This elegant reduction has proven remarkably versatile, finding application beyond neuroscience in cardiac electrophysiology, cell division dynamics, population biology, electronics, and various natural phenomena. In cardiac tissue, the activator-inhibitor dynamics correspond to the rapid depolarization during an action potential and the slower repolarization process, respectively, making the FHN model a workhorse for investigating fundamental questions about wave propagation, re-entry, and spiral wave dynamics [7]. Figure 4 displays the results of a pacemaker

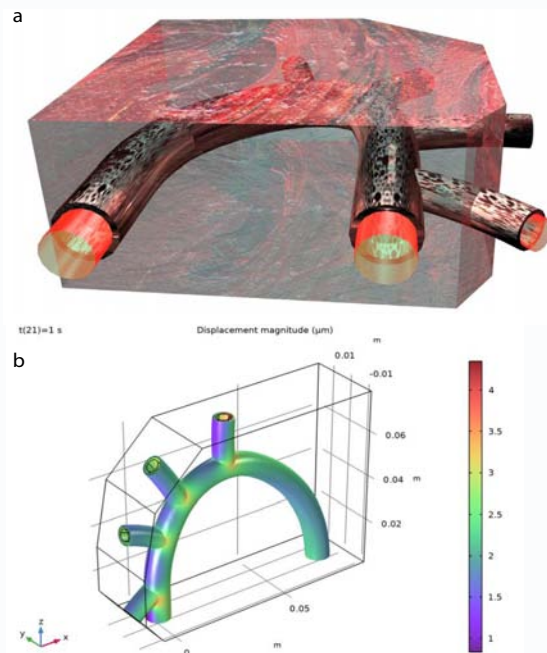
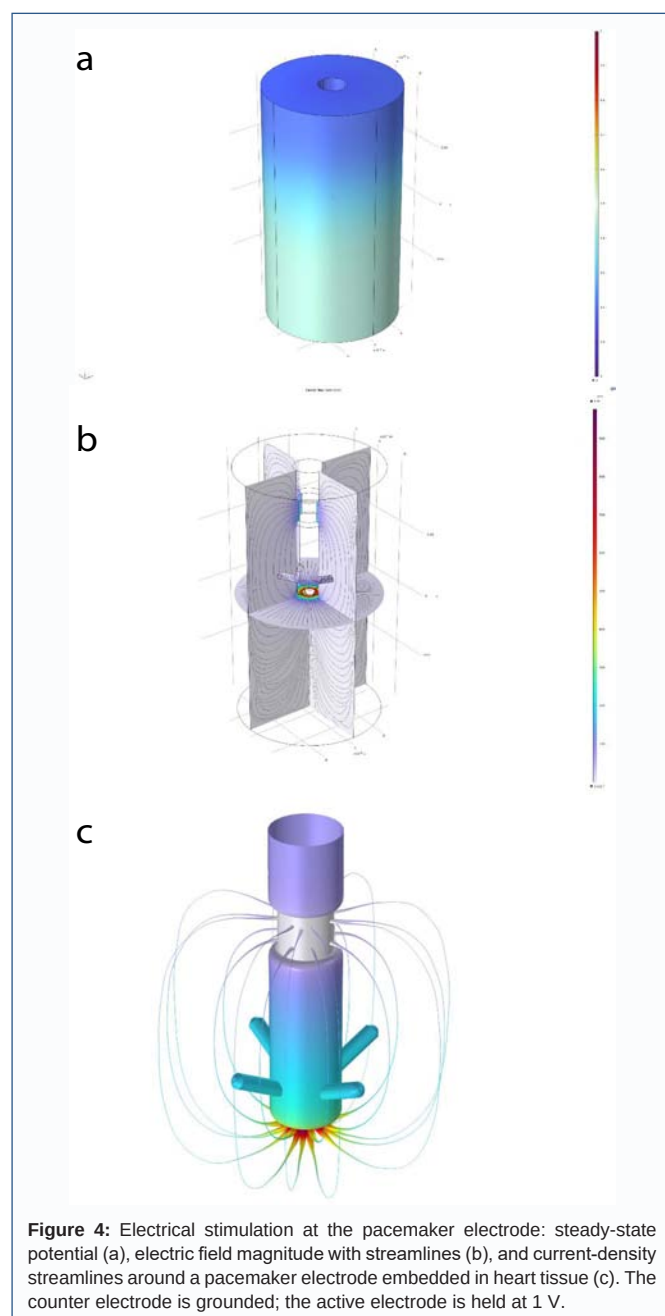


Figure 3: (a) Aorta, its branches, and the surrounding tissue. (b) Displacements in the blood vessel.

