ERYTHROCYTE-ERYTHROCYTE AGGREGATION DYNAMICS AS A BIFURCATION PROBLEM

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ABSTRACT

In this work, the dynamics of doublet Red Blood Cells (RBCs) under shear flow is studied [1]. A close inspection at very low shear rate shows that the pitchfork bifurcation from flat to sigmoid in the absence of flow [2] becomes an imperfect bifurcation in the presence of flow. A remarkable feature found here [A] is that when a single cell performs tumbling the doublet formed due to adhesion (even very weak) remains stable even under a very strong shear rate.

MODEL & METHODS

We consider a set of phospholipid vesicles inside a straight channel, bounded by two rigid walls and they are subject to a linear shear flow.

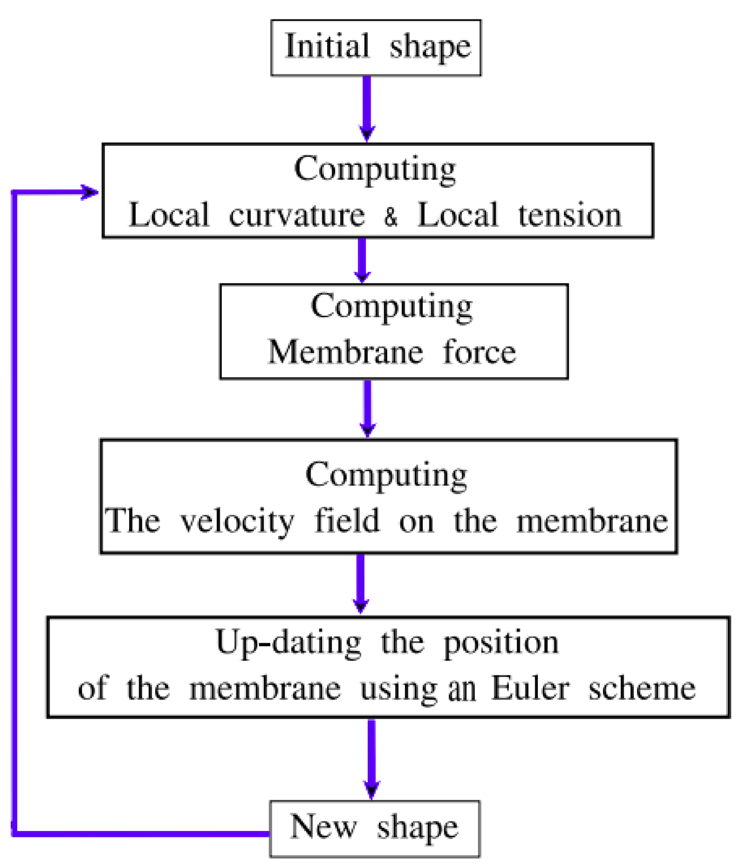

Figure 4: Flowchart showing the main steps carried out to get the vesicle dynamics, the membrane velocity is calculated using the boundary integral method [1].

The membrane energy is the sum of three terms: the **bending energy (Helfrich energy), the membrane incompressiblity** contribution and **the adhesion energy (Lennard-Jones potential)** between two vesicles.

- C_n The confinement.
- λ The ratio between the viscosities of the inner and the outer fluids.
- C_a The flow strength over the membrane bending energy.
- $\bar{\epsilon}_{adh}$ The adhesion strength.

