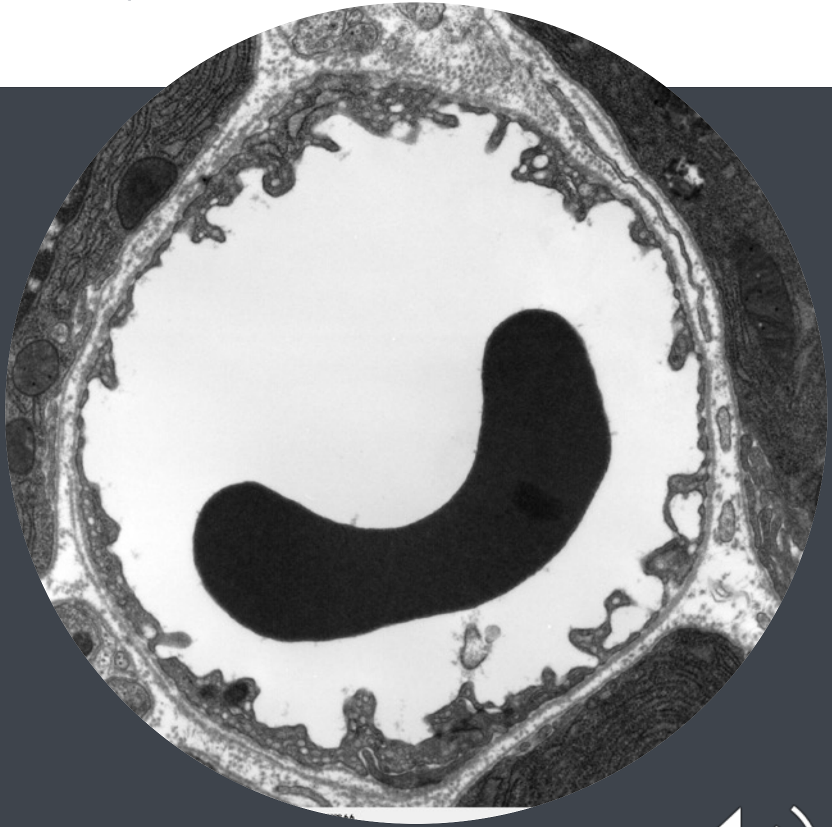
University of Stuttgart
Institute for Modelling Hydraulic and Environmental Systems

Chapter 1

Physiology and basics



Data-integrated Simulation Science A – Part D Biofluidmechnik

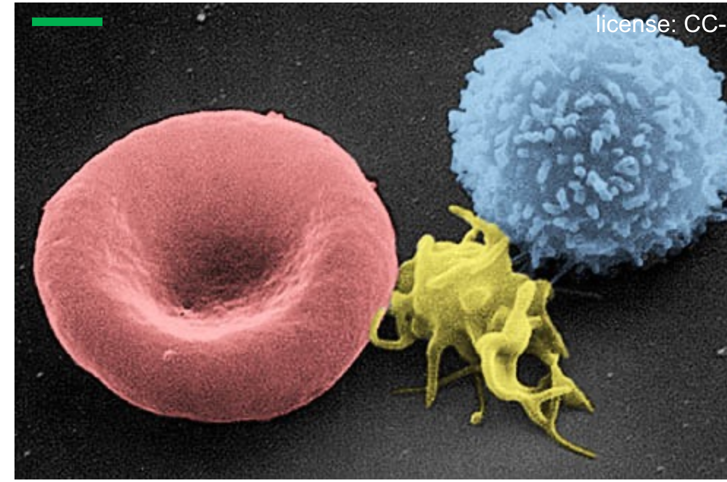
1.2 Properties of blood

Properties of blood

- Blood consists of blood plasma and three groups of cell types:
  - Thrombocytes (platelets)
  - Leukocytes (white blood cells)
  - Erythrocytes (red blood cells)
- Blood plasma: 90% water, 10% proteins and ions (55% of total blood volume)
- Cells: 45% of total blood volume
- **Hematocrit**: volume of erythrocytes/volume of blood: 36% - 50%

