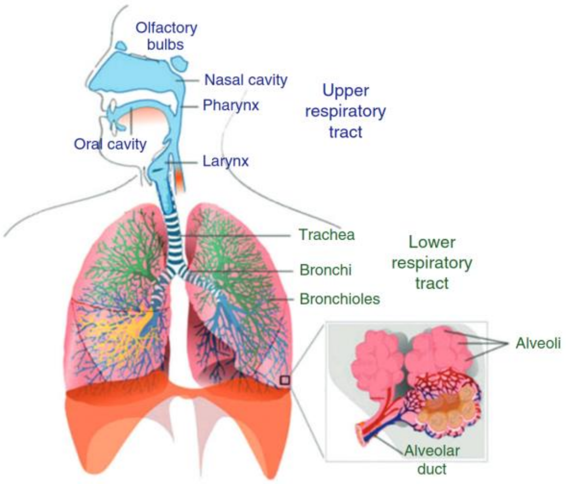
Computational modeling of transport and exchange in human lungs



Computational fluid dynamics (CFD) is a well-established tool for delineating fluid flow and pressure distributions within complex systems. Traditionally, CFD has been used to aid in the effective or improved design of a system or device; however, it has become increasingly leveraged for biological and medical-based applications. Mathematical modeling of gas transport and exchange in the lungs is a valuable tool to mechanistically interpret clinical data and give more insights into the phenomena taking place in the deepest part of the lungs, where access for direct measurements is limited. These mathematical and numerical models can realize precision medicine and patient-specific therapy. The combination of advanced medical imaging and CFD is as well enabling improved device design in aerosol transport, updated biomarkers of lung function in clinical trials, and enhanced predictions and assessment of surgical interventions in the nasal sinuses.

The lung is a complex multi-physics and multi-scale organism, ranging from cellular level to the system level. For lung, anatomical length scales span over three orders of magnitude across the respiratory tract, from centimeters in the trachea down to ~100 μm in cavities of alveolar in the acinar regions. The macroscale simulation of the flow in lung concerns the transient flow and transport of gas species and particles inside the tracheo-bronchial airway tree. Microscale simulation of lung concerns the gas exchange takes place in regions distal to the tree. Fully resolved numerical simulations of complete lungs are still beyond reach. Hence, the overall goal of this study is to couple the microscale simulation of the gas exchange with macroscale modeling of the tracheobronchial tree. In this view, the study in divided into two master's thesis work, as explained below.

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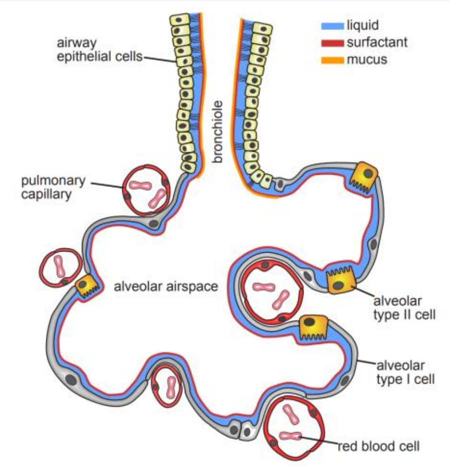
Image-based CFD simulation in the central airways

The main objective of this part is to create geometry from CT-data, provide an automated platform for the process and then focus on the outflow boundary condition. A realistic boundary condition can be patient-specific volume changes of the lung or a 1D model of airway tree. In addition to the outflow boundary, the airway wall should be considered to some extent in this work.

The main tasks of this project are to:

- create patient-specific lung geometry using patient CT-data,
- mimic lung diseases by insighted manipulation of the geometry,
- calculate the gas flow distribution in the updated geometry during inspiration or expiration (taking into account the increased resistance to the flow in airways where the flow is non-established),
- evaluate the exchange fluxes of the gaseous species of interest between the tissues composing the lungs and the lumen, and
- compute the concentration profile of the exchanged species in the lumen of the tracheobronchial tree.

Model development for gas-exchange membrane



Several gas species are exchanged between the lungs and the environment, the most important of them being carbon dioxide and oxygen. The lungs can be divided into two regions, the tracheobronchial tree and the alveolar region, wherein the exchange of oxygen and carbon dioxide occurs in the latter. This process is governed by diffusion through the membrane. The membrane is covered with a film of water on the alveolar side since diffusion of oxygen through the membrane occurs in the liquid phase. The membrane will separate a volume filled with moist air from blood vessels. These blood vessels consist of a system of tubes which transfer blood to and from the heart into the lungs. The current thesis work is concerned with the development of a simulation model of the gas exchange process between the alveoli and the capillaries using computational fluid dynamics. The main aim is to simulate exhaled gas concentrations during breathing. For this work, idealized geometries will be used and the main tasks are to:

- account for changes in the surface area and thickness of the membrane due to lung expansion,
- reflect on changes in the partial pressure of gasses over time due to the respiration,
- include changes of the gasses concentration along the alveoli capillaries,
- extend the model for other gasses such as Nitric Oxide,
- add the capability to explore membrane degradation and fouling, and
- calculate exhaled gas concentrations as a function of time (breath cycles) and relate to experimentally measured gas concentrations in exhaled breath.