Electronic Supplementary Material (ESI) for Lab on a Chip

Biomimetic postcapillary expansions for enhancing rare blood cell separation on a microfluidic chip

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Supplementary Document

Computational Modeling of Blood Flow

To study blood flow in separation microdevices, we assumed blood as 2D incompressible fluid governed by the Navier-Stokes equation:

$$\rho v \cdot \nabla v = -\nabla p - \nabla \cdot \tau \tag{1}$$

and the continuity equation

$$\nabla \cdot v = 0 \tag{2}$$

Here, ρ is the density of blood assumed to be 1060 kg/m^3. v is the 2D velocity vector, p is the pressure and τ is the shear stress term. It is described as

$$\tau = \mu \dot{\gamma} \tag{3}$$

where μ is the dynamic viscosity and $\dot{\gamma}$ is shear rate. We have used two non-Newtonian constitutive equations to describe the stress-strain relationship.

We compute the streamline distribution in the channel and determine the streamline at flow separation (φ). For optimal purity and yield, we designed the extraction region such that the steamline situated one cell radius (5µm) away from the wall upstream is the critical streamline at flow separation between drain and extraction channels (Figure S1). Just above the extraction, the pressure will be equal along the width of the device. Hence, from mass conservation, it can be shown that

$$v_e R_{extraction} \varphi = v_d R_{drain} (w - 2\varphi) \tag{4}$$

where v_e is the mean velocity of the extraction, v_d is the mean velocity of the drain, R_{drain} is the hydraulic resistance of the drain section of the device and $R_{extraction}$ is the resistance of the extraction section. Hence,

$$\varphi = \frac{w}{2 + \left(\frac{v_e R_{extraction}}{v_d R_{drain}} \right)} \tag{5}$$

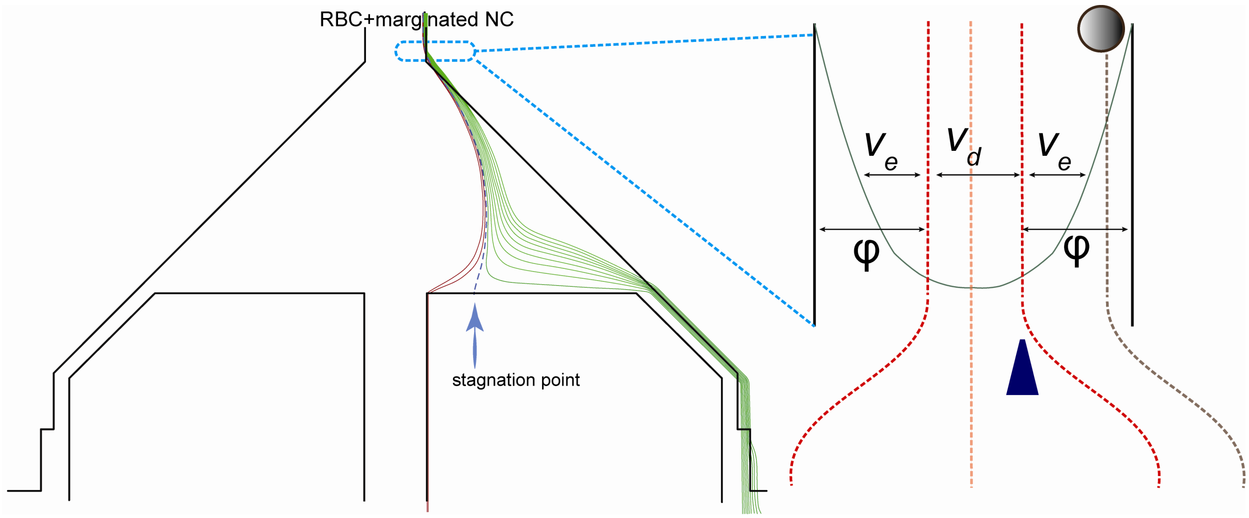

Figure S1 Computational modeling of blood flow in a triangular-margination separation device.

These governing equations are non-linear and therefore, we used a finite element package, COMSOL, to solve the equations. A no-slip boundary condition is assumed along the sidewalls of the device. At the outlets, stress free conditions are applied and the pressure is imposed to be zero. Finally, at the inlet, a parabolic velocity, in the form of $w(x) = v_o\left(1 - \frac{x^2}{a^2}\right)$, where v_o is the centerline velocity and a is the half-width of the channel, is applied.

