From Perlin Noise to Stochastic Partial Differential Equations: a Framework for Modeling Fibrotic Heterogeneity in Cardiac Tissue

Enia Ottavi *, Victor Gonçalves Marques, Ulrich Schotten, Gernot Plank, Elena Zappon, Simone Pezzuto
Gottfried Schatz Research Center: Biophysics, Medical University of Graz, Graz, Austria

Aims: Spatial structural heterogeneity induced by fibrosis strongly influences cardiac conduction and increases arrhythmia risk. However, reproducing realistic fibrotic patterns in computational models remains challenging. Existing methods for generating structurally heterogeneous patterns of fibrosis, such as the Perlin noise method, can produce realistic patterns but are difficult to extend to complex anatomical geometries. This work aims to develop a mathematical framework that overcomes these limitations, particularly in complex geometries.

Methods: We propose a modeling approach based on Stochastic Partial Differential Equations (SPDEs), linking Perlin noise to SPDE-derived Gaussian random fields with oscillating Matérn covariance. The framework enables explicit control of smoothness, correlation length, and oscillation frequency. Multi-scale structure is achieved by combining multiple SPDE solutions, while anisotropy and fiber alignment are incorporated through diffusion tensor formulations.

Results: The proposed method reproduces key features of fibrotic tissue, including multi-scale texture, anisotropy, and spatial density variation. Comparative analyses demonstrate strong agreement with both Perlin-generated patterns and histological data, while improving adaptability to complex 3D geometries such as atrial tissue.

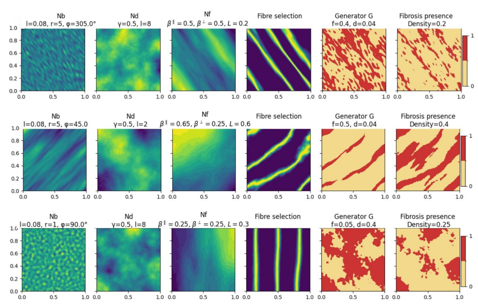

Figure 1. Example of the proposed fibrosis generation framework.

Conclusion: The SPDE-based framework provides a flexible and physiologically realistic approach to modeling fibrotic structural heterogeneity, enhancing the accuracy of cardiac electrophysiology simulations.