Gas transport in the lung using a single- and double trumpet model with anatomically correct geometry

Laboratory Exercise

TBME08 Biomedical Modelling and Simulation

Place: Zoom (Info is available in Lisam)
Tutor: Iulian Emil Tampu
Contact: iulian.emil.tampu@liu.se

Compendium written by Tomas Strömberg

Department of Biomedical Engineering

LINKÖPING UNIVERSITY

1 INTRODUCTION

The aim of this lab is to:

1. Understand the effect of convection and diffusion on gas transport in central and peripheral airways.
2. Relate the mathematical model of gas transport in the lungs with diffusion and convection mechanisms.

An advanced trumpet model with anatomically correct geometry is used to simulate the gas transport in the lungs where both convective and diffusive gas mixing in a single or a double trumpet model is considered. The simulation is performed using a MATLAB GUI. The impact of parameters such as the diffusion constant of gas, the tidal volume and the position of branching can be studied by analyzing gas concentration profiles in time and space.

In the lab report include a brief explanation of the mathematical model governing gas transport in the lung and its simulation. Document your results for Tasks 1-3 using relevant plots. Explain and interpret your findings using literature and/or simple physics laws. Lab reports should be submitted via Lisam within 10 days after the lab session.

1.1 PREPARATORY QUESTIONS

Read the Paiva article focusing on pages the following sections in the new and old version:

Original version: *Introduction* and *Diffusion front* (p245-251).

New version: *Introduction, Diffusion, Convection, Diffusion and Convection during inspiration diffusion front* and *Parallel ventilation and Heterogenity/Single and Multiple branch point models* (p819);

Using the information from the articles and the lectures, answer the following questions before the lab so that you can understand the tasks and interpret your results (<u>no need for submitting your answers</u>).

1. What is convective and diffusive flow?
2. In **Figure 1**, mark the part in the respiratory system that is peripheral and the one that is central/proximal.
3. How does the relationship between generation and total cross-sectional area look like? Fill in the curve in the graph in **Figure 1**.

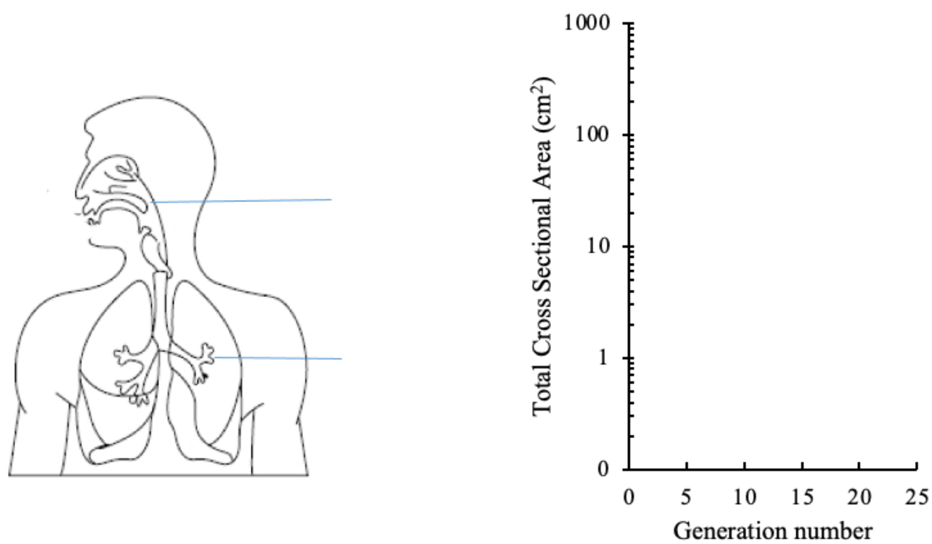

Figure 1. (left) schematic of the peripheral and central respiratory system. (right) Graph that relates generation number and airways total cross-section area

4. For modelling the respiratory system, trumpet models can be used. Draw how the models look like and relate it to the answer in question 3.
5. Write down Eq. 1 from the original Paiva article and identify what the different parts stand for.
6. Why can there be inhomogeneities in lung function between the two lungs and why is it interesting to do simulations of ventilation distribution at all?
7. What is the diffusion front and how can it be quantified?