PHASE DIAGRAM OF DOUBLET

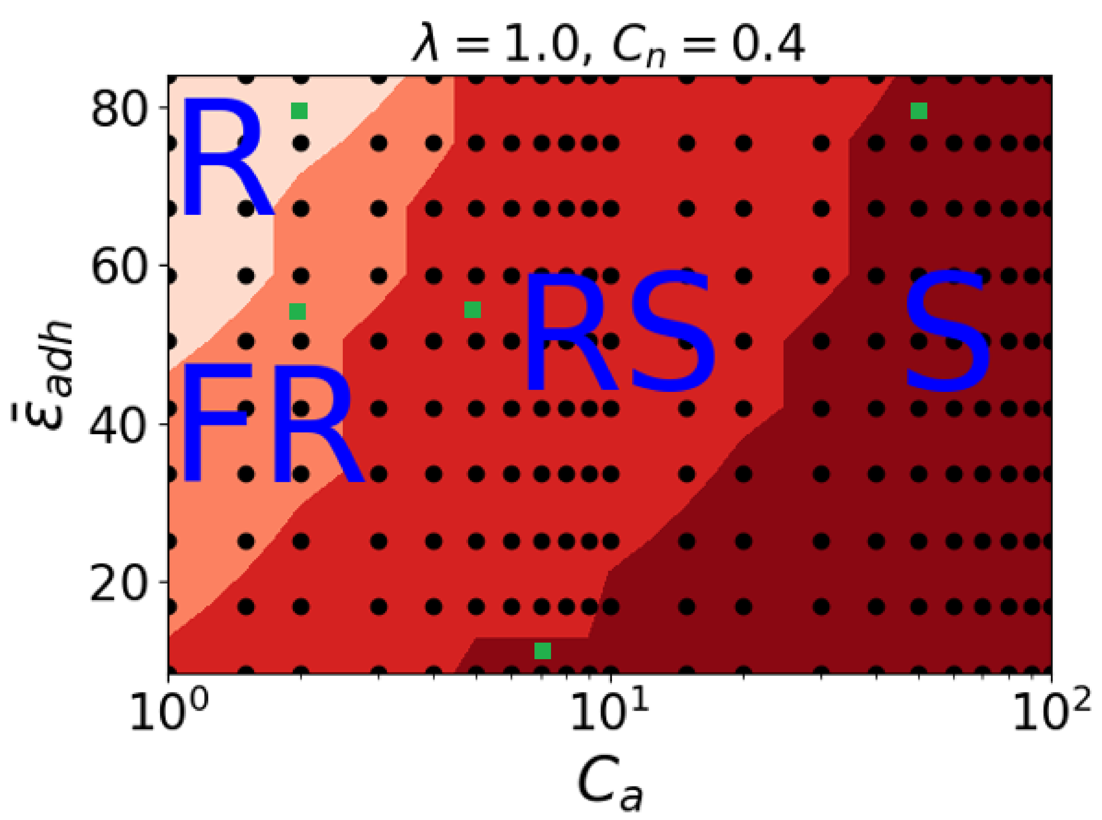

Figure 5: Phase diagrams of doublet dynamics. The square symbol represents 3D simulations

- R : Rolling
- FR : Flexible rolling
- RS : Rolling sliding
- S : Separation

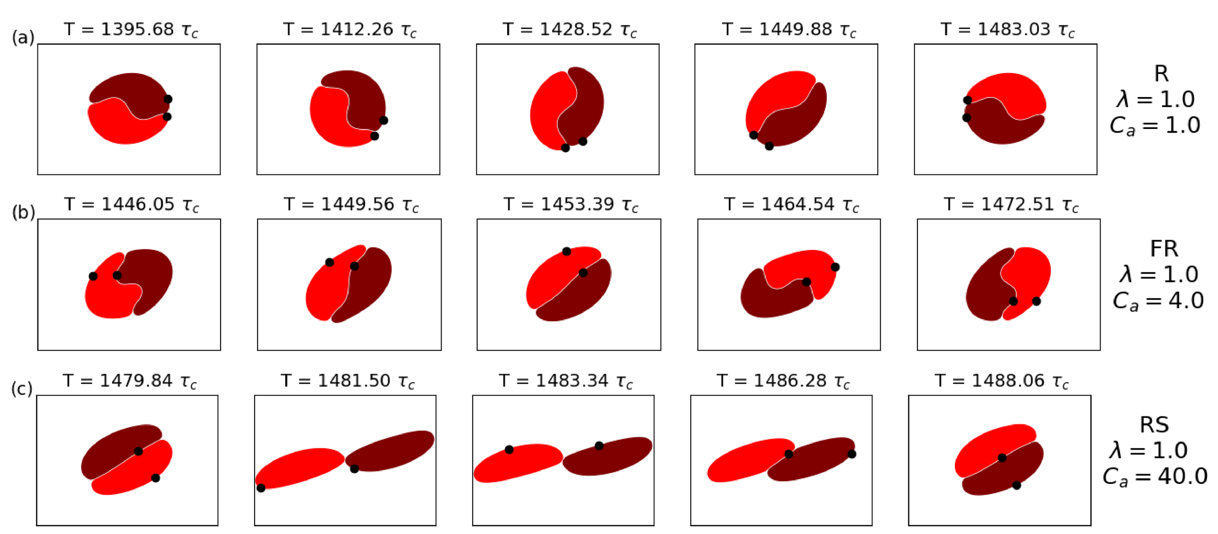

Figure 6: Snapshots showing the doublet dynamics. Here $\bar{\epsilon}_{adh} = 84.00$ and $C_n = 0.4$.

