A 3D Phase-field Method for Multiscale Simulation of the Interaction between Blood/Thrombus in Arterial Vessels

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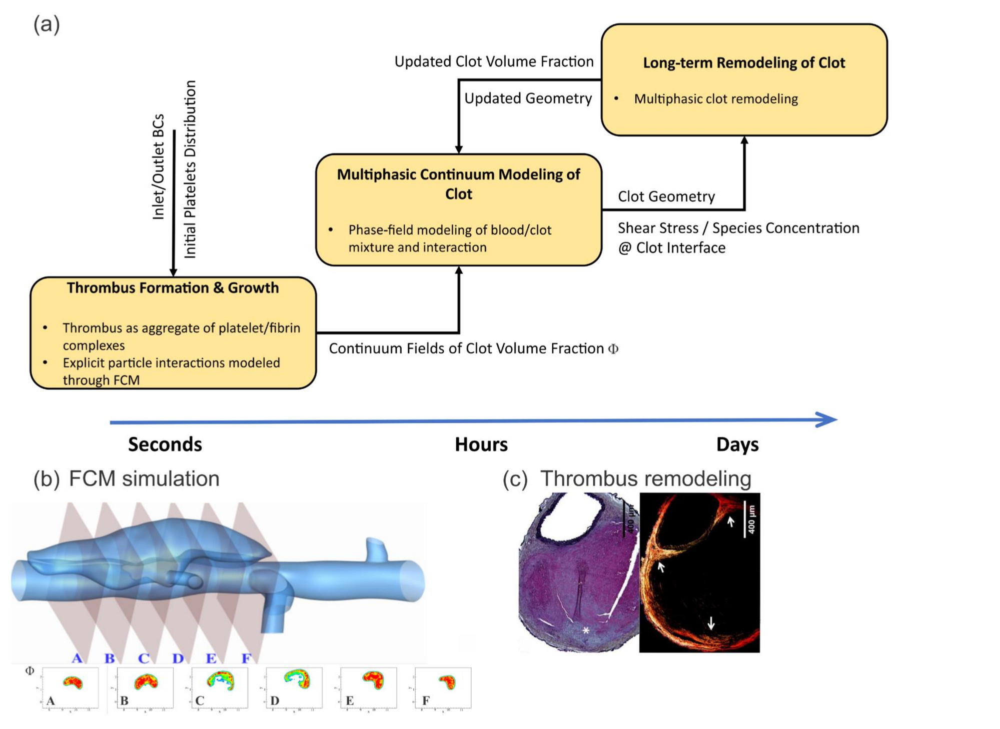
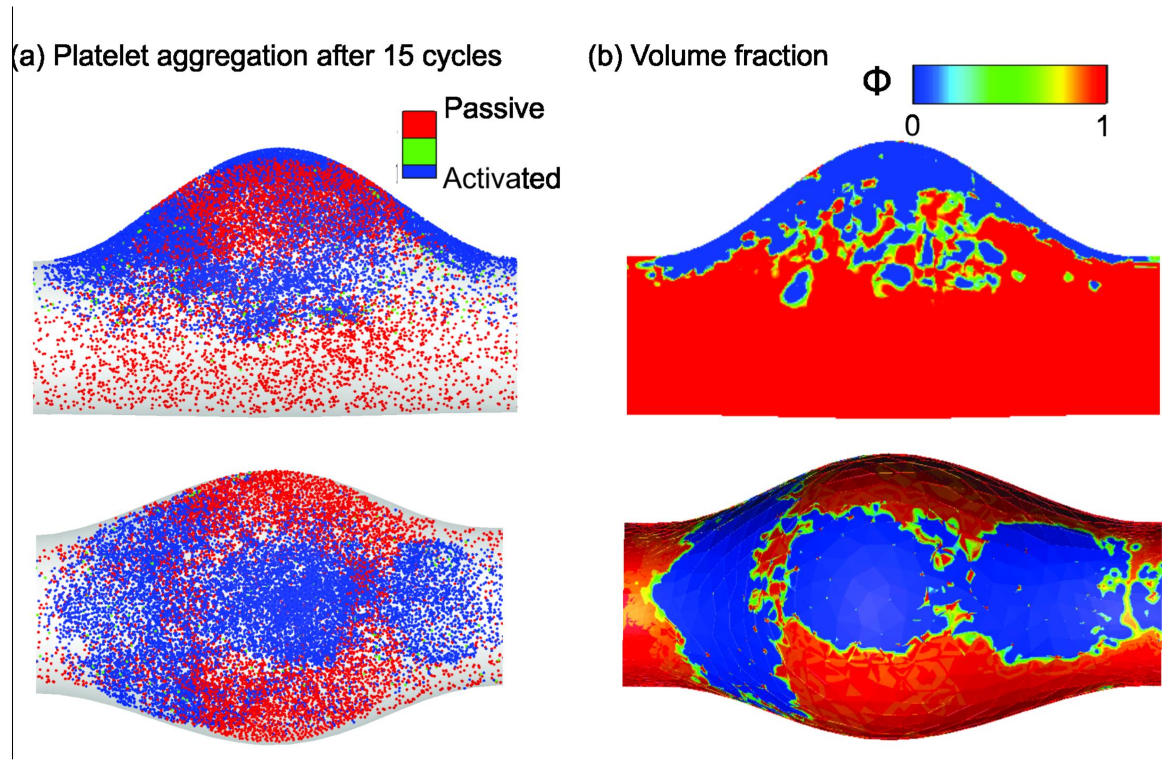
Background and Introduction

