Blood Clot Formation Modelling with LAMMPS: Thrombosis versus Hydrodynamic Stress

學生： B11508002 陳楷霖 指導教授： 張書瑋、周佳靚

Abstract

Blood clot formation is a multiscale biophysical process governed by complex interactions among platelets, red blood cells, plasma flow, and vessel geometry, where the balance between thrombus growth and hydrodynamic stress critically determines clot stability and pathological risk. Under physiological conditions, platelet adhesion and aggregation enable rapid hemostasis, while excessive shear forces generated by blood flow can inhibit clot growth or induce embolization. Understanding this competition between thrombosis and hydrodynamic stress remains challenging due to the coupled mechanical and collective behaviors of blood components at the microscale. Computational particle-based modeling provides a promising framework to isolate and study these mechanisms under controlled conditions. In this study, we model the formation of blood clots (thrombosis) with a LAMMPS-based particle simulation to investigate how platelet and red blood cell's adhesion and flow-induced forces jointly regulate clot growth and resistance to hydrodynamic stress.

Keywords: Thrombosis, Hydrodynamic Stress, Particle-Based Simulation, LAMMPS

1. Introduction

1.1. Objective

The objective of this study is to investigate the formation and stability of blood clots under the influence of platelet-driven aggregation and hydrodynamic stress. By employing a particle-based simulation framework, this work aims to model key mechanical aspects of thrombosis, including platelet adhesion and flow-induced forces, to observe how these factors influence blood clots' growth and resistance to mechanical disruption.

1.2. Research Background

Thrombosis stems from the mechanical interactions mostly between platelets, red blood cells (RBCs), and blood flow, where clot growth is regulated by the balance between adhesive forces and hydrodynamic stress [1]. Computational modeling has become an essential tool for studying blood mechanics at the cellular scale, where experimental control is limited. Multiscale and coarse-grained RBC models have demonstrated that accurate mechanical representation of individual cells is crucial for reproducing realistic blood rheology and deformation dynamics [2,3]. Particle-based simulation methods, such as dissipative particle dynamics (DPD), have been used to model how red blood cells deform and aggregate under

confined spaces and high-shear flow conditions, for example in narrowed micro-vessels [4, 5]. In addition, computational models have been applied to study blood clot formation and to explore thrombotic risks related to vascular implant designs, showing how simulations can be useful for understanding thrombosis from a mechanical perspective [6]. In conclusion, particle-based simulation frameworks can provide a flexible platform for isolating the mechanical contributions of cell–cell adhesion and flow-induced forces in thrombus formation.

1.3. Research Question

This study aims to investigate how blood clot formation is regulated by the hydrodynamic stress and inter-particle adhesion under controlled simulation conditions. Specifically, under varying flow speeds and adhesion strengths. Specifically, we will address the following research questions:

- How does clot size evolve over time under different hydrodynamic pressures induced by varying flow speeds?
- How does stress increase in the simulated model under different adhesion strengths?
- What mechanistic insights can be inferred regarding the balance between thrombosis and hydrodynamic stress from the observed clot growth dynamics?

2. Methodology

2.1. Model Design

Our script constructs a two-dimensional Lennard-Jones based model of blood clot formation in a thin vessel under flow. A simplified vascular is first constructed using fixed particle layers to represent the upper and lower vessel walls, with a localized damaged region on the lower wall designated as a clot seed. The vein is populated with mobile particles representing red blood cells and platelets, which are transported through the channel by a Poiseuille-like body force while the walls remain immobile. Interactions are designed such that platelets strongly adhere to the damaged wall region, where red blood cells do not bind directly to intact vessel walls.

Additionally, to address the saturation problem we observed in single-stage clot models (where newly arriving platelets fail to recruit additional red blood cells), a multi-stage activation strategy is introduced. In this approach, platelets that accumulate near the growing clot are periodically converted into an “activated” state with enhanced attractive interactions to both red blood cells and other platelets. Repeating this activation over multiple stages allows the clot to continue growing over long simulation times, enabling sustained red blood cell recruitment and producing a visually realistic, progressively enlarging thrombus rather than an early-saturated aggregate.