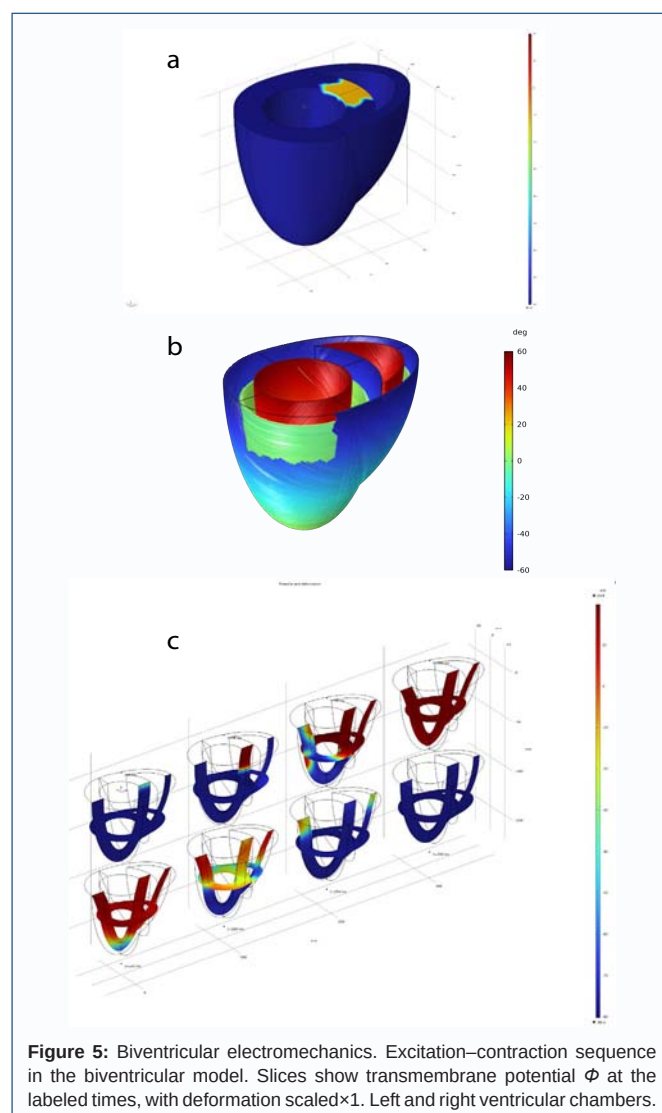
electrode simulation, showing the steady-state electric potential distribution, the electric field magnitude with streamlines, and the current-density streamlines around an active electrode held at 1 V within cardiac tissue.

While the FHN model describes excitable media, the Complex Ginzburg-Landau Equation (CGLE) characterizes the behavior of oscillatory media near a Hopf bifurcation, providing a complementary framework for understanding pattern formation in nonequilibrium systems. Originally developed in the context of superconductivity, the CGLE has emerged as a canonical model for studying spiral wave dynamics and the transition from ordered to chaotic behavior [15]. The equation governs the evolution of a complex oscillating field and admits both plane-wave and spiral wave solutions, making it particularly relevant for modeling the onset of instabilities in cardiac tissue. Kuramoto's comprehensive work on chemical oscillations, waves, and turbulence established the theoretical foundations for understanding how oscillatory media generate complex spatiotemporal patterns [13]. In the cardiac context, the CGLE provides a framework for understanding the transition from organized spiral wave reentry to the turbulent dynamics associated with fibrillation, as it can model the nucleation of multiple spiral cores and the subsequent breakup that characterizes chaotic electrical activity. The simultaneous implementation of both the FHN and CGLE models on identical three-dimensional cardiac geometries facilitates direct comparison of their qualitative behaviors, as demonstrated in the accompanying study, revealing complementary insights into normal and pathological cardiac activity [11-20].

The discovery that spiral waves of excitation occur in cardiac muscle represented a paradigm shift in understanding arrhythmia mechanisms, establishing the "rotor" concept as the basis for re-entrant excitation in cardiac tissue. Davidenko, Pertsov, Salomonsz, Baxter, and Jalife provided the first direct experimental evidence of stationary and drifting spiral waves in isolated cardiac muscle,



using high-resolution optical mapping techniques to demonstrate that re-entrant excitation in ventricular tissue could take the form of spiral waves rotating around a phase singularity [3]. This seminal work superseded earlier leading-circle theories of re-entry, providing a mechanistic explanation for the varied patterns of re-entrant excitation observed clinically. The observation that spiral wave tips could drift, meander, or break up provided insight into the transition from organized tachycardias to disorganized fibrillation. Winfree's theoretical work on electrical instability in cardiac muscle further elaborated the concept of phase singularities and rotors, establishing the mathematical foundations for understanding how rotating waves of excitation could sustain arrhythmias [16]. His analysis of the conditions under which phase singularities form and interact provided a theoretical framework that continues to inform contemporary research on arrhythmia mechanisms. Figure 5 illustrates the excitation-contraction coupling sequence in a



biventricular model, with slices showing transmembrane potential Φ at labeled times and deformation scaled $\times 1$, demonstrating the spatial and temporal progression of electrical activation and mechanical contraction in the left and right ventricular chambers.