Thromboembolism is associated with detachment of small thrombus pieces from the bulk in the blood vessel. These detached pieces, also known as emboli, travel through the blood flow and may block other vessels downstream, e.g., they may plug the deep veins of the leg, groin or arm, leading to venous thromboembolism (VTE). VTE is a significant cause of morbidity and mortality and it affects more than 900,000 people in the United States and result in approximately 100,000 deaths every year.

Mechanical interaction between flowing blood and a thrombus is crucial in determining the deformation of the thrombus and the possibility of releasing emboli. In this study, we developed a combined framework with particle-based method and phase-field method to simulate the development of a thrombus from platelet aggregation to its subsequent viscoelastic responses to various shear flows.





Method

We propose a fully-Eulerian, three-dimensional, phase-field model of thrombus that is calibrated with existing in vitro experimental data.

This phase-field model considers spatial variations in permeability and material properties within a single unified mathematical framework derived from an energy perspective, thereby allowing us to study effects of thrombus microstructure and properties on its deformation and possible release of emboli under different hemodynamic conditions.

we combine this proposed thrombus model with a particle-based model which simulates the initiation of the thrombus.

$$\rho(\frac{\partial u}{\partial t}+u\cdot\nabla u))+\nabla p-\nabla\cdot(\eta(\phi_1)\nabla u)+\nabla\cdot(\lambda_e\phi_1\nabla\cdot(FF^T)+\lambda\nabla\cdot(\nabla\phi\otimes\nabla\phi)+\eta(\phi_1)\frac{(1-\phi)u}{\kappa}=0 \qquad (8)$$