THEORETICAL FOUNDATION TO THE PHASE DIAGRAM

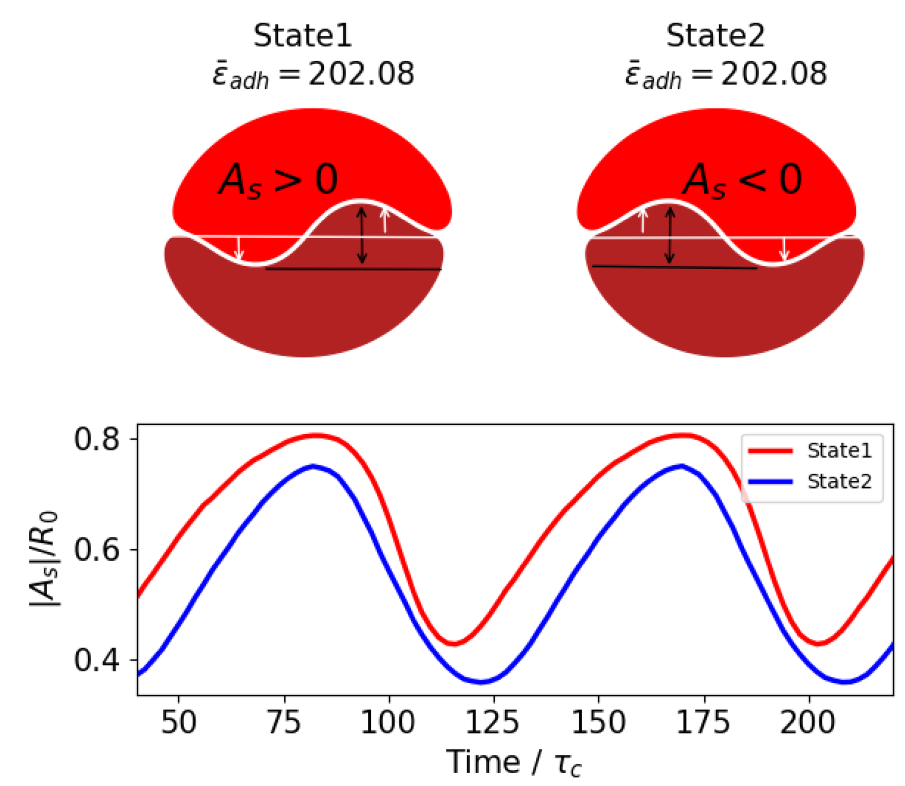

Figure 1: (a) The two states 1 and 2 . (b) The time evolution of the amplitudes A_s of the interface between the two cells for a given situation corresponding to the two branches in Fig.2 in the regime of R phase.

The total energy associated with interface deformation takes thus (apart from numerical prefactors) the form:

$$E = CaA_s + a(\beta_c - \beta)A_s^2 + bA_s^4 \quad (1)$$

We have seen in [2] that at equilibrium (absence of flow) at small adhesion the cell-cell interface is flat while at large enough adhesion energy the interface is deformed. The passage from the flat to the deformed configuration is a supercritical bifurcation. The shape of the cell-cell interface is characterized by the value of the amplitude of deformation of the contact zone between cells A_s (when the contact interface is flat $A_s = 0$, and when the interface has a sigmoid form $A_s \neq 0$)