Subsequent research has firmly established that rotors - rapidly rotating spiral waves - play a central role in sustaining both atrial and ventricular fibrillation, with their breakup into multiple daughter waves producing the complex, turbulent activation patterns characteristic of fibrillation states. Gray, Pertsov, and Jalife demonstrated the spatial and temporal organization during cardiac fibrillation, revealing that despite its apparent chaos, fibrillation exhibits organized spatiotemporal dynamics [17]. Their work showed that during fibrillation, multiple wavelets interact and reorganize, with rotors serving as organizing centers that generate high-frequency wavefronts propagating throughout the myocardium. The breakup of spiral waves into multiple daughter waves produces the complex electrogram patterns observed clinically, and understanding this process has become central to developing therapeutic interventions. Contemporary understanding distinguishes between different mechanisms of fibrillation maintenance, with the "mother rotor" hypothesis suggesting that a single, high-frequency rotor drives global fibrillation, while the "multiple wavelet" hypothesis proposes that

fibrillation results from the continuous breakup and re-formation of numerous wavelets [7]. These mechanisms may operate in different contexts, with rotors serving as organizing centers that can either drift or remain stationary, and their behavior being modulated by tissue properties such as anisotropy, inhomogeneities, and fibrotic remodeling.

Computational modeling of cardiac electrophysiology has evolved from single-cell descriptions to sophisticated whole-organ simulations, enabling increasingly realistic investigations of arrhythmia mechanisms and their clinical implications. Pullan, Buist, and Cheng provided a comprehensive mathematical treatment of cardiac electrical activity, establishing the theoretical foundations for modeling the spread of excitation through the heart in three dimensions [7]. Their work integrated detailed descriptions of ionic currents with spatial propagation in tissue geometries, providing a framework for simulating both normal sinus rhythm and pathological re-entry. Keener and Sneyd's comprehensive text on mathematical physiology further consolidated the principles of wave propagation in excitable media, including detailed analyses of the cardiac action potential, the mechanisms of reentry, and the conditions under which spiral waves form and break up [10]. These foundational texts continue to inform contemporary modeling efforts, providing the mathematical tools necessary for investigating complex spatiotemporal dynamics in cardiac tissue.

The literature reviewed here reveals a rich intellectual trajectory spanning fundamental mathematical modeling, experimental discovery, and computational application, with profound implications for understanding and treating cardiac arrhythmias. The FitzHugh-Nagumo equations provide a minimal but powerful description of excitable media, capturing the essential dynamics of action potential propagation and reentry through a two-variable system that balances physiological realism with mathematical tractability [6, 9]. The complex Ginzburg-Landau equation extends this framework to oscillatory media, modeling the transition from organized spiral waves to turbulent chaos and providing insight into the development of complex arrhythmic patterns [13, 15]. Experimental work has confirmed the existence of spiral waves and rotors in cardiac muscle, establishing them as central mechanisms in life-threatening arrhythmias [3, 16, 17]. Contemporary computational modeling integrates these insights with detailed biophysical descriptions and realistic anatomical geometries, moving toward clinically relevant applications in risk stratification, ablation planning, and therapeutic development [7, 10]. The broader interdisciplinary applications of these methods - from crack patterns in paintings to fuel cell design, from spinal cord stimulation to tumor ablation - highlight the universality of the underlying principles and the value of cross-disciplinary collaboration. As computational power continues to increase and numerical methods improve, these approaches will likely play an increasingly important role in understanding and treating cardiac arrhythmias, ultimately contributing to improved patient outcomes and the development of personalized therapeutic strategies.

The numerical implementation of these models requires careful attention to computational considerations, as the strongly nonlinear nature of the equations and the sensitivity of chaotic regimes to perturbations demand sophisticated numerical methods. The use of higher-order elements, finer meshing, and smaller tolerances has been shown to improve solution accuracy, particularly for the Ginzburg-Landau equations which describe inherently chaotic phenomena [7].

Fenton, Cherry, Hastings, and Evans demonstrated the feasibility of real-time computer simulations of excitable media, showing that modern computing platforms can generate physiologically relevant results within clinically meaningful timeframes [10]. Their work on Java as a scientific language and as a wrapper for C and FORTRAN programs highlighted the importance of computational efficiency and accessibility in cardiac modeling. The development of patient-specific models, incorporating anatomical and electrophysiological data from individual patients, represents a particularly promising avenue for personalized medicine, with potential applications in risk stratification, ablation planning, and drug development.