Non-Newtonian Blood Models

In this work, we have validated two non-Newtonian models along with the Newtonian model for analyzing blood flow. These two models have been shown to be applicable for a wide range of shear rates[1, 2]. In a Newtonian model, the dynamic viscosity (μ) is a constant whereas non-Newtonian models imply shear dependent viscosity. They are described as follows:

Newtonian

$$\mu = \mu_o = 0.0345\ \mathrm{P} \tag{6}$$

Carreau Model[2]

$$\mu = \mu_\infty + (\mu_o - \mu_\infty)\left[1 + (\lambda\dot{\gamma})^2\right]^{\left(\frac{n-1}{2}\right)} \tag{7}$$

where λ=3.313s, n=0.3568, μ_o=0.56P, μ_∞=0.0345P

Generalised Power Law [1]

$$\mu = \lambda|\dot{\gamma}|^{n-1}$$
$$\lambda(\dot{\gamma}) = \mu_\infty + \Delta\mu \exp\left[-\left(1+\frac{\dot{\gamma}}{a}\right)\exp\left(\frac{-b}{|\dot{\gamma}|}\right)\right] \tag{8}$$
$$n(\dot{\gamma}) = n_\infty - \Delta n \exp\left[-\left(1+\frac{\dot{\gamma}}{c}\right)\exp\left(\frac{-d}{|\dot{\gamma}|}\right)\right]$$

where μ_∞=0.035, n_∞=1.0,$\Delta\mu$=0.25,Δn=0.45, a=50,b=3,c=50, d=4

The parameters of these models have been adapted from literature as they have been bound by parameter fitting to experimental data and are accurate for a broad range of shear rates. The shear rate dependence of non-Newtonian viscosity is shown in Figure S1 below

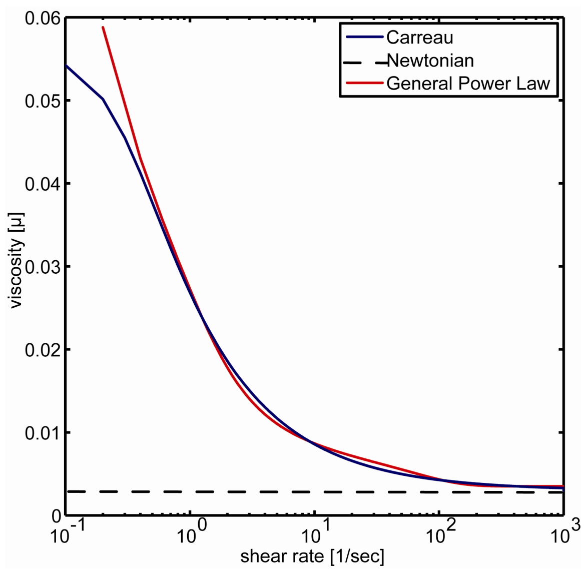

Figure S2 Blood viscosity vs shear rate. It is constant for Newtonian flow but varies with shear rate if non-Newtonian model is assumed

As a result of non-Newtonian behavior, the velocity profile is no longer parabolic and there is a flat region near the centerline as shown in Figure S2. The velocity is normalized by the maximum velocity for the Newtonian case. This is typically observed in blood flow.

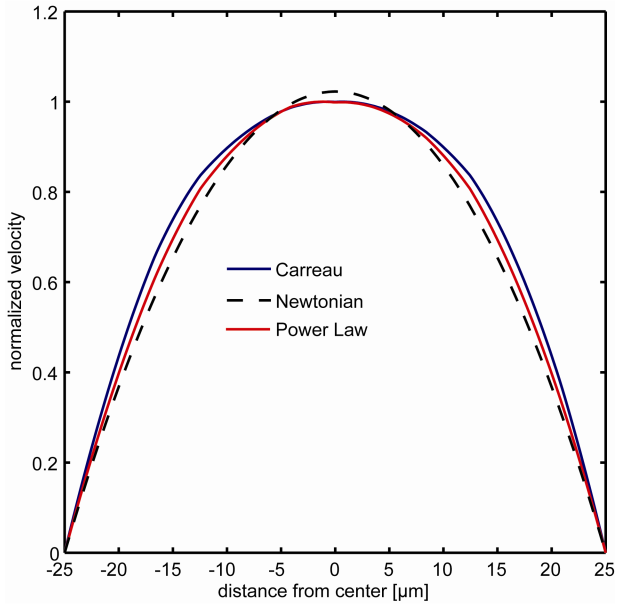

Figure S3 Velocity profile computed in a microfluidic channel for Newtonian and non-Newtonian constitutive equations of shear.

References

1. P. D. Ballyk, D. A. Steinman and C. R. Ethier, *Biorheology*, 1994, **31**, 565-586.
2. Y. I. Cho and K. R. Kensey, *Biorheology*, 1991, **28**, 241-262.