Rheological Modeling of the Blood

Bridging the experiments and computation models of the diseased blood

Linghao Shi

MECHANICAL ENGINEERING
UNIVERSITY OF MICHIGAN

- **State of the Field:** Current clinical hematology primarily relies on standard tests (e.g., complete blood count, erythrocyte sedimentation rate) which, while useful, offer limited insight into the complex **non-Newtonian, viscoelastic, and thixotropic** properties of whole blood.

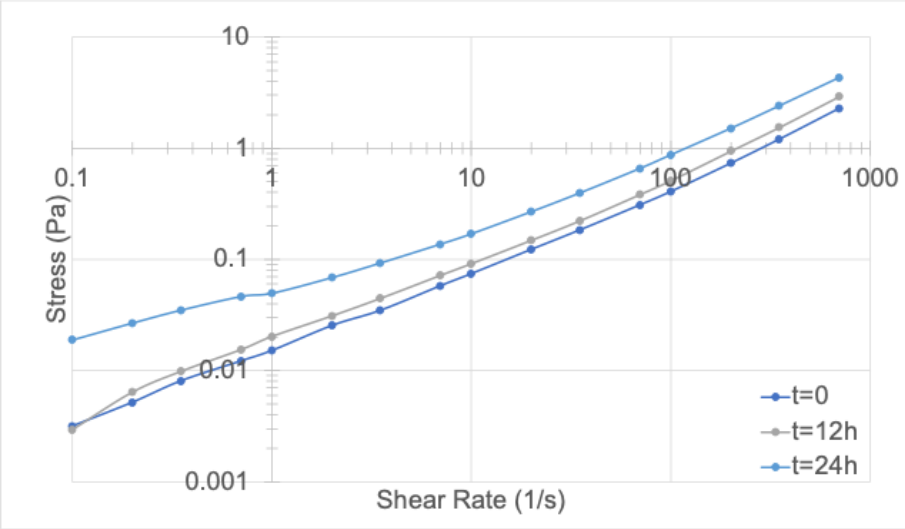
- **The Gap:** There is a critical lack of integrative models that connect measurable blood rheological parameters (like viscosity at different shear rates, yield stress, and viscoelastic moduli) directly to the onset and progression of specific diseases (e.g., sickle cell anemia, sepsis, diabetes).

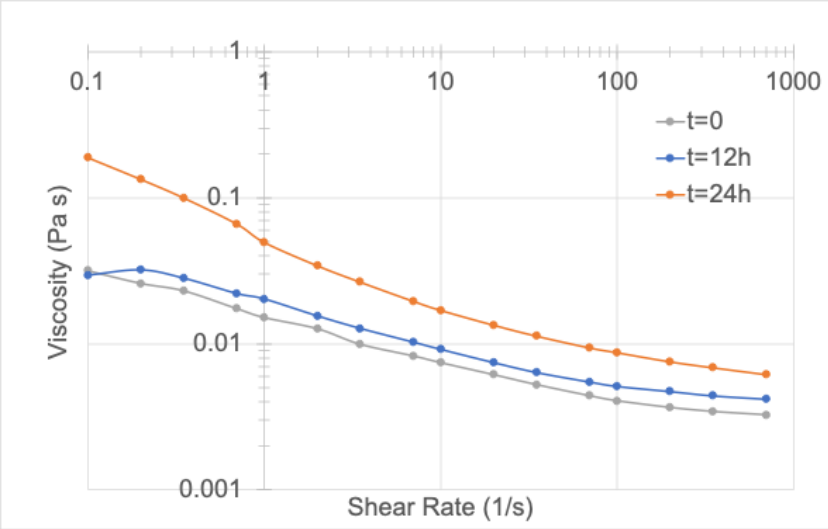
- **Project Aim:** This project aims to develop a multi-scale rheological model of blood that can be calibrated with patient-specific data to serve as a diagnostic tool for identifying serious diseases and quantifying their hemodynamic impact.