The computational and mathematical approaches developed for cardiac electrophysiology have found applications across diverse fields, demonstrating the interdisciplinary nature of nonlinear dynamics and pattern formation research. Jamalabadi's work on optimal rectangular crack patterns based on constructal, fracture saturation, and energy minimization theories applied principles of nonlinear dynamics to understanding material failure in paintings on wood, revealing deep similarities between pattern formation in biological and nonbiological systems [1]. The constructal theory of critical mass, which describes how flow systems evolve to minimize resistance, has been applied to nuclear energy science and technology, demonstrating the universality of optimization principles across different physical domains [2]. The electrophysiological model of epidural spinal cord stimulation represents a direct extension of the modeling approaches developed for cardiac tissue to neural systems, highlighting the broader applicability of excitable media theory [4]. Similarly, Jamalabadi's finite element analysis of needle-tissue interaction mechanics has implications for surgical instrument design and tissue trauma mitigation, showing how computational modeling can inform clinical practice [8]. The comprehensive review of computational modeling in tumor and brain disorders, with a focus on ablation therapies, further underscores the translational potential of these methods beyond cardiology [11]. The principles of bifurcation and branching observed in biological systems have also informed engineering design, as demonstrated by Jamalabadi's work on nature-inspired branching strategies for ultra-compact, high-power PEM fuel cells [5]. This application of bifurcation theory to energy systems reflects the broader theme of how understanding pattern formation in one domain can inspire innovations in another. The optimal design of free convection in elliptical annuli using Al_2O_3 ethylene glycol nanofluid similarly applies computational optimization techniques to thermal engineering problems, with the governing equations sharing mathematical structures with those used in cardiac modeling [12]. Davari, Jamalabadi, and Davari's work on airfoil optimization for low Reynolds number applications in wind turbines further illustrates the cross-disciplinary application of computational optimization methods, with the SG 6043 airfoil optimization benefiting from the same mathematical techniques used to study spiral wave dynamics [14]. These diverse applications collectively demonstrate the power of combining reduced mathematical models with detailed computational implementations to investigate complex phenomena across multiple scales and disciplines.

This study employs two well-established mathematical frameworks to model different aspects of cardiac signal propagation:

1. The FitzHugh-Nagumo equations, which describe excitable media and capture the fundamental characteristics of action potential generation and propagation.

2. The complex Ginzburg–Landau equations, which model the transition from periodic oscillatory behavior to chaotic dynamics under strong external stimuli.

Both systems are solved on the same three-dimensional geometry representing a simplified heart, enabling direct comparison of their qualitative behaviors. The resulting spiral wave patterns are of particular interest, as they share similarities with the electrical activity observed during cardiac arrhythmias.

Theoretical Background

Excitable media and the FitzHugh-Nagumo equations

Excitable media are characterized by three fundamental properties:

- A well-defined rest state.
- A threshold for excitation.
- Diffusive coupling to neighboring elements.

These characteristics manifest in cardiac tissue as the resting membrane potential, the voltage threshold for opening ionic gates, and the diffusive spread of electrical signals through gap junctions. The FitzHugh-Nagumo equations provide the simplest physiological model incorporating these features:

$$\frac{\partial u_1}{\partial \tau} = \Delta u_1 + (\alpha - u_1)(u_1 - 1)u_1 - u_2 \quad (1)$$

$$\frac{\partial u_2}{\partial \tau} = \epsilon(\beta u_1 - \gamma u_2 - \delta), \quad (2)$$

where:

- u_1 is the activator variable (action potential/membrane voltage),
- u_2 is the inhibitor variable (gate dynamics/recovery variable),
- α is the excitation threshold,
- ϵ controls the excitability of the system,
- β , γ , and δ influence the rest state and dynamics.

The activator u_1 exhibits fast dynamics with cubic nonlinearity, while the inhibitor u_2 evolves more slowly, providing the recovery mechanism essential for excitable behavior.

The complex Ginzburg-Landau equations

The Ginzburg-Landau equations model the dynamics of oscillatory systems near the onset of instability. While originally developed for superconductivity theory, these equations have found broad application in pattern formation and nonlinear dynamics:

$$\frac{\partial v_1}{\partial \tau} - \Delta(v_1 - c_1 v_2) = v_1 - (v_1 - c_3 v_2)(v_1^2 + v_2^2) \quad (3)$$

$$\frac{\partial v_2}{\partial \tau} - \Delta(c_1 v_1 + v_2) = v_2 - (c_3 v_1 + v_2)(v_1^2 + v_2^2) \quad (4)$$

where v_1 and v_2 are the real and imaginary components of a complex oscillating field, and c_1 and c_3 are material parameters determining the nature of stable solutions.

The Ginzburg-Landau equations are particularly relevant for modeling phenomena such as vortex formation in fluid flow and oscillating chemical reactions (Belousov-Zhabotinsky type). In the cardiac context, they provide insight into the development of spiral wave turbulence associated with fibrillation.

