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▶ **To cite this version:**

Wang Wen, Dominique Barthès-Biesel, Zhen Wang, Yi Sui, Wen Wang, et al.. Path Selection of a Spherical Capsule in a Branched Channel.. ICBME 2019 - International Congress on Biomechanics and Medical Engineering, Sep 2019, San Diego, United States. pp.42-43, 10.32604/mcb.2019.2019.xxxxx . hal-02504224

HAL Id: hal-02504224
https://hal.utc.fr/hal-02504224

Submitted on 30 Jul 2021

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Path Selection of a Spherical Capsule in a Branched Channel

Zhen Wang[1], Yi Sui[1], Wen Wang[1]

Dominique Barthès-Biesel[2], Anne-Virginie Salsac[2, *]

[1]School of Engineering and Materials Science, Queen Mary University of London, London E1 4NS, UK.

[2]Biomechanics and Bioengineering (UMR 7338), Université de Technologie de Compiègne – CNRS, Alliance Sorbonne Universités, 60203 Compiègne, France.

[*]Corresponding Author: Anne-Virginie Salsac. Email: a.salsac@utc.fr

Abstract:

Capsules are liquid droplets enclosed by a thin membrane which can resist shear deformation. They are widely found in nature (e.g. red blood cells) and in numerous applications (e.g. food, cosmetic, biomedical and pharmaceutical industries [1]), where they often flow through a complicated network of tubes or channels: this is the case for RBCs in the human circulation or for artificial capsules flowing through microfluidic devices. Central to these flows is the dynamic motion of capsules at bifurcations, in particular the question of path selection. A good understanding of this problem is indeed needed to elucidate some intriguing phenomena in human circulation and to design multi-branched microfluidic devices to sort or enrich suspensions of artificial microcapsules or biological cells depending on their properties.

Thanks to the extensive *in vivo* and *in vitro* experiments conducted on blood flows in branched capillaries or microchannels [2], it has been well established that the daughter branch with a higher flow rate receives a larger number of RBCs than the other branch: this is classically referred to as the Zweifach–Fung effect [3,4]. Similar phenomena have also been observed in experiments on suspensions, where the RBCs are modelled as flexible disks and the white blood cells as solid spheres [5], and in dilute suspensions of solid spheres [6]. This is a consequence of the plasma skimming effect due to the particle-free layer near the wall of the vessel [7] and of the particle screening effect due to the deviation of the particle trajectories from the background flow fluid streamlines as a result of the hydrodynamic interaction between the particles and vessel geometry at the bifurcation [8, 6].

In the dilute limit, the problem has, however, not been thoroughly studied experimentally, possibly due to the difficulty of manipulating individual cells. The problem has mostly been studied in recent years using two-dimensional numerical models [9, 10]. The results showed that, at equal flow rate between the two downstream channels, the capsule tends to flow into the side branch in particular when the capsule is highly deformable. But to what extent the results obtained from previous two-dimensional simulations can be applied to three-dimensional flows remains unclear.

The objective of the present study is to conduct a systematic and in-depth three-dimensional numerical study of a deformable capsule in a branched tube and to determine the influence of inertia. Contrary to many biological systems, for which neglecting inertia is a good assumption, capsules are not necessarily small in size and the flow speed can be fast in some applications [11].

In the present work, we computationally study the motion of an initially spherical capsule flowing through a straight channel with an orthogonal lateral branch, using a three-dimensional immersed-boundary lattice Boltzmann method [12, 13]. Our primary focus is to study the influence of the geometry of the side branch on the capsule path selection. The capsule is enclosed by a strain-hardening membrane and contains an internal fluid of the same viscosity as the fluid in which it is suspended. It is initially centered on the axis of the feed channel. We impose the flow rate split ratio between the two downstream

DOI: 10.32604/mcb.2019.2019.xxxxx www.techscience.com/mcb

branches of the bifurcation. We analyze the reference cases wherein the side channel has the same cross-section as the main branch, and then compare the results to other geometries, in which the side branch has a half cross-sectional area as compared to the main branch. We consider different capsule-to-channel size ratio, flow Reynolds number (Re) and ratio of capillary to Reynolds numbers, and summarize the results in phase diagrams indicating the critical flow split ratio above which the capsule flows into the side branch.

The capsule trajectory does not always obey the classical Fung's bifurcation law. For Re $\leqslant$ 5 and equal flow rate split between the two downstream branches, the capsule will enter a branch which is narrow in the spanwise direction, but will not enter a branch which is narrow in the flow direction. We show that this novel phenomenon results primarily from the background flow which is strongly influenced by the side branch geometry. For higher values of Re, the capsule relative size and deformability also play a specific role in the path selection: increasing the capillary number generally promotes cross-stream migration of the capsule towards the side branch. The present results obtained for dilute systems open new perspectives on the design of microfluidic systems with optimal channel geometries and flow conditions to enrich cell and particle suspensions.

Keywords: microcapsule, bifurcated microchannel, fluid-structure interactions, lattice-Boltzmann, finite elements

Acknowledgement:

The authors thank the SEMS/QMUL (start-up grant), the Royal Society (International Exchange Research Grant IE140496), the high-performance computer clusters of QMUL and the ERC (772191, MultiphysMicroCaps project, ERC-2017-COG) for funding.

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