- **Relevant Data:** The project will utilize data from experimental studies on diseased blood and computational models of blood flow to build and validate this diagnostic framework.

Experiment datasets

- A series of datasets produced by Armstrong et al. on Mendeley[1-5], record the linear and nonlinear viscoelastic data of the human blood. They are precious source for testing the constitutive or molecular models from the experimental values. Some data is shown in the figures below





- The papers written by the same team tested the fitting performance of their own models[5,6], setting a standard for my models.

References

[1] Armstrong, Matthew (2020), "DEC17 ARESG2 Human Blood Rheology: SS, SAOS, LAOS, STEPS, etc.", Mendeley Data, V1, doi: 10.17632/d43r5ydpx8.1

[2] Armstrong, Matthew; horner, jeff (2020), "FEB18 Blood Rheology ARESG2 SS SAOS LAOS STEP", Mendeley Data, V1, doi: 10.17632/jdzpx6hy6r.1

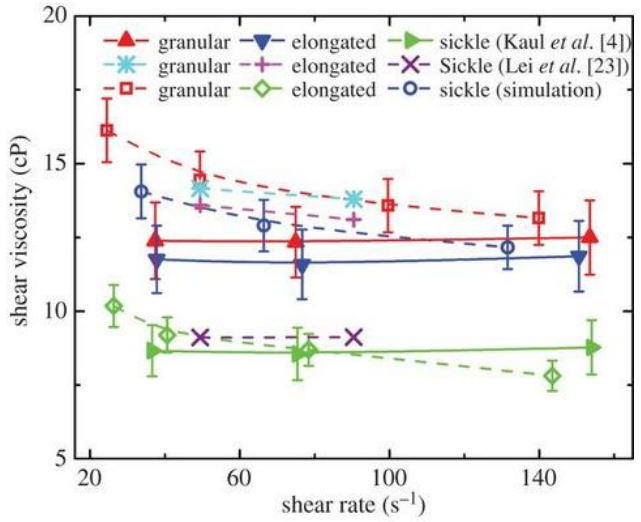
[3] Armstrong, Matthew; Horner, Jeff (2020), "Rheology data of human blood JUN18", Mendeley Data, V1, doi: 10.17632/948ffnypjs.1

[4] Armstrong, Matthew; horner, jeff (2020), "JUL18 Human blood rheology", Mendeley Data, V1, doi: 10.17632/s8w6s6f68b.1

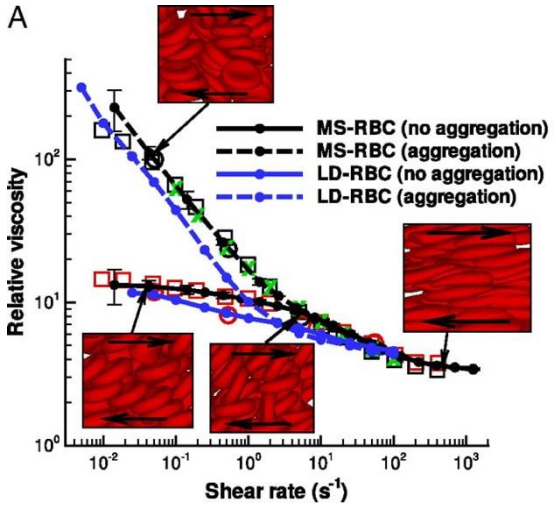
[5] Horner, J. S., Armstrong, M. J., Wagner, N. J., & Beris, A. N. (2018). Investigation of blood rheology under steady and unidirectional large amplitude oscillatory shear. *Journal of Rheology*, *62*(2), 577-591.

[6] Armstrong, M., & Tussing, J. (2020). A methodology for adding thixotropy to Oldroyd-8 family of viscoelastic models for characterization of human blood. *Physics of Fluids*, *32*(9).