Geometry construction

A simplified heart geometry was constructed as in Figure 1, following the two-chamber, semi-spherical cavity design of the original Application Library model. The geometry combines primitive shapes through a sequence of Boolean operations:

1. A sphere of radius 54 (dimensionless units) and an ellipsoid with semiaxes 54, 54, and 70 were created.
2. Two auxiliary blocks (110×110×110, centered and offset by $z = \pm 55$) were used to remove the lower hemisphere of the sphere and the upper half of the ellipsoid.
3. The remaining upper half-sphere and lower half-ellipsoid were fused (union) to create an egg-shaped outer shell.
4. The entire shell was scaled by a factor of 2/3 and subtracted from the original shell, leaving a hollow wall of finite thickness that defines the internal cavity.
5. A cylinder (radius 45, height 10, axis along x, offset from center) was unioned into the geometry to form the septal wall separating the two chambers, with interior boundaries between the two solids removed for a conforming mesh.

The resulting solid represents a hollow, two-chambered “heart” on which the reaction–diffusion equations of Section 2 are solved.

Simplified heart geometry: an egg-shaped outer shell (fused half-sphere and half-ellipsoid), a concentric internal cavity scaled by a factor of 2/3, and a cylindrical wall separating the two chambers.

Model parameters

The parameters used for the FitzHugh-Nagumo model are listed in Table 1. For the Ginzburg-Landau model, parameters are given in Table 2. Figure 6 presents the electronic circuit designs for an artificial heart, including the basic heart-beating circuit and an Electromagnetic Pulse (EMP)protected version, demonstrating the practical implementation of EMP protection for cardiac assist devices.

Initial and boundary conditions

FitzHugh-Nagumo model: Boundary conditions are insulating (Neumann) for both variables, assuming no current flows into or out of the heart. The initial conditions are:

$$\left(\begin{aligned} V_0, (x+d) > 0 \text{ or } (z+d) > 0, \\ u_1(0, x, y, z) = \\ 0, \text{ otherwise,} \end{aligned} \right.$$

$$\left(\begin{aligned} v_0, (-x+d) > 0 \text{ or } (z+d) > 0, \\ u_2(0, x, y, z) = \\ 0, \text{ otherwise.} \end{aligned} \right.$$

$$\left(\begin{aligned} v_0, (-x+d) > 0 \text{ or } (z+d) > 0, \\ u_2(0, x, y, z) = \\ 0, \text{ otherwise.} \end{aligned} \right.$$

$$\left(\begin{aligned} v_0, (-x+d) > 0 \text{ or } (z+d) > 0, \\ u_2(0, x, y, z) = \\ 0, \text{ otherwise.} \end{aligned} \right.$$

The logical expressions evaluate to 1 when true and 0 otherwise.

Ginzburg-Landau model: Insulating boundary conditions are also applied. Initial conditions are:

$$v_1(0, x, y, z) = \tanh(z), v_2(0, x, y, z) = -\tanh(z).$$

Numerical implementation

Both models were implemented using the General Form PDE.

Table 1: FitzHugh-Nagumo model parameters.

Parameter	Symbol	Value	Description
α	alpha	0.1	Excitation threshold
ϵ	epsilon	0.01	Excitability
β	beta	0.5	System parameter
γ	gamma	1.0	System parameter
δ	delta	0.0	System parameter
V_0	V0	1.0	Elevated potential value
v_0	nu0	0.3	Elevated inhibitor value
d	d	10-5	Off-axis shift distance

Table 2: Ginzburg-Landau model parameters.

Parameter	Symbol	Value	Description
$c1$	c1	2.0	Coupling parameter
$c3$	c3	-0.2	Nonlinearity parameter

The key implementation details include:

FitzHugh-Nagumo Implementation:

- Conservative flux for u_1 : $\Gamma_{u1} = [-u_{1x}, -u_{1y}, -u_{1z}]$.
- Conservative flux for u_2 : $\Gamma_{u2} = [0, 0, 0]$.
- Source terms as defined in Eqs. (1) – (2).

Ginzburg-Landau Implementation:

- Conservative flux for v_1 :

$$\Gamma_{v1} = [-v1_x + c1v2_x, -v1_y + c1v2_y, -v1_z + c1v2_z].$$

- Conservative flux for v_2 :

