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To cite this version:

Sylvain Chateau, Jean Mercat, Zhe Li, Sébastien Poncet, Julien Favier, et al.. Emergence of metachronal waves in cilia arrays: a hydrodynamic mechanism. 24th International Congress of Theoretical and Applied Mechanics (ICTAM 2016), Aug 2016, Montreal, Canada. hal-01705684

HAL Id: hal-01705684

https://hal.science/hal-01705684v1

Submitted on 4 Mar 2019

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EMERGENCE OF METACHRONAL WAVES IN CILIA ARRAYS: A HYDRODYNAMIC MECHANISM

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Summary The present work reports the emergence of metachronal waves in cilia arrays immersed in a two-fluid environment using a coupled lattice Boltzmann - Immersed Boundary method. The periciliary layer (PCL) is confined between the wall and the mucus layer. Its depth is chosen in such a way that the tips of the cilia can penetrate the mucus layer. The cilia are initially set in a random state but quickly synchronize with their immediate neighbors with a phase shift giving birth to sympleptic or antipleptic metachronal waves, depending on the strength of the fluid retroaction onto the cilia. Antiplectic waves are found to be the most efficient to transport mucus compared to other random or synchronised cilia motions.

INTRODUCTION

Fluid propulsion by moving cilia is an universal phenomenon that can be found everywhere in Nature from the locomotion of micro-organisms to multiple processes in biological organisms at the cellular scale. For examples, in the early human embryonic development, cilia are responsible for the heart placement on the left side of the chest. Cilia move also the ovules in the Fallopian tubes, or the nutriments in the brain. In the specific problem of mucociliary clearance, cilia are responsible for transporting the mucus outside the lungs. In severe respiratory diseases, such as cystic fibrosis or asthma, the number of cilia clusters is decreased compared to the case of a healthy patient, and many cilia may beat in an abnormal way resulting in a less efficient transport of mucus. It has been experimentally observed [1] that cilia beat in a synchronised way with a phase shift between two neighboring cilia, forming a metachronal wave which appears to greatly enhance the transport of mucus. Then, it is of great importance to understand how this wave emerges and which type of waves provides the most efficient transport. This work could result in a better understanding of the mucociliary clearance process.

NUMERICAL METHOD

The fluid part is solved on a Cartesian grid using the lattice Boltzmann method with a D3Q19 scheme. The model of Porter et al. [2] is used to model the fluid-fluid repulsion forces. The cilia are modeled with a set of 20 Lagrangian points, and the immersed boundary method is used to ensure the no-slip condition along the cilia [5]. The equations of motion for the cilia are taken from Chatelin [3] and the motion of each cilium is decomposed into a finite number of steps during a period. If needed, an interpolation between two steps can be done in order to have the right velocity values along the cilia. The code is suitable for High Performance Calculation using a MPI parallelization. Cilia are set in arrays in a two-fluid layer, with PCL at the bottom and mucus above it. The PCL depth is set in such a way that the tips of the cilia emerge into the mucus layer. Periodic boundary conditions are used in the X and Y directions. A Bounce-Back Rule condition is imposed at the bottom of the domain and a free-slip velocity condition at the top using the "mirror method". The fluid retroaction onto the cilia is evaluated by projecting the immersed boundary forces calculated at each time step for every Lagrangian points onto the corresponding velocity vectors, and then the torques are computed. By doing so, only the norm of the velocity vector, but not its direction, is modified. A new parameter α controls then the intensity of the retroaction: $||\vec{V}|| = ||\vec{V}|| \pm \alpha ||d\vec{V}||$

RESULTS

Starting from an initially random state, cilia quickly synchronize with their immediate neighbors with a phase shift. With time, metachronal waves -antipleptic or sympleptic- emerge. The sign of the parameter α, and the ratio h/L_{cil} of the PCL depth with regards to the cilia length are two key parameters that determine the kind of emerging waves. Positive (resp. negative) α-values correspond to sympleptic (resp. antipleptic) waves. A proper value of h_{PCL}/L_{cil} is needed for the metachronal waves to emerge. As it can be seen on figures 1(a) and 1(b), cilia move along a plane and so can be subjected to collisions. But, since a 3D configuration is considered, one can suppose that cilia would actually slip onto each other in reality. Figure 2 shows the mean mucus velocity evolving with time. It can be seen that, for the same set of parameters, antipleptic metachronal coordination appears to greatly enhance the transport of mucus compared to random or other synchronized