$$\nabla\cdot u=0$$

$$\frac{\partial F}{\partial t}-u\cdot(\nabla F)=\nabla V\cdot F$$

$$\frac{\partial\phi}{\partial t}+u\cdot\nabla\phi-\lambda\Delta\mu_1=0$$

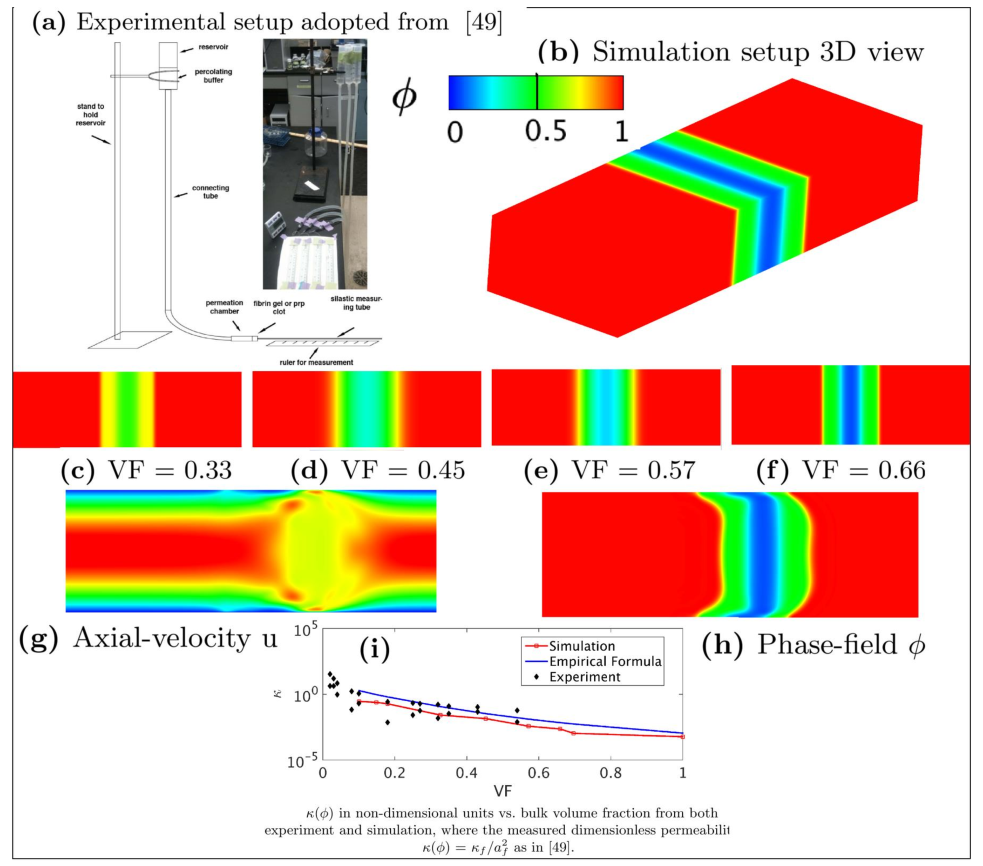
$$\mu_1=-\lambda\Delta\phi+\lambda\gamma g_1(\phi)+\frac{\lambda_e}{2}tr(FF^T)$$