$$\Gamma_{v2} = [-c1v1_x - v2_x, -c1v1_y - v2_y, -c1v1_z - v2_z].$$

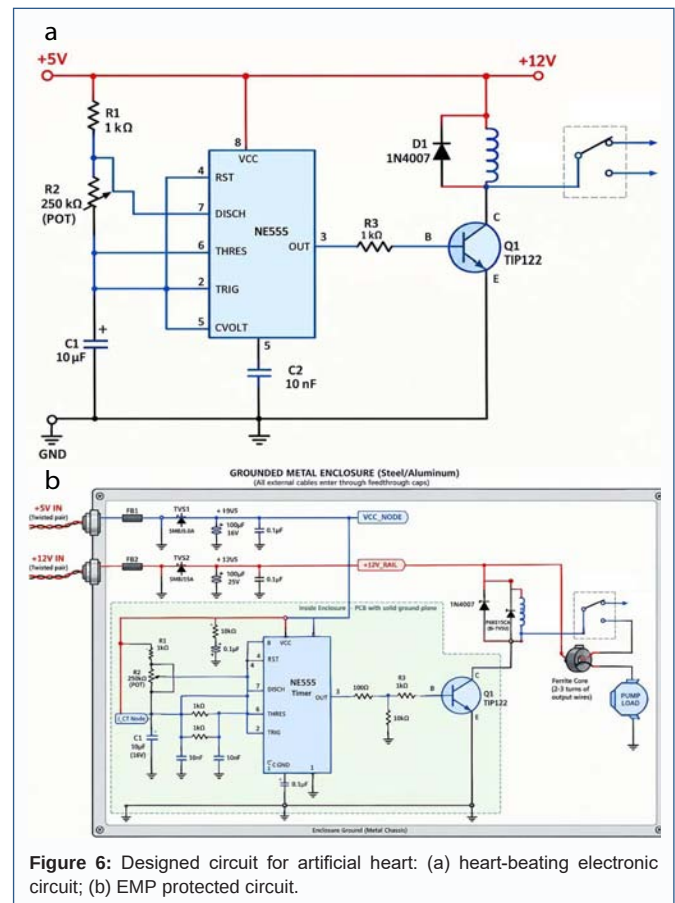
- Source terms as defined in Eqs. (3) – (4), using Hermite (cubic) shape functions for improved accuracy.

Solver Settings:

- FitzHugh-Nagumo (Study 1): time-dependent solver, output times range (0, 5, 500) (i.e., $t = 0$ to 500 in steps of 5), default tolerances.
- Ginzburg-Landau (Study 2): time-dependent solver, output times range (0, 5, 75) (i.e., $t = 0$ to 75 in steps of 5).
- Relative tolerance: 10^{-3} , manually tightened by an order of magnitude relative to the default for the Ginzburg-Landau study.
- Absolute tolerance: 10^{-4} (manual), likewise tightened for the Ginzburg-Landau study.
- Shape functions: cubic Hermite elements for the Ginzburg-Landau interface, in place of the default quadratic Lagrange elements, to improve solution accuracy for this more sensitive, chaotic system.

The strongly nonlinear nature of these equations necessitates careful numerical treatment. The Ginzburg-Landau equations describe inherently chaotic phenomena and are highly sensitive to perturbations in initial conditions and numerical errors. Therefore, recommendations include:

- Use of fourth-order Hermite elements.
- Finer meshing than the minimal resolution.


Figure 6: Designed circuit for artificial heart: (a) heart-beating electronic circuit; (b) EMP protected circuit.

- Smaller relative and absolute tolerances.
- 64-bit computing platforms for larger models.

For the exploratory results presented here, coarser settings were used to demonstrate qualitative behavior with computational times of approximately a few minutes on a standard PC.

Results

The solution to the FitzHugh-Nagumo equations reveals the propagation of an action potential wavefront through the cardiac tissue (Figure 7). The initial pulse, localized in one quadrant of the heart, triggers a re-entrant wave that travels around the tissue without damping. The characteristic spiral pattern emerges from the interaction between the activator (u_1) and inhibitor (u_2) variables. Figure 7 presents the spatiotemporal evolution of spiral wave patterns, with the FitzHugh-Nagumo model producing persistent re-entrant waves at $t = 120$ s and $t = 500$ s, while the complex Ginzburg-Landau model exhibits increasingly complex spiral patterns with multiple interacting cores, resembling the transition from organized re-entry to chaotic fibrillation.

At $t = 120$, the wavefront has established a clear spiral structure extending through the tissue. By $t = 500$, the pattern has evolved while maintaining its re-entrant nature, demonstrating the persistent excitation wave typical of excitable media.

The Ginzburg-Landau model reveals increasingly complex spiral patterns in the v_1 variable over time (Figure 7). The diffusive coupling and nonlinear interactions produce characteristic spatiotemporal patterns with growing complexity.