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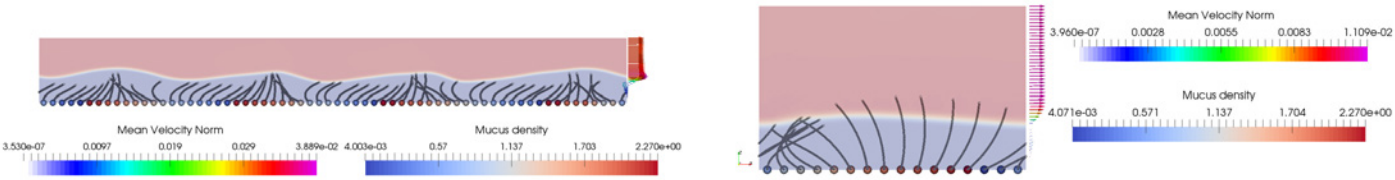

(a) (b)

Figure 1: (a) Sympleptic metachronal wave emerging from an array of 64 cilia disposed along the X direction, with $\alpha = 3$. Spacing between two cilia is 7 lattice units, and $h_{PCL}/L_{cil} = 0.9$. Size of the domain in X, Y, Z is 449, 8, 50. (b) Antipleptic metachronal wave emerging from an array of 16 cilia disposed along the X direction, with $\alpha = -3.5$. Spacing between two cilia is 5 lattice units, and $h_{PCL}/L_{cil} = 0.6$. Size of the domain in X, Y, Z is 81, 6, 50. In both cases (a) and (b), $L_{cil} = 22$ lattice units and the viscosity ratio is set to 15.

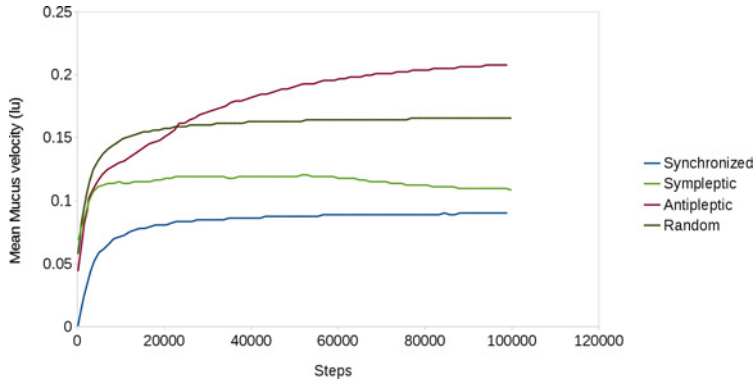

Figure 2: Mean mucus velocity for different kind of coordinations.

collective motions. As for sympleptic metachronal coordination, the mean mucus transport is weaker that in the case of cilia beating randomly. We explain this by the fact that this kind of synchronization induces large recirculations in the mucus phase. Moreover, the cilia tips are always in the PCL phase and never emerge into the mucus. Confirming the simulations of Ding et al. [4] using the regularized Stokeslet method, antiplectic waves are the most efficient for mucus transport.

CONCLUSIONS

An efficient and validated 3D lattice Boltzmann solver coupled to the immersed boundary method has been applied for the first time to investigate the emergence of metachronal waves and their superiority to transport mucus in a two-phase flow environment. A simple and efficient method has been applied successfully to take into account the fluid retroaction onto the cilia. Metachronal waves emerge quickly before the flow reaches a steady state. The efficiency of the metachronal waves for the mucus transport has been calculated, and antipleptic waves are found to be the most efficient ones compared to other random or synchronised motions.

The authors acknowledge the support of the Physio-Assist company. The PhD of Sylvain Chateau is funded through the NSERC discovery grant program.

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