1µm

Leukocyte

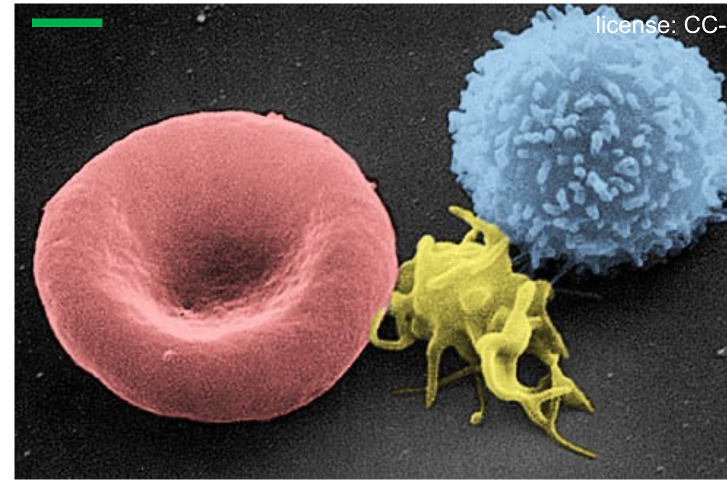


Erythrocyte (RBC)

Thrombocyte

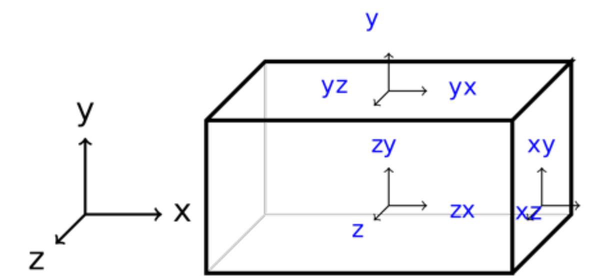
Properties of blood

- Two-phase model:
  - Blood plasma (Newtonian fluid, similar properties as water)
  - Blood cells
- „One-phase“ model:
  - Can we parameterize two phase effects and describe blood as a single pseudo-phase?



Properties of blood

Viscosity



- Newtonian fluid

  Linear relationship between stress und rate-of-strain tensor with proportionality constant μ (dynamic viscosity)

  Stokes stress constitutive equation (incompressible Newtonian fluid):

$$\boldsymbol{\tau} = \begin{bmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{bmatrix} = \mu \begin{bmatrix} 2\frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} & \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} & 2\frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \\ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} & \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} & 2\frac{\partial w}{\partial z} \end{bmatrix} = \mu\left(\nabla \boldsymbol{v} + (\nabla \boldsymbol{v})^T\right) = 2\mu \boldsymbol{D}$$

$\boldsymbol{\tau}$: (Deviatoric) stress tensor
τ_{ij} : shear stresses
σ_{ii} : normal stresses
$\boldsymbol{v}$: velocity vector
μ : dynamic viscosity
$\nabla \boldsymbol{v}$: velocity gradient
$\nabla \boldsymbol{v}^T$: transposed velocity gradient
$\boldsymbol{D}$: rate-of-strain tensor

Properties of blood

Viscosity

$$\dot{\gamma} = \sqrt{2\boldsymbol{D} : \boldsymbol{D}} \equiv \sqrt{2D_{ij}D_{ij}} \qquad \dot{\gamma} : \text{shear rate}$$

- Blood as Newtonian fluid?

  Good blood model for high shear rates (>10-100 s^{-1})

  Good blood model as approximation for larger vessels (> 1mm)

- Blood as non-Newtonian fluid?

