# Rheological Characterization of Blood-Mimicking Fluids for Use in Particle Image Velocimetry

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## BACKGROUND

Blood-mimicking fluids (BMF) are often used to model blood flow in physical replicas of vessels with cardiovascular disease. Flow is measured using particle image velocimetry (PIV) in silicone (PDMS) phantoms.

Blood is part elastic and part viscous due to its cellular and aqueous components. Blood decreases in viscosity when agitated (shear-thinning) due to the disaggregation of red blood cells [1].

## OBJECTIVE

Confirm the properties of published blood-mimicking fluids in terms of their ability to match the following:

1. shear-thinning profile of blood;
2. viscous ($\eta'$) and elastic ($\eta''$) components of blood; and
3. refractive index of PDMS.

## METHODS

12 BMFs were made as shown in Table 1.

**Table 1:** BMF formulations. *Low/High refers to the ratio of glycerol to water.

| BMF Name | Water (wt.%) | Gly. (wt.%) | NaI/Urea (wt.%) | Xanthan Gum (wt.%) |
|---|---|---|---|---|
| NaI – Low* [1] | 51.9 | 22.2 | 25.9 NaI | 0.02/0.04/0.06 |
| Urea – Low | 51.9 | 22.2 | 25.9 Urea | 0.02/0.04/0.06 |
| NaI – High* [2] | 44.1 | 34.5 | 21.4 NaI | 0.02/0.04/0.06 |
| Urea – High [2] | 44.1 | 34.5 | 21.4 Urea | 0.02/0.04/0.06 |

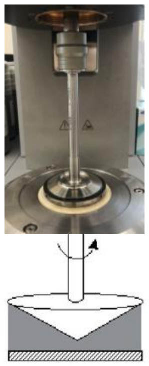


**Fig. 2:** An Anton Paar MCR302 rheometer was used to measure the shear stress (tangential force) required to deform the sample at a certain shear rate (rotational speed). A 1° cone-plate tool was used to apply a uniform shear rate across the sample for a given rotational speed.

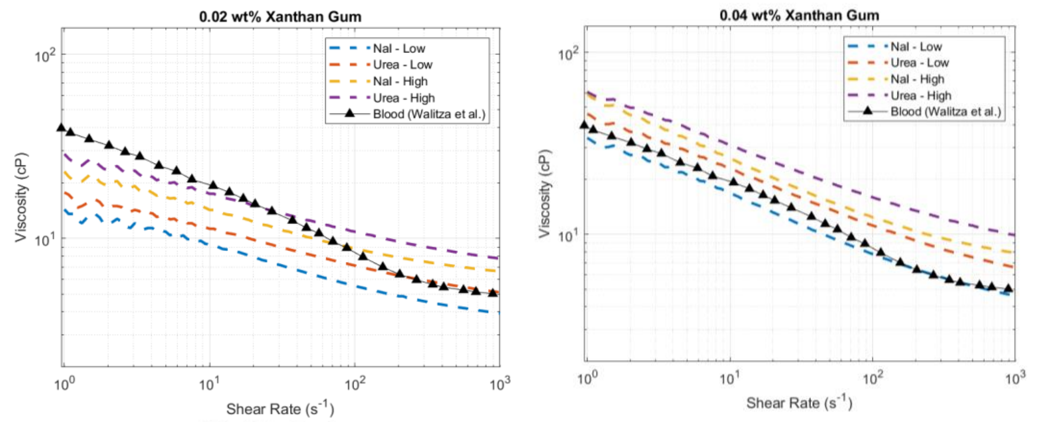
The ratio of shear stress ($\sigma$) over shear rate ($\dot{\gamma}$) gives viscosity.
$\boldsymbol{\eta = \sigma / \dot{\gamma}}$

The loss (G") and storage modulus (G') were measured using 2 Hz oscillations, then converted to the storage viscosity ($\eta''$) and dynamic viscosity ($\eta'$).

$$\eta' = \frac{G''}{\omega}$$

$$\eta'' = \frac{G'}{\omega}$$

## RESULTS



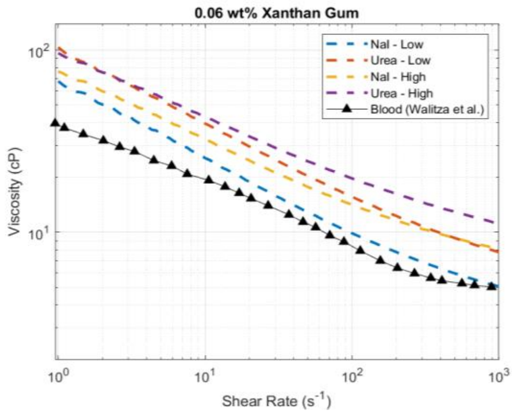




**Fig. 3:** Viscosity curves for BMFs with 0.02, 0.04, and 0.06 wt.% xanthan gum, which causes shear stress and viscosity to be dependent on the rate at which the deformation is applied (*i.e.*, the shear rate). Viscosity was measured as shear rate was increased from 1 to 1000/s, and results are compared with normal human blood (black markers) [3].