Governing Equation

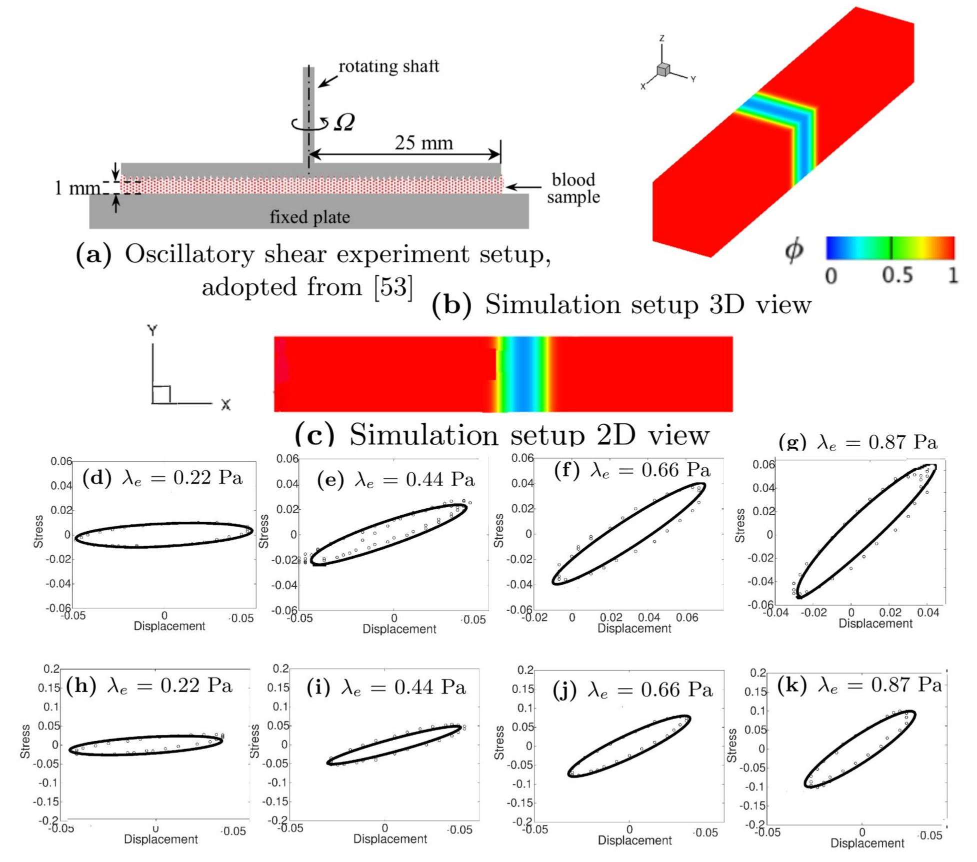
Results

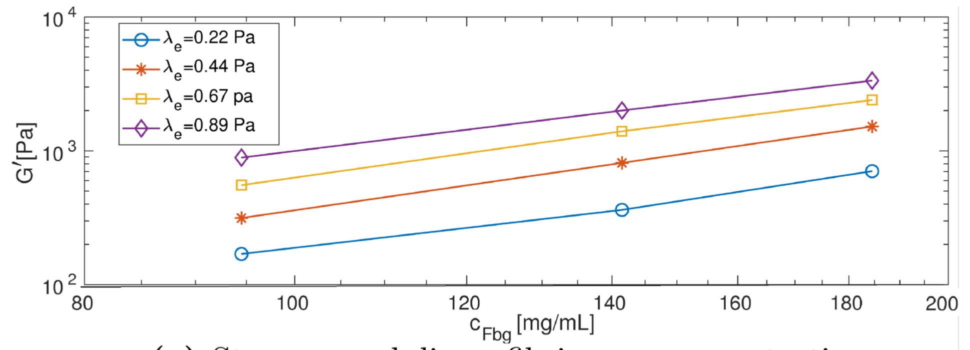
Calibration of model parameters was achieved by comparing the simulation results with existing in vitro experimental data for the poro-viscoelastic behavior.