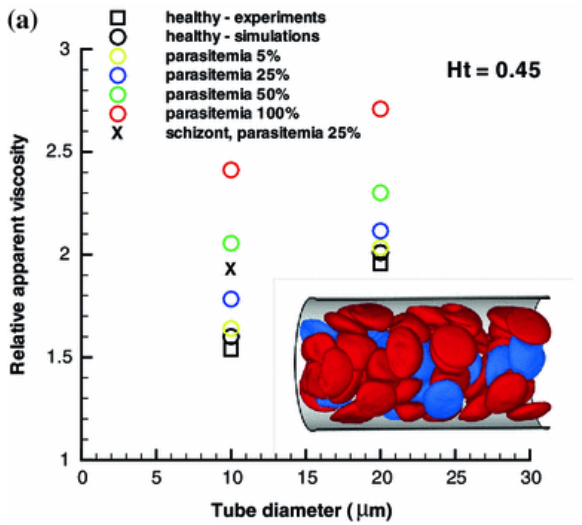
Particle-Based Models



The comparison between simulations and experiments by Li et al.



Plot of non-Newtonian relative viscosity of the whole blood and erythrocyte suspensions. The snapshots show the behavior of the aggregation. (Fedosov et al.)



Flow resistance of the healthy red cells and those infected by malaria in Poiseuille flow in a tube. (Fedosov et al.)

The plots shown in this slide are all particle-based simulation to attain the viscosity data. Since the experimental measurement is normally at least at ~ms level, the simulation that needs to reach this time scale must be very fast. The simulations in this slide all use dissipative particle dynamics (DPD) method. They provide one possible route to bridge the simulation and the experiment results.

References

Li, X., Du, E., Lei, H., Tang, Y. H., Dao, M., Suresh, S., & Karniadakis, G. E. (2016). Patient-specific blood rheology in sickle-cell anaemia. *Interface focus*, *6*(1), 20150065.

Kaul, D. K., & Xue, H. (1991). Rate of deoxygenation and rheologic behavior of blood in sickle cell anemia.

Lei, H., & Karniadakis, G. E. (2013). Probing vasoocclusion phenomena in sickle cell anemia via mesoscopic simulations. *Proceedings of the National Academy of Sciences*, *110*(28), 11326-11330.

Fedosov, D. A., Dao, M., Karniadakis, G. E., & Suresh, S. (2014). Computational biorheology of human blood flow in health and disease. *Annals of biomedical engineering*, *42*(2), 368-387.

Fedosov, D. A., Pan, W., Caswell, B., Gompper, G., & Karniadakis, G. E. (2011). Predicting human blood viscosity in silico. *Proceedings of the National Academy of Sciences*, *108*(29), 11772-11777.

Constitutive Equations

Blood Sample	Model	Reference
Healthy Human Blood	Oldroyd-8	Armstrong et al.
Healthy Human Blood	Bi-exponent Quemada K–L Casson Wang Cross Power law	Zhang et al.
Healthy Human Blood	Horner-Armstrong-Wagner-Beris (HAWB)	Horner et al.
Healthy Human Blood	Casson Model	Apostolidis et al.

These papers construct constitutive equations for the blood sample. They validate the feasibility to use mathematic equations to describe the healthy blood, laying the foundation of using constitutive models to describe those infected by the diseases.

References

Armstrong, M., & Tussing, J. (2020). A methodology for adding thixotropy to Oldroyd-8 family of viscoelastic models for characterization of human blood. *Physics of Fluids*, *32*(9).
Zhang, J. B., & Kuang, Z. B. (2000). Study on blood constitutive parameters in different blood constitutive equations. *Journal of Biomechanics*, *33*(3), 355-360.
Horner, J. S., Armstrong, M. J., Wagner, N. J., & Beris, A. N. (2019). Measurements of human blood viscoelasticity and thixotropy under steady and transient shear and constitutive modeling thereof. *Journal of Rheology*, *63*(5), 799-813.
Apostolidis, A. J., & Beris, A. N. (2014). Modeling of the blood rheology in steady-state shear flows. *Journal of Rheology*, *58*(3), 607-633.