Results show that all BMFs decrease in viscosity with increasing shear rate, analogous to blood. The BMF 'NaI–Low–0.04' gave the best match to blood.

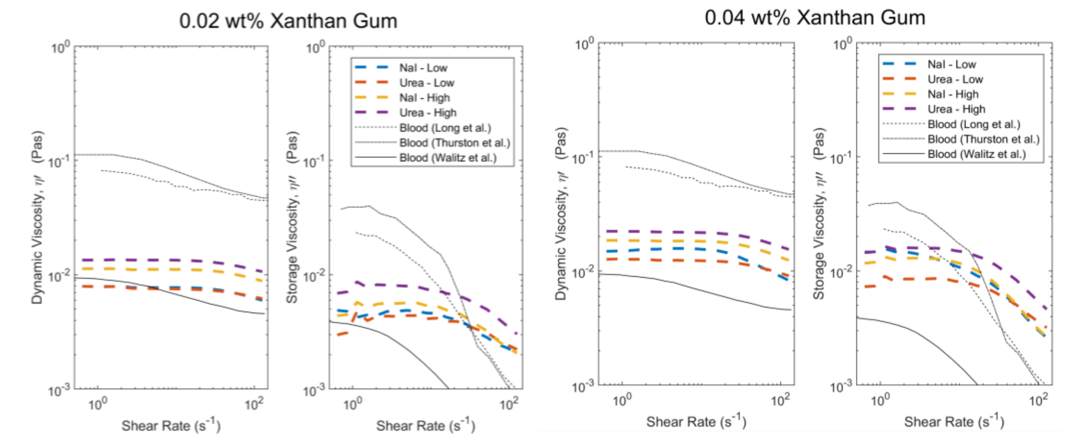
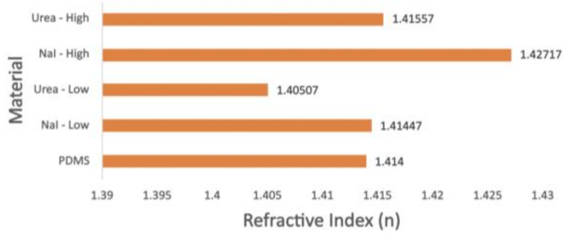



**Fig. 4:** Amplitude sweeps for BMFs with 0.02 and 0.04 wt.% xanthan gum, compared with normal human blood (black lines) from three published sources [3, 4, 5]. Amplitude sweeps are used to determine rheological stability by increasing the amplitude of the shear rate at a constant frequency. Dynamic ($\eta'$) and storage viscosity ($\eta''$), as derived from G" and G', were measured as the shear-rate oscillations increased in amplitude from 0.6 to 126/s.

Results show that 0.04 wt.% xanthan gum – similar to 0.06 wt.% – best match the viscoelasticity of blood.

**Fig. 5:** Bar graph of refractive index for the BMFs compared to PDMS [6] showing that solutions with urea have a lower refractive index than their sodium-iodide counterparts.

Index of BMF 'NaI–Low' is closest to phantom material PDMS [6], which is important for reducing optical distortion.




## CONCLUSIONS

Increasing the concentration of xanthan gum resulted in higher low-shear-rate viscosities and larger values for the storage and dynamic viscosities.

Fluids with 0.04 wt.% xanthan gum best match the shear-thinning viscosity profile of blood (*i.e.*, the rate of change in viscosity with increasing shear rate).

Fluids with 0.04 wt.% xanthan gum best match the viscous and elastic components of blood, and therefore more accurately mimic the deformability and aggregability properties of blood.

Refractive index can be matched using either urea or sodium-iodide formulations with low ratios of glycerol to water, but urea is less expensive and doesn't stain.

Best BMF candidates for use with PIV in PDMS phantoms are 'NaI–Low–0.04' and 'Urea–Low–0.04'.

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