Development and Validation of a Cellular Automaton Framework for Simulating Heterogeneous Ventricular Restitution Dynamics and Functional Re-entry

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Introduction: The elevated computational cost of high-fidelity cardiac simulations often limits their clinical utility. We developed and validated an efficient cellular automaton (CA) framework to model functional ventricular arrhythmias and handle electrophysiological variability.

Methods: By embedding the biophysically detailed ToR-ORd model into the CA via action potential duration (APD) and conduction velocity restitution properties, we extend the population-of-models paradigm to a CA environment for the first time. Hypertrophic cardiomyopathy served as a validation exemplar for large-scale simulations of intra-individual variability.

Results: The proposed framework accurately captured the electrophysiological diversity of the underlying biophysical population, with mean average errors of 1.39–6.18 ms (<2.3% relative error; Panel A) in APD reconstruction. Under complex S1-S5 pacing, the CA reproduces 96% of stimuli with high fidelity (5.9% mean APD error; Panel B) and captures complex functional reentrant patterns, such as ventricular tachycardia, consistent with full biophysical simulations (Panel C).

Conclusions: These results demonstrate that the proposed CA model can retain high-fidelity predictive power while enabling rapid, population-based arrhythmia risk assessment at scale across diverse cardiac pathologies.