PhD Position in High-fidelity Multiphase Flow Simulation of Surfactant Delivery in Human Airway Models

Context

Surfactant replacement therapy (SRT) consists of instilling a liquid surfactant mixture into the trachea of premature newborns, whose lungs are stiff and difficult to inflate due high alveolar surface tension. Despite indisputable efficacy, the administration mode (dose volume, flow rate, patient posture, number of doses) and surfactant properties (viscosity, density, surface tension, all concentration-dependent) are decisive parameters in this regard, that have been largely directed by trial and error, and are frequently adjusted at clinician discretion. As a result, the debate over which surfactant to use, when, and how to deliver it, is ongoing.

Developing new numerical modalities to predict, engineer, and optimize patient-specific surfactant delivery in complex situations via accurate adjustment of instillation and surfactant functional parameters is thus of tremendous medical and societal interest. This will help improve personalized treatment decision-making and its outcomes, while expanding applicability to other disorders and age groups, for instance to acute respiratory distress syndrome (ARDS) in adult patients, for which SRT has been so far largely unsuccessful in controlled clinical trials - a perspective now being questioned by recent numerical findings that adults should be treated to larger doses of surfactant, to cope with the greatly increased airway surface area for coating loss compared with neonates.

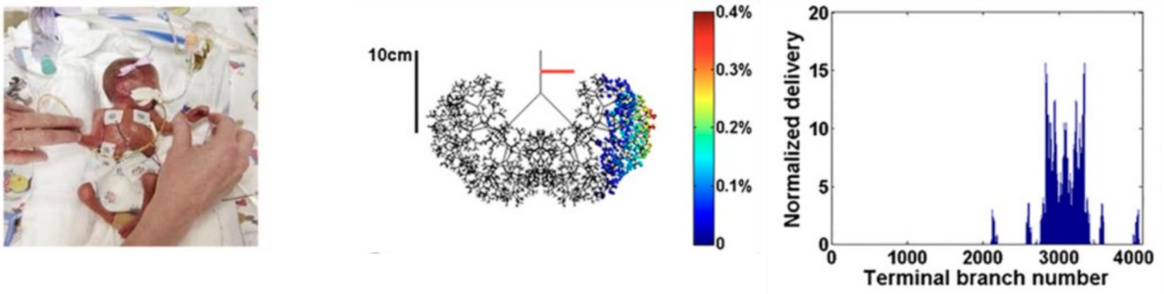

Fig. 1: Left: SRT in premature neonates. Right: Homogeneity and efficiency, as computed using a 0D model of SRT delivery in an adult airway tree with 12 generations plus a trachea (adapted from [Filoche et al. 2015]).

Objective

This work is conducted as part of INHALE, a selected ANR-funded project to launch in September 2024, that seeks to leverage advanced modeling approaches combining computational fluid dynamics (CFD) and artificial intelligence (AI) to develop data-informed decision-making tools for ARDS management. As the first milestone in this process, this PhD aims to establish the general CFD framework for high-fidelity simulations of surfactant-laden liquid plug propagation in realistic conducting airway trees. Robust, flexible, and resource-efficient methods will be pursued to easily accommodate a large diversity of airways size and structure and surfactant physical properties. The PhD is structured around the following main tasks:

- extend the existing CFD multiphase framework to Navier-Stokes flow solutions coupled to surfactant diffusion, advection, adsorption and desorption kinetics,
- verify the implementation against analytical manufactured solutions
- check applicability and accuracy on challenging numerical cases from literature involving Marangoni forces caused by surfactant concentration gradient,
- integrate all numerical developments into an automated workflow for pulmonary simulations of surfactant delivery in large-scale, air-filled airway tree models,
- assess performance in a high-performance computing context.

Selected cases emphasizing the sensitivity of delivery efficiency (the fraction of surfactant that reaches the terminal airways) and homogeneity (the extent to which it is evenly distributed between all terminal airways) to geometric architecture, gravitational orientation and truncation level of the airway tree model will also be examined and validated by experimental observations, for which dedicated pilot studies will be conducted.

Participants

INHALE builds of a multidisciplinary consortium of three French laboratories bringing together the complementary expertise of specialists in high-performance computing for complex multiphysics CFD applications and its coupling with AI (P. Meliga, E. Hachem, CEMEF), transport and delivery in the pulmonary airway system (M. Filoche, IMRB, Paris) and surfactant rheology (J.-F. Berret, MSC, Paris). Work will take place at CEMEF, in Sophia-Antipolis (on the French riviera), in close collaboration with corresponding units at IMRB (Créteil) and MSC (Paris).

CEMEF is an internationally-recognized research center of Mines Paris PSL and CNRS, whose activity covers the broad field of materials and industrial transformation processes. The successful candidate will be part of the Computing and Fluids (CFL) group, whose research is focused at the intersection of fluid dynamics and major societal challenges in energy, environment and health (biofluids). CFL comprises of 50+ scientists with expertise across the full range of fluid mechanics disciplines, who benefit from cutting edge facilities in high-performance computing, cloud platforms and 3D printing technology to integrate advanced computational tools and theory with laboratory experiments and bring innovative, science-based solutions to real-world fluid-flow problems. The group is deeply committed to goal-oriented, collaborative research as closely integrated with industry as possible. Il also offers exhaustive training opportunities for high-level professionals and academics through master's and doctoral programs in core areas linked to mechanics, computer engineering and artificial intelligence, and provides top-class students an opportunity to pursue their training in a dynamic, high-quality research environment, while developing their network and allowing them to connect with the world of science in entertaining and exciting ways.

The PhD therefore provides a unique multidisciplinary environment to carry out new challenging research machine learning biomedical engineering, as well as an outstanding opportunity to work on real-world healthcare applications.

Applicants

The duration of the PhD is 3 years, to start to start in the fall of 2024. Applicants will have (or be in the process of obtaining) a master's degree in fluid mechanics, applied mathematics, or a related field, with an outstanding academic record (at or near the top of their class) at master’s level. Preferred candidates will possess demonstrable experience in the numerical modelling and simulation of flow transport phenomena, a working knowledge of finite element analysis, numerical programming ability using C++ and python, professional command of English, good presentation skills, and the ability and willingness to work collaboratively within a multi-disciplinary team. Prior experience in collaborative projects using git would be appreciated.

Contact

Formal applications should include a detailed cv, letter of motivation, list of publications (in case of joint authorship, please clearly indicate your own contribution), official transcript of grades for the qualifying degree, and the names, affiliations, and email addresses of two academic referees who can provide details about your academic profile in relation to this position (please do not include any reference letters in your application). Applicants must also provide samples of research papers or sections of dissertation demonstrating their ability to engage in doctoral level academic writing.

Enquiries and applications should be directed to:

- Dr. Philippe Meliga : philippe.meliga[at]minesparis.psl.eu
- Prof. Elie Hachem : elie.hachem[at]minesparis.psl.eu