- **Rigid body Definition:**

```
# ======================================================================
# RIGID BODY DEFINITION: Vessel geometry, walls, and clot seed
# ======================================================================

# 2D LJ Poiseuille flow with multi-stage clot at damaged wall (thin vein)

units       lj
dimension   2
boundary    p s p

atom_style  atomic
neighbor    0.3 bin
neigh_modify delay 5

# Geometry: thinner channel
lattice     hex 0.7
region      box block 0 40 0 8 -0.25 0.25
create_box  5 box
create_atoms 1 box                          # start all as type 1

# Atom types
# 1 = wall, 2 = seed, 3 = RBC, 4 = platelet, 5 = activated platelet
mass        1 1.0
mass        2 1.0
mass        3 1.0
mass        4 1.0
mass        5 1.0

# Walls by region
region      lower block INF INF INF 1.25 INF INF
region      upper block INF INF 6.75 INF INF INF
group       lower region lower
group       upper region upper

# Damaged patch (clot seed) in lower wall
region      seedreg block 15.0 25.0 INF 1.25 INF INF
group       seed region seedreg

set         group lower type 1
set         group upper type 1
set         group seed  type 2

group       wall union lower upper seed    # fixed solid (walls + seed)
```

- **Flow Dynamics:**

```
# ======================================================================
# FLOW DYNAMICS: Blood particles, interactions, and driven flow
# ======================================================================

# Lumen region
region      fluid block 0 40 1.25 6.75 -0.25 0.25
delete_atoms region fluid

# Create RBCs
create_atoms 3 random 200 12345 fluid

# Initial groups
group       rbcs type 3
group       platelets_free type 4
group       platelets_act type 5
group       mobile union rbcs platelets_free platelets_act
group       flow union mobile

# Convert fraction of RBCs into free platelets
set         group mobile type/fraction 4 0.10 98765

# Rebuild groups
group       rbcs type 3
group       platelets_free type 4
group       platelets_act type 5
group       mobile union rbcs platelets_free platelets_act
group       flow union mobile

# Lennard-Jones interactions (Stage 1)
pair_style  lj/cut 2.5

pair_coeff  1 1  1.0 1.0 1.12246
pair_coeff  1 2  1.0 1.0 1.12246
pair_coeff  2 2  1.0 1.0 1.12246

pair_coeff  1 3  0.5 1.0 1.12246
pair_coeff  1 4  0.5 1.0 1.12246
pair_coeff  1 5  0.5 1.0 1.12246
```

```
pair_coeff  2 3  0.5 1.0 1.12246
pair_coeff  2 4 12.0 1.0 2.5
pair_coeff  2 5 12.0 1.0 2.5

pair_coeff  3 3  1.0 1.0 1.12246
pair_coeff  3 4  1.0 1.0 1.12246
pair_coeff  3 5  1.0 1.0 1.12246

pair_coeff  4 4  1.5 1.0 2.5
pair_coeff  4 5  1.5 1.0 2.5
pair_coeff  5 5  1.5 1.0 2.5

# Remove overlaps
delete_atoms overlap 0.8 mobile wall
delete_atoms overlap 0.8 mobile mobile

# Rebuild groups
group       rbcs type 3
group       platelets_free type 4
group       platelets_act type 5
group       mobile union rbcs platelets_free platelets_act
group       flow union mobile
group       wall union lower upper seed

# Dynamics & flow
compute     Tmobile mobile temp
velocity    mobile create 0.08 482748 dist gaussian

fix         1 mobile nve
fix         2 mobile temp/rescale 200 0.08 0.08 0.02 1.0
fix_modify  2 temp Tmobile

velocity    wall set 0.0 0.0 0.0
fix         3 wall setforce 0.0 0.0 0.0

fix         6 flow addforce 0.006 0.0 0.0

timestep    0.001
thermo      1000
thermo_modify temp Tmobile

dump        allDump all xyz 1000 "C:/Users/kaili/Desktop/nve/dump.clot_thinvein_multistage.xyz"
dump_modify allDump sort id

# Stage 1: platelet plug formation
run         40000
```