8. In the 3D graph in **Figure 2**, specify at which time interval the process is stationary and where the diffusion front is. Where is the flow convective?
9. Describe the multi-breath washout test. What are the parameters measured?

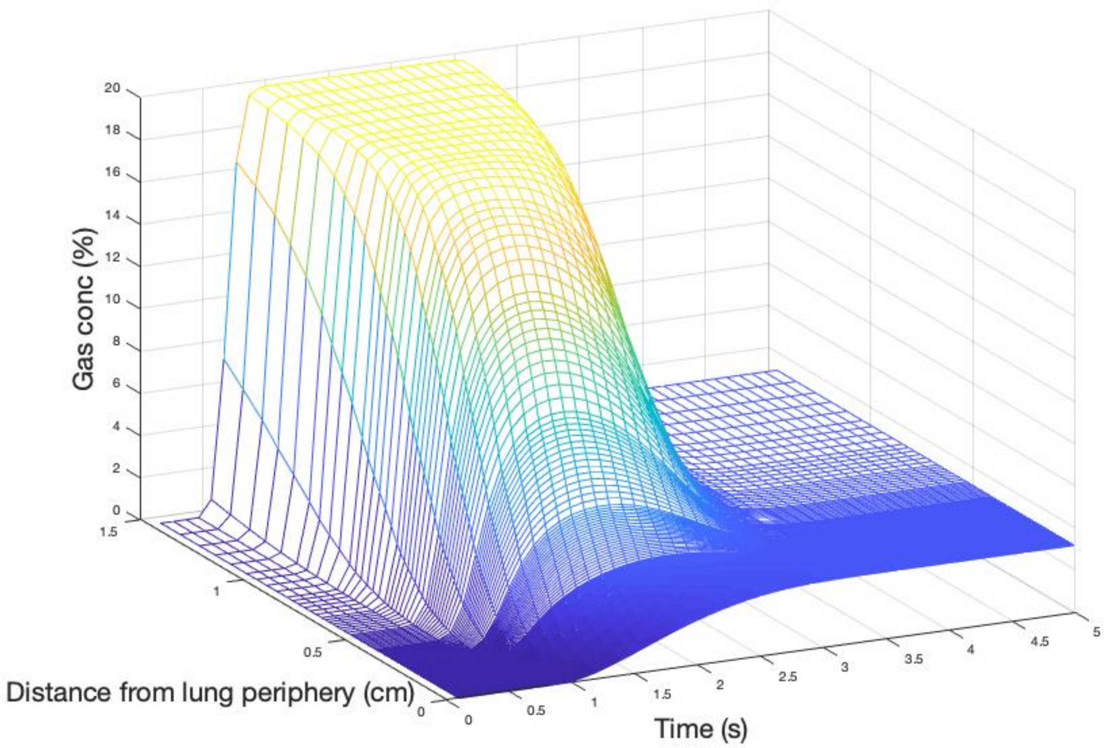

Figure 2. Example showing the convection-diffusion interaction in the most peripheral airways: The single trumpet model in an initially oxygen free lung during inspiration (0-2.5s) and expiration (2.5 – 5s) in the most peripheral parts of the lung (1.5 – 0 cm from the alveoli).

2 LABORATORY TASKS

To get started, download the `.zip` folder from the Lisam course documents. Open MATLAB and navigate to the downloaded folder. The simulation program is started by typing `Lungsim` in the MATLAB command window.

While doing the lab, make sure to save the plots you obtain as you go. Add titles and legends to the graphs using the *Tools* in the menu bar in the figure window. Where relevant include more than one plots in one graph to allow a better comparison.