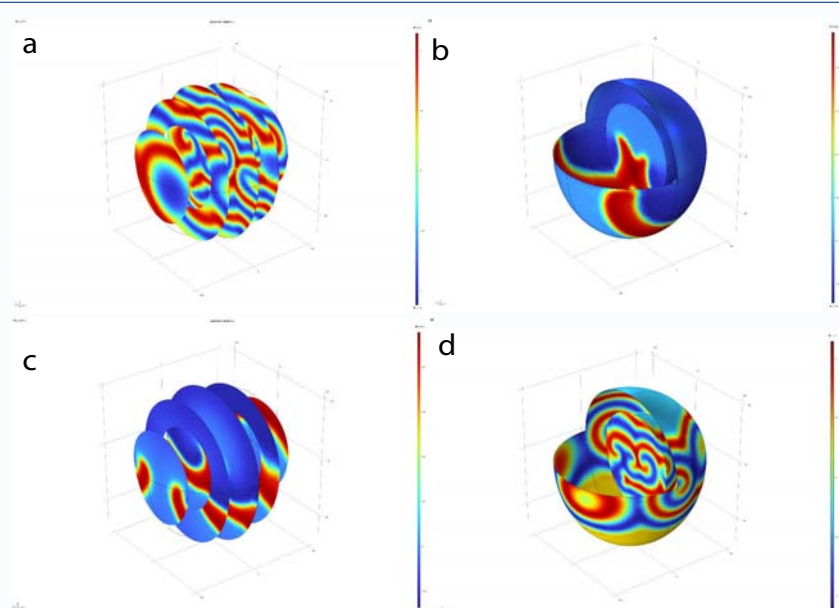


Figure 7: Snapshots of the dimensionless excitation variable u_1 (FitzHugh-Nagumo) at (a) 120 s and (b) $t = 500$ s and recovery variable v_1 (complex Ginzburg-Landau) showing spiral-wave propagation in a simplified cardiac domain (c) at times $t = 75$ s and (d) $t = 45$ s.

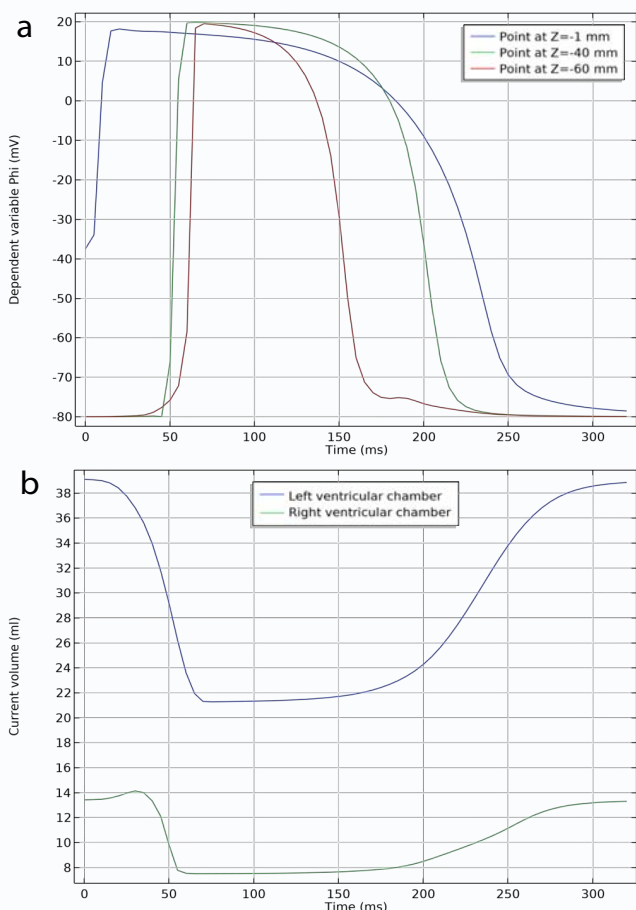


Figure 8: (a) Potential values at three different locations. (b) Internal volume variation during a heartbeat.

At $t = 45$, well-defined spiral waves with a small number of cores are visible. By $t = 75$, the patterns have become considerably more

complex, with interactions between multiple spiral cores leading to finer-scale, turbulent-looking dynamics. This behavior mirrors the transition from organized re-entry to chaotic fibrillation observed in pathological cardiac conditions. The two mathematical models employed in this study capture complementary aspects of cardiac electrical activity. The FitzHugh-Nagumo equations successfully reproduce the fundamental behaviors of excitable media, including threshold effects, propagating waves, and re-entrant patterns. The Ginzburg-Landau equations extend this framework by modeling the transition to chaotic dynamics, providing insight into the development of complex arrhythmic patterns. The spiral wave patterns observed in both models are of particular clinical significance. Spiral waves (also called rotor waves) are believed to underlie many forms of cardiac arrhythmias, including ventricular tachycardia and fibrillation. When spiral waves become unstable, they can break into multiple daughter waves, leading to the chaotic electrical activity characteristic of fibrillation. Figure 8 shows the time course of the dependent variable Φ (mV) at three distinct spatial locations within the cardiac tissue, illustrating the temporal profile of action potential depolarization and repolarization during the cardiac cycle.

During the cardiac cycle the activation lapse is not constant throughout the myocardium. Regions that are depolarized last are the first to repolarize. This effect is obtained through a space-dependent time scale βt . Both chambers contract during the depolarization of the excited myocardial cells causing a reduction of the internal volume. They slowly return to their initial configuration for the next heartbeat.

The construction of a three-dimensional geometry with internal cavity and separating wall enables more realistic simulation of cardiac tissue compared to two-dimensional models. The simplified geometry used here could be extended with more anatomically accurate representations using CAD import capabilities.