- **Multi-stage Modelling**

```
# ============================================================================
# MULTI-STAGE MODELLING: Platelet activation and sustained clot growth
# ============================================================================

# Activated platelet interactions
pair_coeff  3 5  8.0 1.0 2.5
pair_coeff  4 5  3.0 1.0 2.5
pair_coeff  5 5  3.0 1.0 2.5

# Activation region near clot
region      clotzone block 14.0 26.0 0.0 2.2 -0.25 0.25

# ---- Stage 2 ----
group       platelets_near region clotzone
group       platelets_to_activate intersect platelets_near platelets_free
set         group platelets_to_activate type 5
run         1000000

# ---- Stage 3 ----
group       platelets_near region clotzone
group       platelets_to_activate intersect platelets_near platelets_free
set         group platelets_to_activate type 5
run         1000000

# ---- Stage 4 ----
group       platelets_near region clotzone
group       platelets_to_activate intersect platelets_near platelets_free
set         group platelets_to_activate type 5
run         1000000

# ---- Stage 5 ----
group       platelets_near region clotzone
group       platelets_to_activate intersect platelets_near platelets_free
set         group platelets_to_activate type 5
run         1000000
```

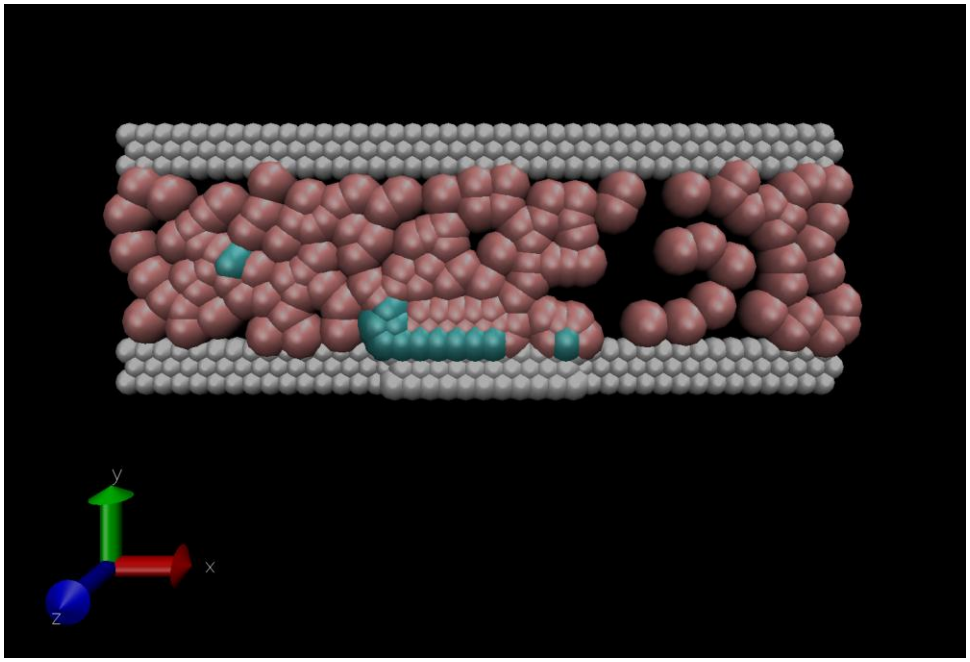

Fig.1. A frame of the simulated rigid body and flow particles (red = red blood cell, cyan = platelets, smaller white spheres = vein wall, bigger white spheres = clot seed). In this frame, we can observe that the clot is forming on the clot seed as particles are closely sticking to each other.

2.2. Post-processing: Stress estimation from LAMMPS output

- **Clot Size Analysis**

  Clot growth was quantified by manually counting the number of particles adhered to the clot region at fixed time intervals. Specifically, the trajectory was inspected every 500 frames, and particles stably attached to the clot were counted to track the temporal evolution of clot size under different flow conditions. This approach should provide a direct and intuitive measure of clot growth dynamics without introducing additional model assumptions.

