Efficient mixing of protoplasm in tubular vein networks of the slime mould *Physarum polycephalum*

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ABSTRACT

The unicellular slime mould *Physarum polycephalum* forms an extended vascular network used for transportation of protoplasm through the cell. Although the flow in the veins is always laminar, protoplasmic particles are effectively distributed within the cell. To elucidate how effective mixing is achieved in such a microfluidic system, we performed micro-PIV experiments and advect virtual tracers in the flow fields. This work was presented at PhysNet 2015.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Distributed Networks; J.2 [**Physical Sciences and Engineering**]: Physics

Keywords

Physarum polycephalum, transportation network, laminar mixing, synoptic Lagrangian maps

1. INTRODUCTION

The plasmodium of the unicellular, but multi-nucleate slime mould *Physarum polycephalum* may reach extensions up to square metres. Large plasmodia form extended networks of connected tubular veins, in which protoplasm is periodically transported back and forth. The vein network of *P. polycephalum* forms regular graphs [1, 2] that are optimized to provide an efficient transport of protoplasm [1, 2, 3, 4, 5]. With respect to flow efficiency, the architecture of these networks is hierarchic and self-similar [4].

The driving force for the almost periodic (shuttle) streaming of protoplasm through the veins is the peristaltic contraction and dilation of the veins. The generated pressure gradients provide for the transportation of nurtients, oxygen, and signalling factors throughout the giant cell. The flow profiles in the veins of *P. polycephalum* are always parabolic, indicating laminar flow [6]. However, such extended cells also require that the protoplasm is efficiently spread and mixed and, in fact, it is known that protoplasmic particles are effectively and rapidly distributed within the cell. Here we elucidate how an effective mixing can be achieved in such a microfluidic system with Poiseuille flow.

2. METHODS

Time-dependent flow fields at a junction of 3 vein segments were extracted by micro particle imaging velocimerty (μPIV) [7]. We have started arrays of virtual tracers and advect them in the time-dependent flow-fields obtained from μPIV measurements. We follow the flow of an initially dense array of 50×50 virtual tracers at a junction of veins. Furthermore, we study into which of the three vein segments leaving a junction the virtual tracers are advected over a series of contraction-dilation cycles. To this purpose we start virtual tracers at a given line and construct synoptic Lagrangian maps (SLM) [8]. SLMs are geographic maps where each virtual particle is colour-coded according to the vein segment through which it leaves the region of interest (ROI).

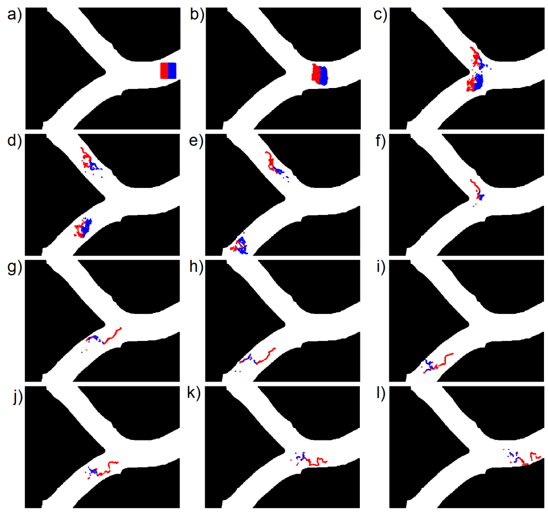

Figure 1: Snapshots of a propagating array of 50×50 virtual tracers. The left half of tracers are labelled in red, the right half in blue. Snapshots are taken at 0.7 s intervals.

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3. RESULTS

Neither the shuttle streaming [9] nor the contraction of the individual veins that encounter at a junction [10] is perfectly periodic. Consequently, the flow does not reverse simultaneously in all of the 3 veins joining at a junction. Fig. 1 shows a dense array of virtual particles that were started at the right vein segment and propagate to the left. At the junction, the particles divided among the two left branches. The flow pattern in Fig. 1 shows that the differences in the flow through the individual veins may lead to a stretching, splitting, and a reshuffling of volume elements. This can be seen in the bottom left branch, where the first portion of tracers arrives substantially earlier than the second package.

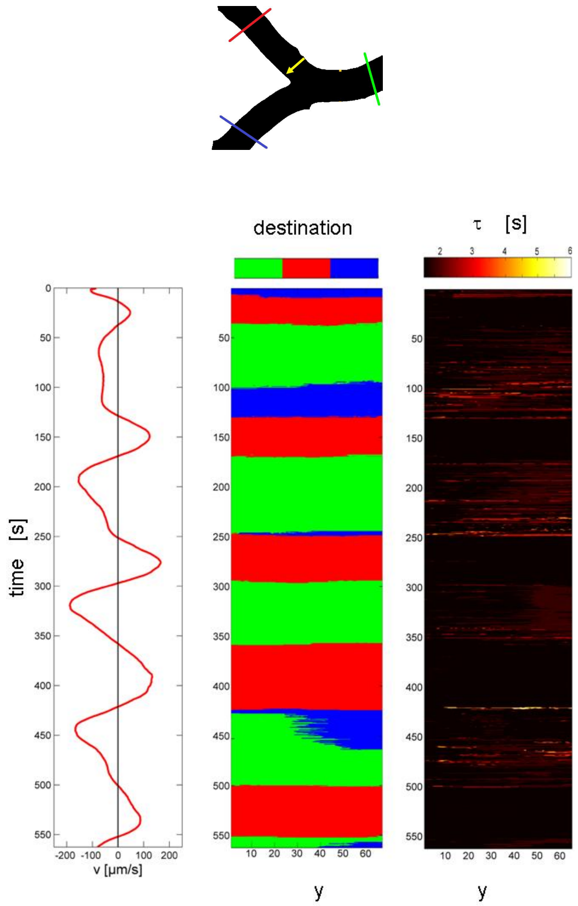

Figure 2: (top) Coordinates for the synoptic Lagrangian map (SLM). The green, red, and blue lines denote the limits of the ROI. 70 virtual tracers are started along the yellow arrow. (left) Mean flow velocity in the "red" vein segment; (centre) SLM and (right) map of the residence times τ of the particles at the junction. Every 50 ms, 70 virtual tracers along the starting line are initiated. In the SLM the colour codes through which of the three vein segments a particle leaves the ROI.

The fate of virtual particles were investigated over several periods of the shuttle streaming. They were started along a line y in one of the branches of a junction at every time step Δt. The particles were tracked and their fate recorded in a SLM (Fig. 2). As the flow in the red branch reverses, the flow pattern, however, through which of the two bottom branches a particle leaves the ROI varies from period to period of the shuttle streaming. There is no fixed temporal sequence through which of the branches the particles leave the ROI. Furthermore, episodes where the protoplasm is transported out of the ROI through 2 different veins are also observed (Fig. 2). The map of residence time distribution shows that particles remain considerably longer in the ROI, when they are subject to changes in the direction of flow. Furthermore, the residence times are not uniform along the coordinate y, demonstrating that the position of the particle in a vein may also influence its fate.

4. CONCLUSIONS

Small fluctuations in the pressure at the vein segments joining at a junction lead to a distribution of flows through the veins that does not follow any regular pattern. Flow reversals in all three segments are not synchronous, thus, providing for a mechanism of stretching an folding of volume elements of the protoplasm. This leads to an efficient mixing of protoplasm at a junction.

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