Computational considerations are paramount for these models. The strongly nonlinear nature of both systems demands careful numerical treatment. The Ginzburg-Landau equations are particularly

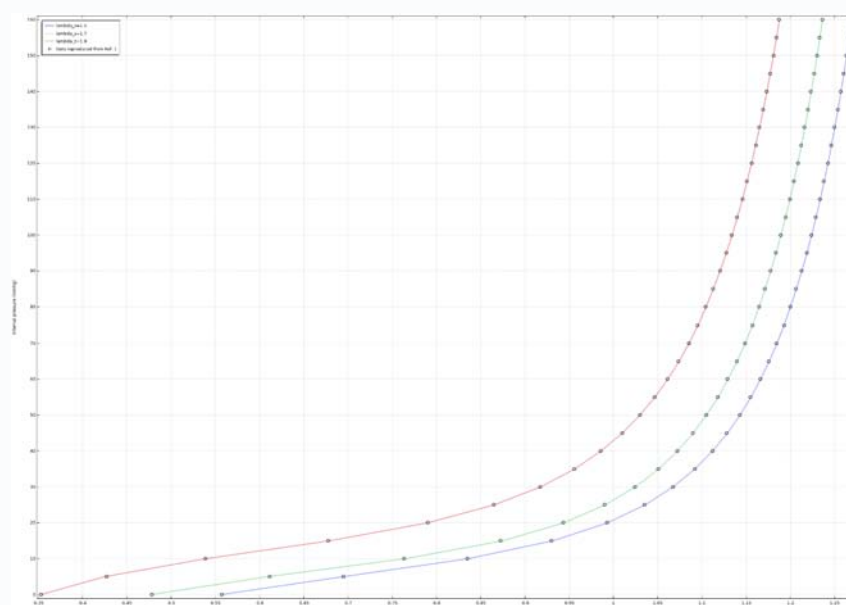


Figure 9: Arterial wall viscoelasticity.

sensitive, requiring higher-order elements, finer meshing, and smaller tolerances for quantitatively accurate results. The exploratory results presented here demonstrate qualitative behavior; quantitative predictions would require more refined computational settings.

The simultaneous implementation of both models on the same geometry facilitates comparison and integration of their insights. Future work could explore coupling between these models or incorporating additional physiological details such as tissue anisotropy, inhomogeneities, and realistic dimensions. Figure 9 presents the viscoelastic creep behavior of the arterial wall, showing the time-dependent deformation under sustained loading and illustrating the material's viscoelastic properties relevant to cardiovascular biomechanics.

Conclusion

This study demonstrates the utility of multiphysics simulation for modeling cardiac electrical signal propagation using the FitzHugh-Nagumo and complex Ginzburg-Landau equations. The two models provide complementary perspectives on normal and pathological cardiac activity, with both systems producing characteristic spiral wave patterns on an identical simplified three-dimensional cardiac geometry.

The FitzHugh-Nagumo model successfully captures the excitable nature of cardiac tissue, reproducing threshold behavior, propagating wavefronts, and persistent re-entrant waves that do not damp over time. These results are consistent with the established understanding of spiral wave re-entry as a mechanism of cardiac arrhythmia. The complex Ginzburg-Landau model extends this framework by describing the transition from organized oscillatory behavior to chaotic dynamics. Its results reveal the emergence of increasingly complex spatiotemporal patterns, with multiple interacting spiral cores and fine-scale turbulent structures that mirror the transition from organized re-entry to fibrillation observed in pathological cardiac conditions.

The simultaneous implementation of both models on the same

geometry facilitates direct comparison of their qualitative behaviors and provides a unified computational platform for investigating the mechanisms underlying arrhythmogenesis. The spiral wave patterns observed in both models are of particular clinical significance, as rotors and their breakup into daughter waves are believed to underlie many life-threatening arrhythmias, including ventricular tachycardia and fibrillation.

The construction of a three-dimensional geometry with an internal cavity and separating wall enables more realistic simulation of cardiac tissue than two-dimensional models, though the simplified geometry used here could be extended with more anatomically accurate representations through CAD import. Computational considerations remain paramount: the strongly nonlinear nature of both systems demands careful numerical treatment, and the Ginzburg-Landau equations are particularly sensitive to perturbations, requiring higher-order elements, finer meshing, and tighter tolerances for quantitatively accurate results. The exploratory results presented here demonstrate qualitative behavior; quantitative predictions would require more refined computational settings.

Future work should focus on refining the numerical implementation, incorporating more realistic anatomical geometry and tissue anisotropy, and exploring coupling strategies between the two model systems. The integration of patient-specific anatomical and electrophysiological data represents a particularly promising avenue for personalized medicine, with potential applications in risk stratification, ablation planning, and therapeutic development. As computational power continues to increase and numerical methods improve, these approaches are likely to play an increasingly important role in understanding and treating cardiac arrhythmias, ultimately contributing to improved patient outcomes.

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