  Large vessels: for slow and pulsating blood flow or due to transient effects → non-Newtonian effects are important (e.g. during diastole)

  z.B. generalised power-law model or Casson model

$$\boldsymbol{\tau} = 2\mu(\dot{\gamma})\boldsymbol{D} \qquad \mu(\dot{\gamma}) := \lambda(\dot{\gamma})\dot{\gamma}^{n(\dot{\gamma})-1}$$

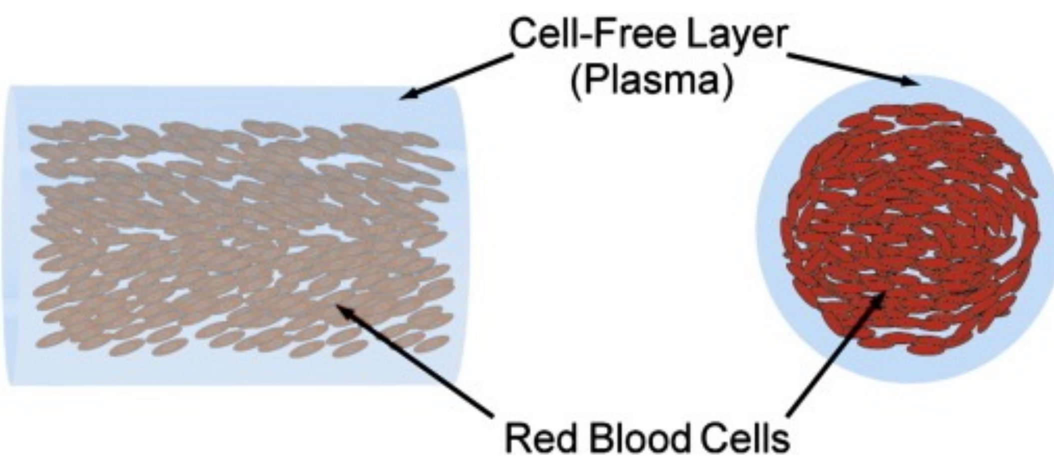
  Johnston et al (2006) **“Non-Newtonian blood flow in human right coronary arteries: Transient simulations”**, Journal of Biomechanics, https://doi.org/10.1016/j.jbiomech.2005.01.034.

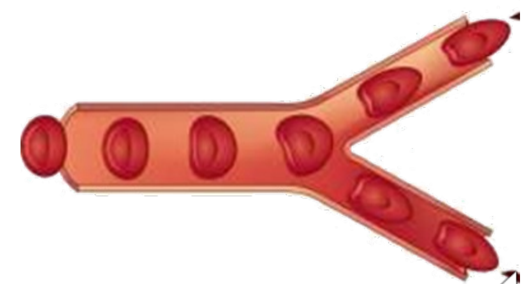
  Small vessels? → Strong non-Newtonian effects (next slides)

Properties of blood

Fåhræus-Lindqvist-effect

In small vessels, RBCs preferrably occupy the middle of the lumen (*axial migration*), whereas close to the vessel wall a cell-free layer emerges with low friction.
This effect is amplified in slow and laminar flow regimes in the **small vessels**.
It leads to a **reduction of the apparent viscosity** the smaller the diameter.
In the **capillaries**, **apparent viscosity strongly increases** again, since RBCs have to flow in single file (plug flow).





