Developing rheological characterization methods for bovine blood and hydrogel-based artificial blood

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Blood rheology for the design of cardiovascular medical devices and implants

Fig. 1 Erythrocytes (left) are represented by hydrogel beads dispersed in a continuous glycerol phase for optical characterization (middle) combined with rheological characterization (right). The erythrocyte schematic has been taken from [1].

Motivation from a medical and physiological perspective

- The complex rheological behavior of blood is relevant for the design of medical devices or implants such as blood pumps, grafts, and stents[1].
- Blood is a complex multiphasic fluid consisting of blood plasma and blood cells (see also Fig. 1 depicting red blood cell measuring 7.5 µm in diameter, 1.5 µm in inner and 2.5 µm in outer cross section).
- Due to similar cell sizes and volume fraction (hematocrit), bovine blood is often used as substitute for human blood, thus, it is an interesting material for bio-rheological characterization[2].

Motivation for artificial blood design and rheological studies

- Due to its limited stability and its opaqueness, the flow-induced behavior of blood cells is difficult to study[3].
- This is our motivation for the development of a blood substitute fluid with similar rheological behavior as bovine blood with a transparent continuous phase.
- We investigate several approaches for the shear rheological and optical characterization of artificial blood with hydrogel-based particles as model erythrocytes, dispersed in a glycerol-water phase and compare with bovine blood samples.

Artificial blood samples and rheo-optical characterization

Artificial blood

- Erythrocytes were represented by hydrogel beads made from poly-sodiumacrylate-co-acrylamide (pSSAm) obtained with a microfluidic setup.
- The beads were dispersed in a 36 vol.% glycerol solution at a concentration of 40 vol.%.
- A fraction of the hydrogel beads was functionalized with hemoglobin and dispersed in a phosphate-buffered saline solution (PBS) at a concentration of 20 vol.%.

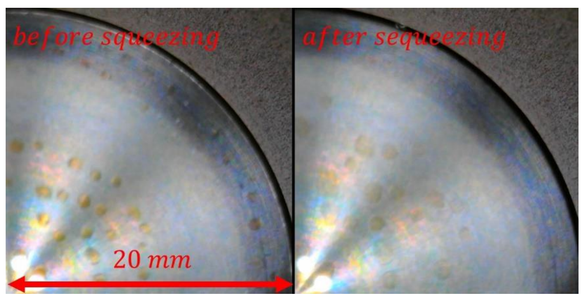

Fig. 2 The deformable nature of artificial blood hydrogel particles functionalized with hemoglobin can bee seen before and after squeezing between the upper and lower plate at a speed of 0.1 mm·s^{-1}.

Bovine blood samples

- Bovine whole blood (hematocrit of 45 vol.%), bovine erythrocyte concentrate (100 vol.%), and bovine platelet rich plasma (PRP) samples were used as references in this study.

Rheo-optical characterization

- A Kinexus Prime ultra+ rotational rheometer (NETZSCH-Gerätebau GmbH, Germany) equipped with a cylinder Peltier-cartridge and a quartz glass plate (cf. Fig. 2) and a USB camera with up to 200 x magnification.
- Shear viscosity measurements at constant shear rates of 1 s^{-1}, 10 s^{-1}, and 100 s^{-1} were performed at 25 °C.

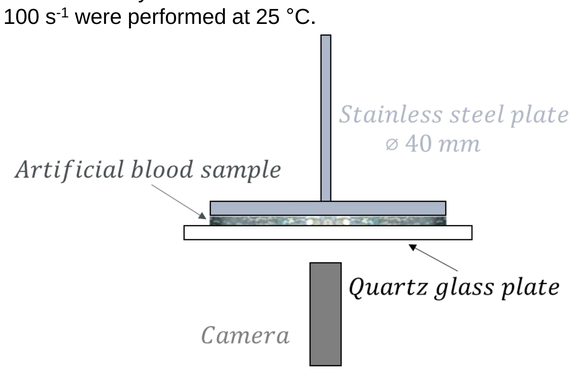

Fig. 2 Rheo-optical setup with a camera and Quartz glass plate

Complementary bovine blood measurements

- Carried out with the same instrument, using an active hood Peltier-cartridge and stainless steel plate-plate geometries.
- Measurements with a concentric cylinder geometry (C14).

