SYSTEM ANALYSIS: UNDERSTANDING VASCULARIZATION VIA CELLULAR AUTOMATA

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INTRODUCTION

This project uses a **cellular automaton (CA)** to simulate and understand:

- Blood vessel **growth and propagation**
- **Vascular** response to **damage**.
- Functional or **pathological changes** in glomeruli.
- How arterial structure affects **systemic stability**.
- The role of **local feedback i**n maintaining healthy flow.
- How small **initial differences** can lead to **divergent** biological **outcomes** (chaos).

METHODOLOGY

Inputs: Histological Kidney Images

The system processes high-resolution PAS-stained kidney histology (see Figure 1).

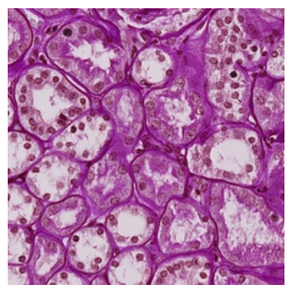


Figure 1

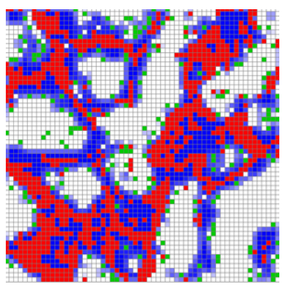


Figure 2

Cellular Automaton Grid: A 60×60 grid simulates biological **cells with distinct behaviors** (e.g., arteries, vessels, aneurysms, see Figure 2).

Biological Rules:

Cells **interact based on local rules**—vessel propagation, aneurysm formation, healing, and glomerular function.

SYSTEMIC PROBLEM ANALYSIS

High sensitivity to initial conditions:

Minor differences in arterial distribution or vessel density can drastically alter the development of vascular architecture, leading to either stability or dysfunction.

Nonlinear interactions:

Vascular cells act locally, but their interactions create emergent behaviors—like aneurysm chains or glomerular failure—not predictable from individual rules.

Chaotic feedback loops:

Local vessel overload may trigger aneurysms, which destroy surrounding vessels, increasing stress on nearby cells. These loops can amplify small instabilities into system-wide degradation.

Threshold-based responses:

Cells change state (e.g., from healthy to aneurysmal or failing) only after crossing specific biological thresholds, simulating real-world tipping points.

SYSTEM RULES

A Artery (A)

Spawns vessels in all directions (↑ ↓ ←→) every step.

Vessel (V)

Grows into nearby empty/dead cells with 30% chance. Dies if isolated. Turns into aneurysm if ≥5 neighbors (A or V).

Aneurysm (X)

Explodes if ≥2 neighboring aneurysms → destroys nearby vessels. Heals back to vessel if ≥4 nearby vessels.

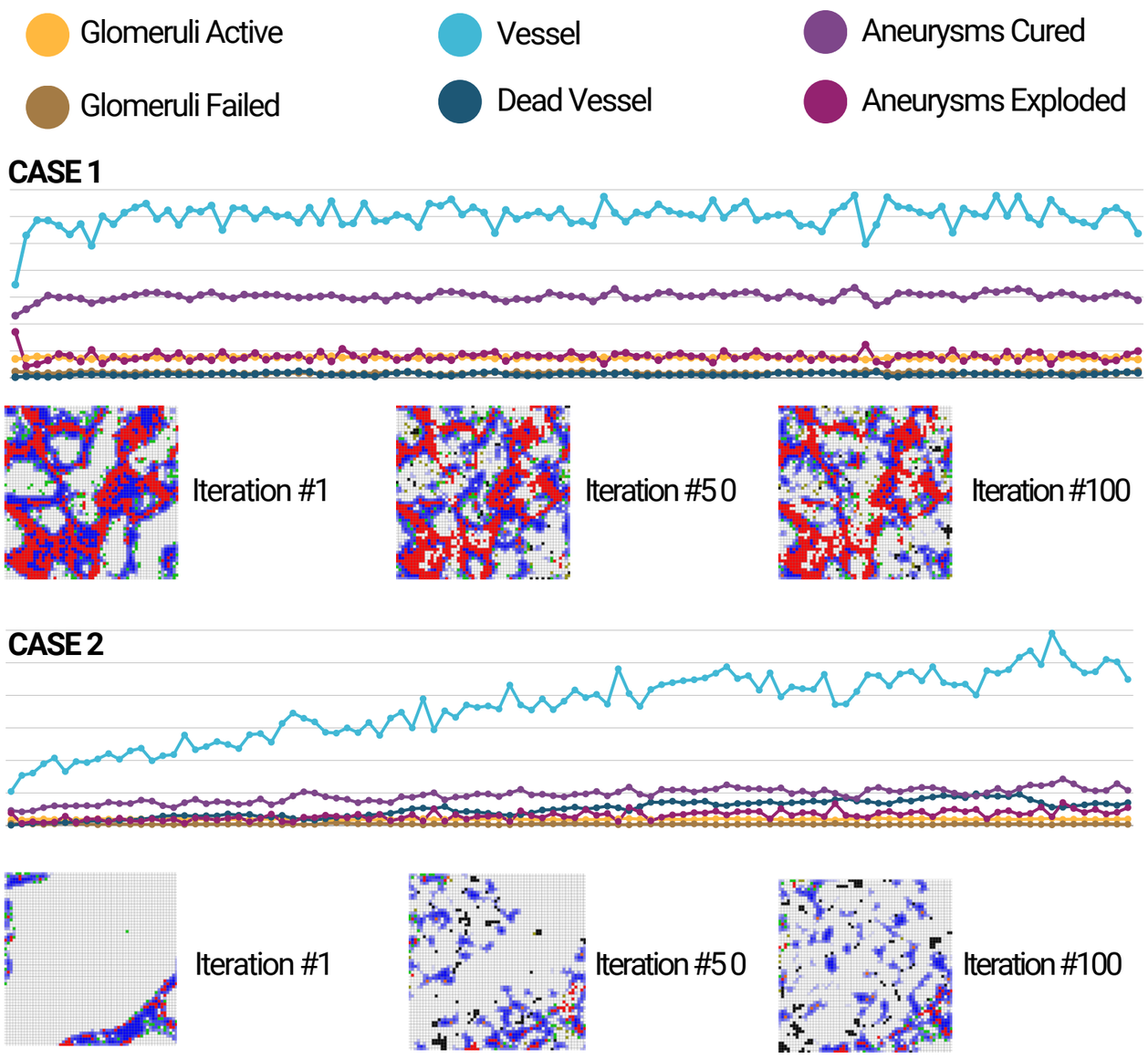
Dead Cell (D)

Revives into vessel if ≥1 neighbor is a vessel or artery.

Glomerulus (G)

Remains functional if supported by vessels/arteries Becomes failing (GF) if under-vascularized.

SYSTEM SIMULATIONS



MAIN FINDINGS

Case 1

structured arterial input

a well-organized network leads to:

- Consistent and stable vessel growth.
- Controlled aneurysm formation with steady healing.
- Balanced arterial pressure over time.
- Preservation of overall vascular architecture and systemic stability

Case 2

disorganized arterial input

the lack of structure causes:

- Erratic and insufficient vessel generation.
- Gradual accumulation of pressure and vascular stress.
- Increase in dead zones due to local hypoperfusion.
- Progressive breakdown of vascular structure and failure to maintain homeostasis.