- **Stress Analysis**

  Mechanical loading during clot formation was quantified using the per-particle virial stress tensor computed in LAMMPS. The simulation timestep was 0.001 (reduced LJ units), and stress data were sampled every 1000 timesteps to match the thermo and trajectory output frequency. Using compute stress/atom, per-atom stress tensor components were obtained and spatially averaged over clot-associated particle groups (e.g., activated platelets). The in-plane trace of the stress tensor was then converted into a pressure-like scalar during post-processing. The resulting time series was visualized using Python and Matplotlib to examine how mechanical stress evolves across successive clot growth stages.

3. Results

3.1. Sample Video

A sample video of the full simulation is uploaded onto YouTube.

URL link: https://www.youtube.com/watch?v=MNIYOgBUk14

3.2. Results Analysis

- **Clot Size under different flow strengths:**

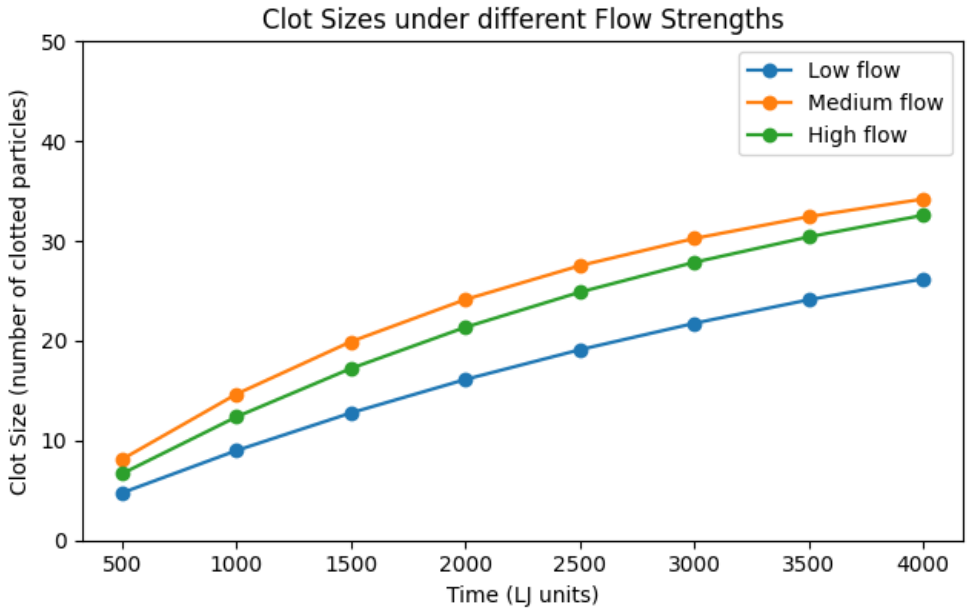

Fig.2. Clot size over time under different flow strengths, showing maximal clot growth at intermediate flow due to optimized balance between inter-atomic potential and hydrodynamic stress.

The figure shows the growth of clot size under low, medium, and high flow strengths. In all three conditions, clot size increases monotonically with time, indicating sustained particle accumulation once clot formation is initiated. However, clear differences emerge in both the growth rate and the final clot size. Medium flow consistently produces the largest clot throughout the simulation, followed by high flow, while low flow results in the smallest clot at all time points. This trend suggests that an intermediate flow strength provides an optimal balance between particle transport and adhesion: sufficient flow enhances the delivery of platelets and red blood cells to the clot site, while excessive shear at high flow partially limits stable accumulation. In contrast, low flow conditions are adhesion-dominated but transport-limited, leading to slower growth and smaller final clot size. *Overall, the results showed that medium flow maximizing clot growth in this model.*