Calibration of permeability

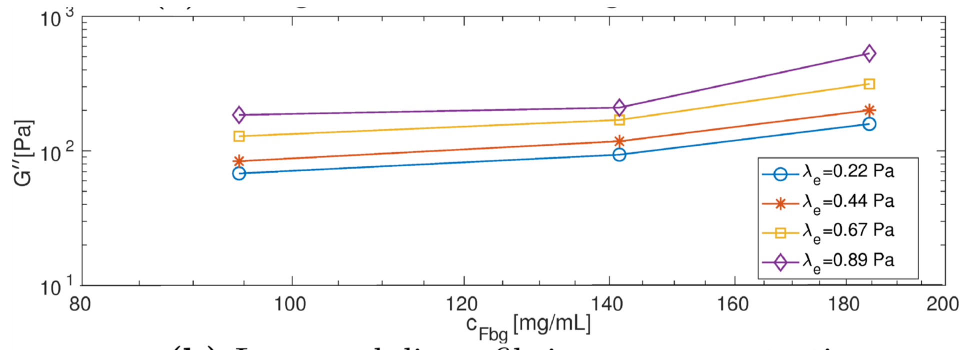


Calibration of elastic shear modulus





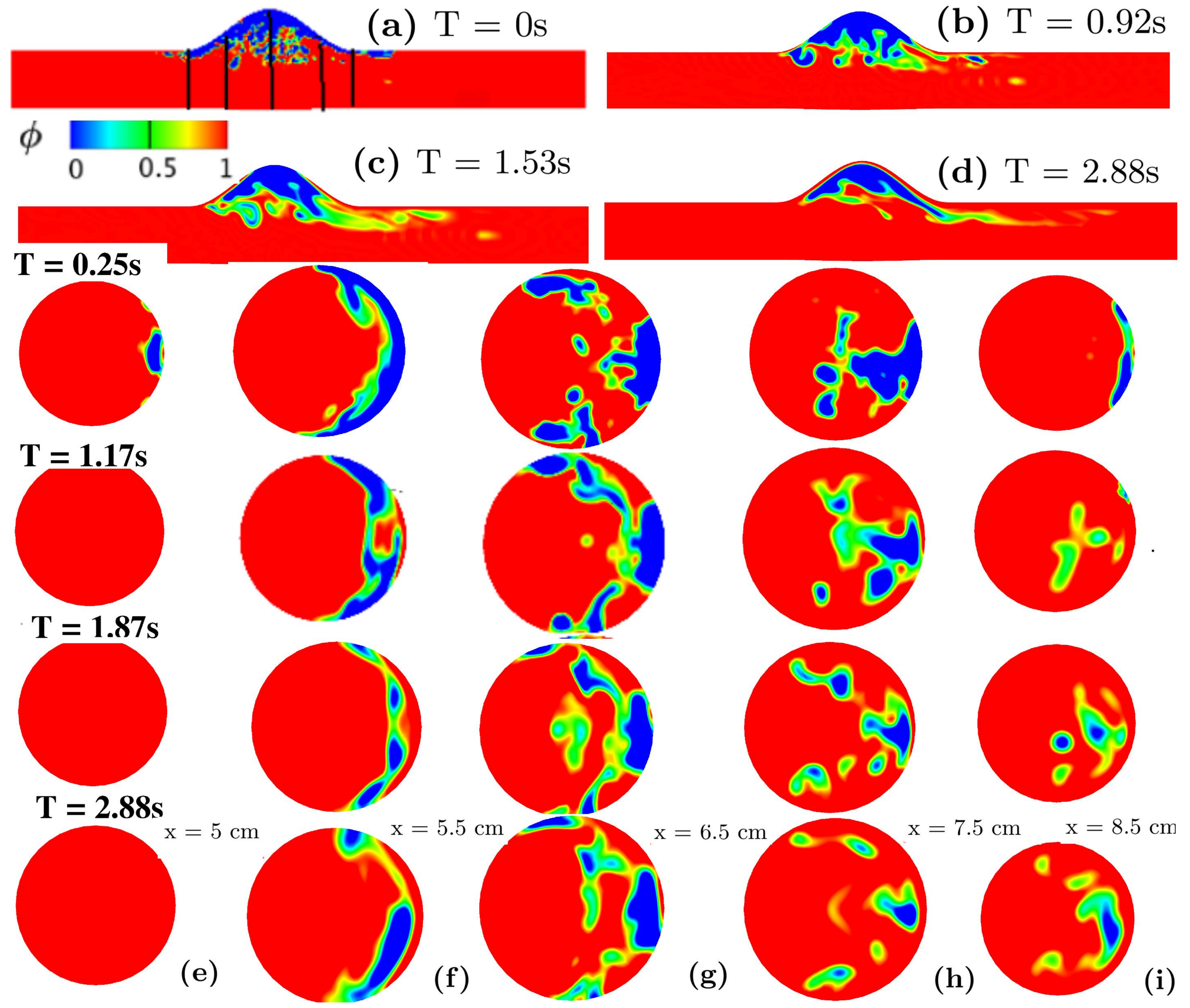
(a) Storage moduli vs. fibrinogen concentration



(b) Loss moduli vs. fibrinogen concentration

Results (Continued)

The proposed 3D phase-field model can be combined with FCM to simulate the process from platelet activation and deposition to subsequent deformation while exposed to steady or pulsatile blood flow



Conclusion Guided by patientspecific clinical data, such as lesion geometry and the local blood flow rate, this multiscale framework has the potential to predict the risk of thrombotic-embolic events, which are responsible for significant morbidity and mortality.

We are working on solving this set of governing equations with PINNs (physics informed neural network) and inferring the mechanical properties of the thrombus (permeability and visco-elastic modulus)

References

Tierra G, Pavissich JP, Nerenberg R, Xu Z, Alber MS, 2015