AN EFFICIENT COMPUTATIONAL MODEL FOR STRAIN-BASED HEMOLYSIS PREDICTION IN EULERIAN FRAME

Nico Dirkes, Marek Behr

Chair for Computational Analysis for Technical Systems, RWTH Aachen University, Schinkelstr. 2, 52062 Aachen, Germany

Introduction

Flow-induced red blood cell damage (hemolysis) is a key factor in the design process of blood-handling medical devices, such as ventricular assist devices. The numerical prediction of this phenomenon is based on computational fluid dynamics (CFD) simulations. The most basic hemolysis models post-process the CFD results by directly applying empirical correlations to fluid stress (stress-based models). More recent models use the CFD results to explicitly resolve cell deformation (strain-based models). A disadvantage is that these models are typically written in a Lagrangian formulation, i.e., they require particle tracing. This can lead to gaps in coverage and a selection bias. In addition, they are generally expensive to evaluate if they explicitly resolve membrane structure and deformation. They are thus not well-suited for the design of real-world mechanical circulatory support systems.

Methods

We present the new tank-treading morphology model (TTM), a more practical strain-based hemolysis model. It takes into account the characteristic membrane deformation time of red blood cells and allows for an Eulerian formulation. The equations are derived in detail in [1]. As a result, we obtain a field for the effective shear rate $G_{eff}(x,t)$. This effective shear rate is a measure for the instantaneous membrane strain of red blood cells. It can be evaluated at every point x inside the domain and for every time t. This enables designers of medical devices to evaluate precisely where the most hemolysis occurs.

The Eulerian formulation is implemented as part of our in-house multiphysics finite element code [1]. We additionally provide an open-source Python code HemTracer [2] to apply our model in Lagrangian frame and compare it to other common hemolysis models.

Results

We apply our model to a selection of test cases, among them a simple three-dimensional blood pump. We compare the Eulerian formulation to the Lagrangian formulation in Figure 1. The Lagrangian solution exhibits gaps in coverage. In particular, the region around the inner tips of the impeller blades is not penetrated by any of the selected red blood cells.

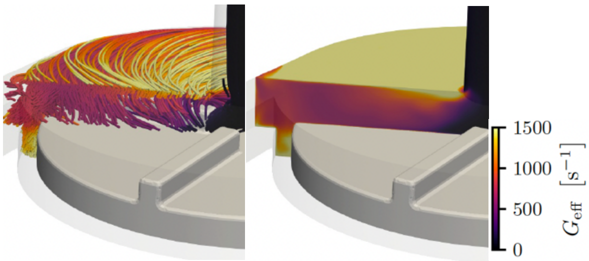

Figure 1: Effective shear rate as predicted by the Lagrangian (left) and Eulerian (right) formulation in a simple blood pump

Simulation	Time
CFD	20 h
Full-order Eulerian morphology	4000 h
Tank-treading Eulerian morphology	8 min

Table 1: Execution times of simulations on 192 cores

As Table 1 shows, our new model, the TTM, is two orders of magnitude faster than the CFD simulation and four orders of magnitude faster than a comparable Eulerian strain-based hemolysis model.

Discussion

In contrast to Eulerian stress-based models, the TTM is able to capture the viscoelastic behavior of the cell membrane by resolving cell deformation time. Compared to Lagrangian strain-based models, the TTM is computationally more efficient and does not require tracking individual cells, enabling a more effective analysis of localized hemolysis. These qualities will make it a valuable tool for the design process of future generations of medical devices.

References

1. Dirkes et al., Comput. Methods Appl. Mech. Engrg. 426:116979, 2024
2. https://github.com/nicodirkes/HemTracer

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