- **Stress curve in the simulated model under different adhesion strengths**

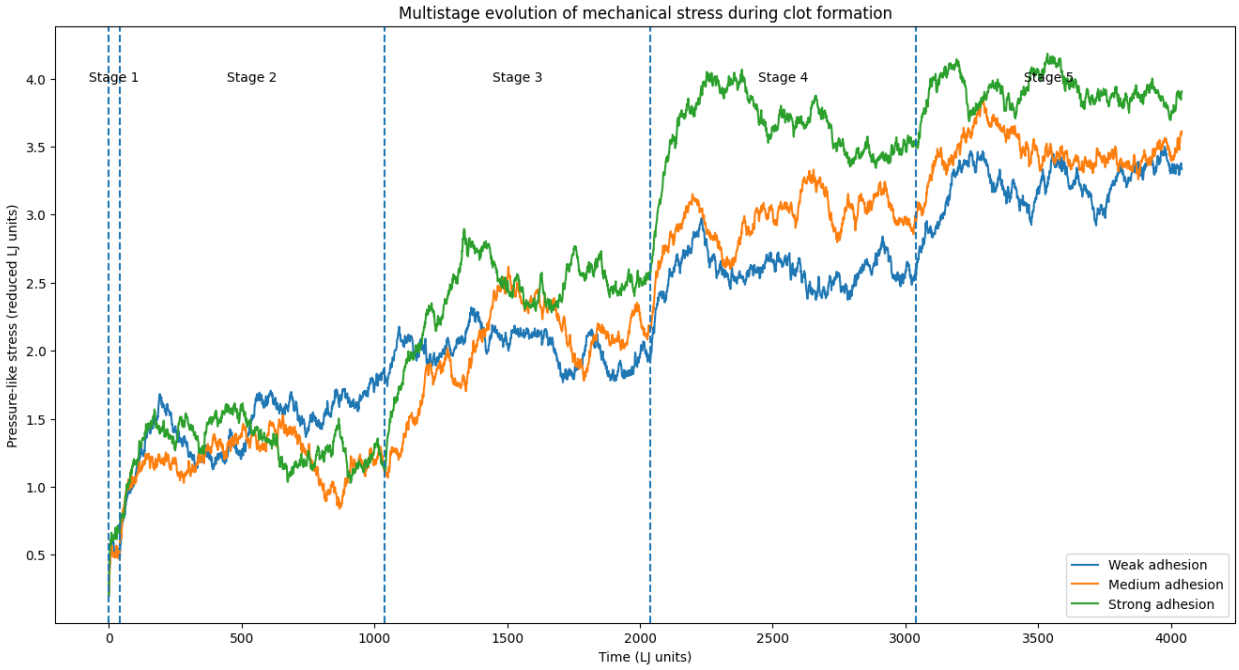

Fig.3. Stress curve of the simulated model during clot formation under different adhesion strengths.

The figure shows the time evolution of stress during clot formation for weak, medium, and strong adhesion strengths (LJ potential). In all cases, stress increases stepwise across stages due to the multistage modeling method utilized in the script. We can see that stronger adhesion produces higher stress levels due to more effective force transmission within the clot. The plateau-like behavior within each stage indicates mechanical stabilization following activation events, whereas the sharper stress increases at stage boundaries correspond to changes in clot composition and adhesion state. *Overall, the results demonstrate that increasing adhesion strength enhances both the magnitude and stability of mechanical stress sustained by the clot during multistage development.*

- **Other conclusions/MythBusters that are inferred from the results:**

1) **Slower blood flow always leads to larger clots.**

   The simulation results show that clot size is maximized at intermediate flow strength rather than at the lowest flow. Under low-flow conditions, particle transport to the injury site is limited, slowing clot growth despite favorable adhesion. In contrast, moderate flow enhances the delivery of platelets and red blood cells while avoiding excessive shear that can disrupt attachment, resulting in the largest clot formation. This demonstrates that clot growth depends on a balance between transport and shear, rather than flow magnitude alone.

2) Larger clots necessarily experience higher mechanical stress

Stress analysis reveals that stronger adhesion consistently produces higher pressure-like stress, even when clot sizes are comparable. This indicates that adhesion strength controls the internal force transmission and mechanical rigidity of the clot, enabling it to sustain larger loads under flow. Therefore, clot stability and mechanical resilience are not solely determined by size, but also by the strength of inter-particle binding within the clot.

3) Drinking less water accelerates clot formation by increasing adhesion

Reduced hydration can increase effective adhesion between blood components, leading to faster clot stabilization and higher mechanical stress within the clot. Stronger adhesion promotes tighter particle binding and enhanced force transmission, resulting in mechanically more robust clots that are better able to withstand hydrodynamic loading.

4. References

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