Shear rate dependency and hydrogel particle structure

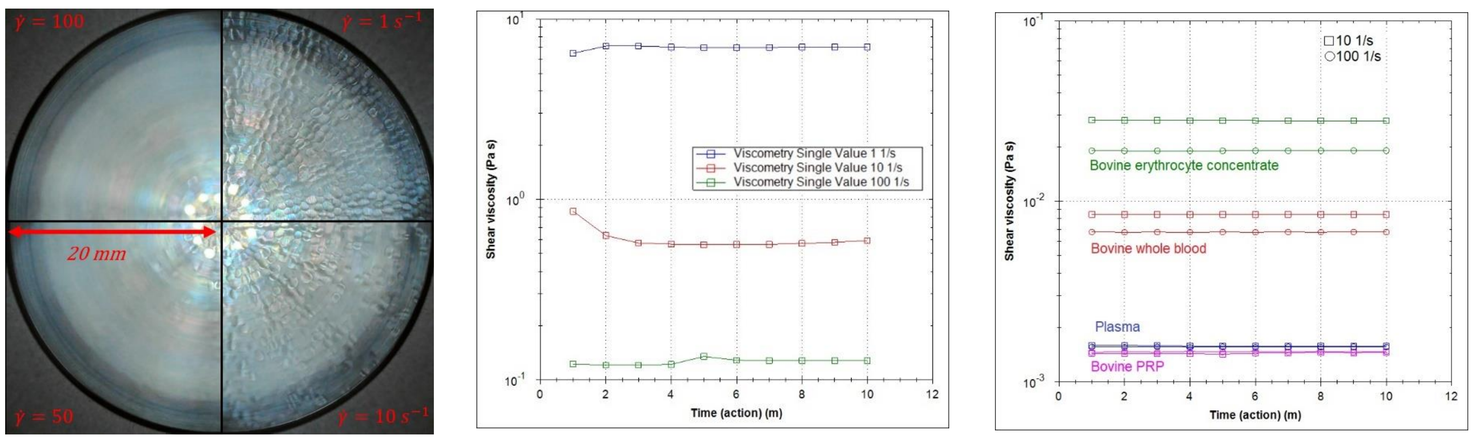

Fig. 4 Artificial blood at different shear rates (left). Time dependent shear viscosity of artificial blood (middle) and bovine blood samples (right) at the respective constant shear rate.

Hydrogel particle orientation and interaction at different shear rates

- Particle-particle contact, which can be expected at the relatively high solid volume fraction of the artificial blood.
- Change in the measured shear viscosity over time could be explained by sedimentation of relatively big particles or by time-dependent structural changes in the sample (cf. Fig. 4).

- Hydrogel particles tend to be oriented from the inside to the outside of the plate-plate geometry. This can be attributed to the squeeze-flow-like flow when lowering the upper plate before the measurement.
- Only a slight movement visible of the particles close to the lower quartz-glass plate which can be seen as an indication of wall adhesion.

→ Low shear rate 1 s^{-1}

- The particles close to the lower quartz-glass plate tend to move.
- More pronounced movement with bigger plate diameters can be explained by the shear rate distribution within the shear gap of a plate-plate geometry or possible edge effect.

→ Medium shear rate 10 s^{-1}

- Particles stick to the lower Quartz glass surface only occasionally.
- This behavior can be explained by hydrodynamic forces induced by the shear velocity gradient over the particle.

→ Increased shear rate 100 s^{-1}

Comparison of different bovine blood samples

- No pronounced changes in shear viscosity were observed (see Fig. 4).
- For the bovine erythrocyte concentrate and the bovine whole blood sample, there was a decrease in shear viscosity at 100 s^{-1} compared to 10 s^{-1}.
- This shear-thinning behavior was not observed for the plasma sample as well as for the bovine platelet rich plasma sample.

Conclusion and outlook

- Shear thinning behavior of the model blood fluid, bovine whole blood and bovine erythrocyte concentrate could been well observed.
- The shear viscosity of the model fluid was higher as compared to those of the bovine blood samples.

- Additional measurements are required to investigate shear viscosity values comparing bovine plasma and platelet rich plasma.
- Lower absolute shear viscosity values of the model blood fluid would be desirable to be closer to the real blood sample.
- The beads should be further reduced in size to get closer to the size of erythrocytes and to reduce sedimentation during rheological measurements.
- The authors will implement optical methods with higher time and spatial resolution.

References

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