Note: For a breading rate of 0.2 Hz, the breath cycle will be 5s with the initial 2.5s identifying the inspiration and the last 2.5s the expiration.

Task 1 – Study the effect of diffusion constant and tidal volume using the single trumpet model

In this task you will determine the effect of diffusion constant and tidal volume on the location of the diffusion front in the airway using the single trumpet model. Run the simulation using the single trumpet model with the default parameters.

1- plot the 3D graph showing the relation between gas concentration, distance from lung periphery and time: use this to understand the results for one breath cycle. Use the 3D plot to identify where convection or diffusion are dominant and relate this to the mathematical model of gas mixing.

Now that you are familiar with the results of the simulation, change the diffusion constant and the tidal volume as described below and estimate the position of the stationary diffusion front.

2- use a tidal volume of 500mL and change diffusion constant to be D = 0.225 and D = 6*0.225.
3- use a diffusion constant of 0.225 and adjust the tidal volume to be 500 mL, 1000 mL and 2000 mL.

Hint: Choose time points using the 3D plot, then use 2D plot in the `Lungsim` GUI to get the graphs you will use to estimate the position of the diffusion front.

Define the diffusion front and how its position can be estimated. Analyze your results and relate the changes in diffusion front position with the changes in diffusion constant and tidal volume. Use what you have read in the Paiva paper to relate your results to the theoretical model.

Task 2 – Ventilation inhomogeneity simulation in the double trumpet model

In this task you will determine the position in the airways where diffusion is able to compensate for ventilation inhomogeneity between the two branches of the trumpet (i.e. lungs). Select the double trumpet model in the `Lungsim` GUI and set the simulation parameters so that the ventilation inhomogeneity ratio is equal to 3. At the end inspiration and expiration, measure the oxygen concentration in the alveoli. Find the branching generation where alveoli gas concentration ratio between the two branches is 2.

Start by branching in generation #10 and increase with steps of 3 generations and then refine the search.
In the report describe how branching generation affects alveoli oxygen concentration difference between the two branches. How much the concentration difference will be if only convection or diffusion is present? Discuss your results in terms of the interrelation between convection and diffusion.

Hint: When discussing your results, use the information that you can find in the Pavia articles (original article p257-258 *B. Theoretical* and new article p819 *Single branch point - two trumpet model*).

Task 3 – Wash-in efficiency in the double trumpet model

In this task you will study the effect of branching generation on the lung washing efficiency. Use the double trumpet model and simulate at least 20s with branching in generation #10 and in generation #18. Let the ventilation ratio between trumpets be 3.

In your report, show and discuss the effect that branching generation has on washing efficiency when comparing the well ventilated and poorly ventilated lungs.

Hint: To plot the changes in time of peripheral airways oxygen concentration, write in the MATLAB command window:

```
plot(konc(rl,:));
hold on;
plot(konc(ll,:));
```

This will produce the time plot for the right (`rl`) and left (`ll`) lungs. Remember to identify the well ventilated and poorly ventilated branch in your plot.

Description of some of the variables available in the workspace

`konc(i,j)`	→	concentration of gas in position #i in airway at time point #j
`a`	→	area of conducting airways
`aa`	→	area of a and alveoli
`x`	→	distance from lung periphery
`dmol`	→	diffusion constant
`vtot`	→	tidal volume

REFERENCES

Paiva, M., and L. A. Engel. 1989. Gas mixing in the lung periphery. *In* H. K. Chang and M. Paiva, editors. Respiratory Physiology: An Analytical Approach. Marcel Dekker, New York. 245-276.

Verbanck S, Paiva M. Gas mixing in the airways and airspaces. Comprehensive Physiology. 2011 Jan;1(2):809-34.

Author	Year	Comments on modifications
Tomas Strömberg	~	Original exercises, codes and software
Iulian Emil Tampu	2021	Revision. Overall text refinement, addition of specific references to literature, addition of specific points to address in the report.