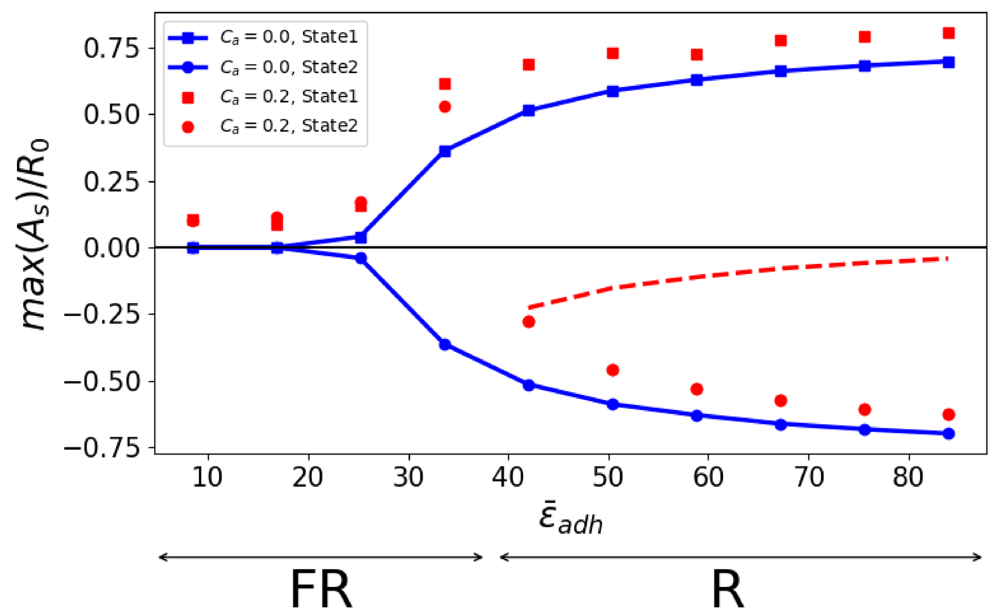

Figure 2: Bifurcation diagram in the absence of flow (blue) and in the presence of flow (red) showing maximum deformation amplitude of the contact line. Dashed line is the unstable branch (drawn by hand since the unstable branch can not be captured by dynamics).

SUPRESSION OF DOUBLET SEPARATION

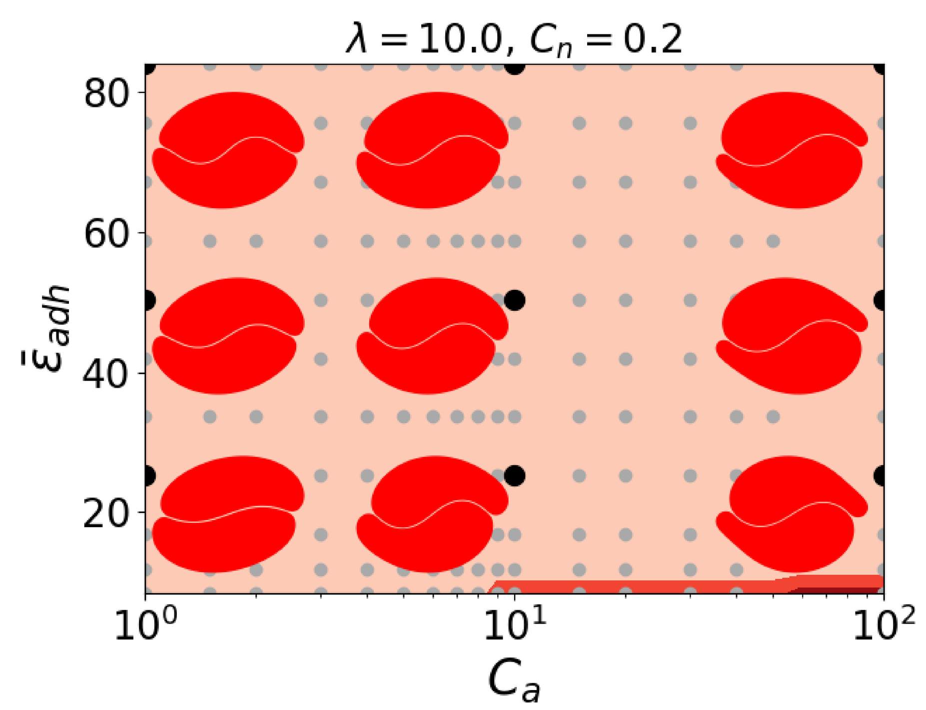

Figure 3: Phase diagram of the doublet dynamics. We clearly see shape adaptation as C_a increases.

In human vascular networks we expect membrane tank-treading to take place in arterioles only. In some RBCs diseases, such as thalassemia, sickle-cell disease and malaria, the membrane shear modulus as well as cytoplasm viscosity may be significantly higher than healthy ones. We can speculate that in this case RBC doublets and larger aggregates become irreversible, a fact which should affect blood perfusion in microcirculation.

REFERENCES

[1] *Mehdi Abbasi, et al. Erythrocyte-erythrocyte aggregation dynamics under shear flow. Physical Review Fluids 6.2:023602, 2021.*
[2] *Daniel Flormann et al. The buckling instability of aggregating red blood cells. Scientific reports, 7(1):7928, 2017.*

ONGOING WORK

A systematic numerical study in 3D including cytoskeleton is necessary is ongoing for drawing more practical conclusions. Our preliminary simulations in 3D presented in [1] support phases like R, FR, RS and S in the same range of flow strengths explored in 2D.

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