Properties of blood

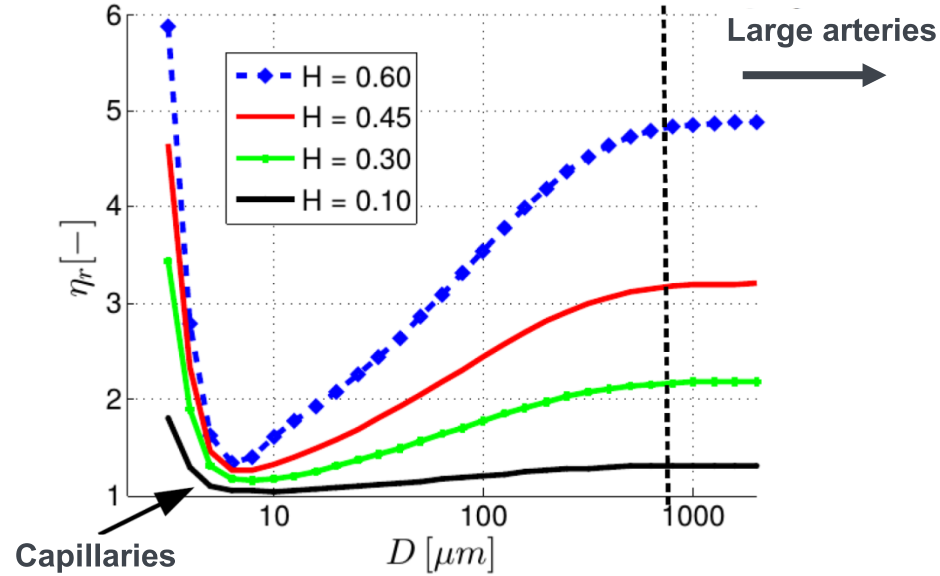
Fåhræus-Lindqvist-effect

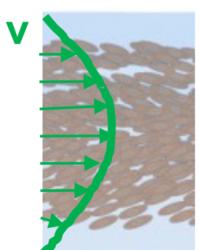
Dependence of "effective" viscosity on vessel diameter and hematocrit

η_r relative viscosity: ratio of effective blood viscosity and dynamic viscosity of blood plasma

H hematocrit

D vessel diameter





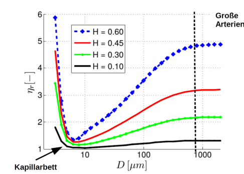
related: **Fåhræus-effect**
Axial migration leads to smaller hematocrit than in feeding large vessel / reservoir. Mean RBC velocity is higher than mean plasma velocity.

(reversible) aggregation:
“Rouleau“-formation may additionally hinder flow in small vessels

Pries, A. R., D. Neuhaus, and P. Gaehtgens. "**Blood viscosity in tube flow: dependence on diameter and hematocrit**." *American Jour. of Phys.-Heart and Circulatory Physiology* 263(6), 1992

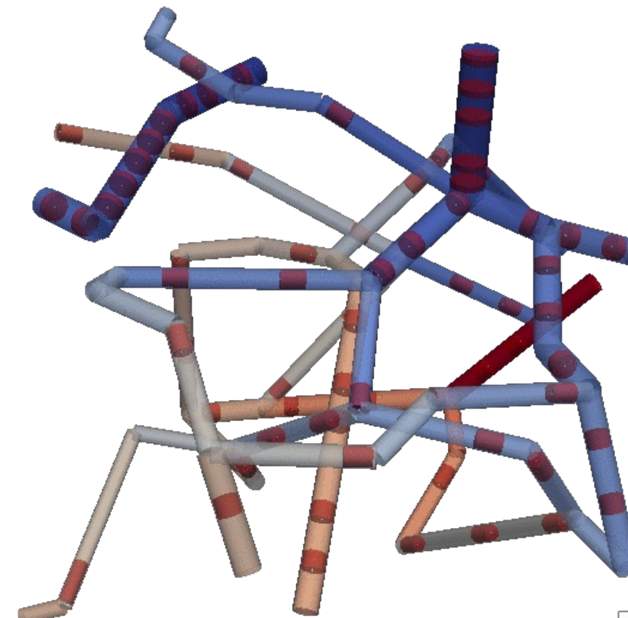
Properties of blood (Summary)

- Blood can be modelled as an incompressible fluid ($\varrho \approx 1050$ kg/m^3)
- In **large** vessels, blood may be modelled as a Newtonian fluid ($\mu \approx$ 3-4 mPa s)



- Simulation in **small vessels**:
  - Blood as a single fluid phase with hematocrit- and diameter-dependent **effective viscosity**
  - Or additionally: Two-phase description with individual cell tracking (variable complexity of the RBC model)

Two-phase simulation (variable hematocrit) taking into account Fåhræus-Lindqvist effect, Fåhræus effect, (and Zweifach-Fung bifurcation rule).



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SimTech
Cluster of Excellence

Thank you!

LH²

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