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MODELING SHEAR STRESS DISTRIBUTION IN A DEFORMABLE AIRWAY TREE

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ABSTRACT

The interaction between air and mucus in the bronchial tree can play an important role on mucus transport at high ventilation regimes, such in exercise, chest physiotherapy or cough. In order to improve our understanding of this interaction, we analysed with modelling approaches the distribution of shear stress in airway trees during expiration. We use models with the minimal possible complexity in order to keep the models tractable and in order to identify the driving phenomena. We explore how the shear stress induced by air can overcome mucus typical yield stress and how it might be distributed in the tree. Our models allow to highlight several behaviors, and show that both tree structure and bronchi deformation play a crucial role in the way mucus is affected by air. In particular, we determined, in the limit of our models, that the shear stress distribution exhibits a bell-like profile along the tree whose properties are directly related to lung's geometry, tissue pressure and to the amount of air flow.

Keywords: Bronchial tree, shear stress, mucus yield stress, mathematical model, fluid mechanics, bronchi mechanics

INTRODUCTION

How mucus is motioned by its interactions with air in the lung is not well understood because of the complex biophysics, biomechanics and geometry involved. Yet, this interaction is thought to be the driving phenomenon for mucus motion during cough, exercise and chest physiotherapy [12]. Improving our understanding has become even more crucial for chest physiotherapy since it has been the center of a controversy about its efficiency. As an empirical discipline, practitioner has not yet been able to prevail because of the lack of

scientific understanding of their technics [1, 6].

By flowing, air induces a shear stress on the air-mucus interface: if the shear stress is strong enough and overcomes the mucus yield stress (threshold effect [4, 8]) then mucus starts moving. So the distribution of shear stress along the bronchial tree plays an important role on how mucus can be affected by air. Air mechanics is however itself strongly affected by the fact that lung's bronchi are organized into a tree structure. Shear stress in a bronchus is proportional to the ratio of air velocity in the bronchus over the bronchus radius. Since both velocity and radius are decreasing when going deeper into the bronchial tree, the resulting balance is not trivial. Moreover, bronchi are deforming depending on the pressure difference between their surrounding tissue and their inner air, allowing a possible saturation effect of air pressure inside the distal bronchi [5, 11]. Consequently, the analysis of shear stress behavior and distribution in the bronchial tree is complex but crucial in order to improve our understanding of air-mucus interactions.

Hence, this study aims at analyzing how shear stress is distributed in an airway tree during expiration. We use modeling approaches based on first order approximation hypotheses in term of flow (laminar, low flow regime) and geometry (symmetric branching tree). We show first that in a quasi-fractal rigid tree, shear stress should vary monotonously along the airway tree, either increasing, stalling or decreasing, depending on the tree geometry. Then, still in the hypothesis of a rigid tree, we show that in a more realistic lung's model based on Lambert et al's work [5], the geometrical characteristics implies that shear stress has a bell-like shape along the tree, increasing first, then decreasing. Finally, using Lambert et al model for bronchi deformation, we show that the maximum for shear stress still exists, but is less marked in high flow rates and that its position in the tree is the result of a trade-

off between the lung's tissue pressure and the lung's inner air pressure, that itself results from fluid dynamics in a tree.

MODELLING

This work is based on geometrical models of the lung whose bifurcations are symmetric. Although this is a simplification, this choice has proven very valuable in the literature to improve our understanding of the lung's biophysics [2, 7, 8, 10, 11]. We model the bronchial tree with a cascade of cylinders. To mimic lung's bifurcations, each cylinder is connected to two smaller cylinders. The tree is thus divided in levels called generations, two branches in the same generation count the same number of bifurcations on their path to the tree root. The size reduction at bifurcation is called h and is either independent on the generation index or dependent on the generation index. The parameter h is always smaller than one.

In the case where h is constant, the model is called a quasi-fractal model [10, 14]. It is difficult to give a good estimate for h but a value around 0.82 in humans has been proposed [13]. In the quasi-fractal model, the size of a branch in generation $i \in \{0, 1, \dots, N\}$ is h^i the size of the first generation.

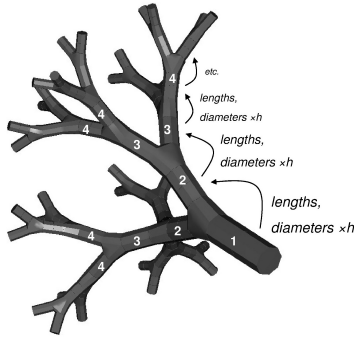


Figure 1: Typical model geometry for the lung used in this work: symmetric bifurcations with size reductions at each bifurcation. The numbers on the bronchi indicate the generation index of the corresponding bronchus.

In the case where h depends on the generation, we use Lambert et al [5] model, that proposes static section-transmural pressure relationships of bronchi depending on their generation index, as shown on figure 2. Notice that transmural pressure is defined as the pressure difference between air inside the bronchi and the tissue around the bronchi. Air is considered as a Newtonian fluid with viscosity $\mu_a = 1.8 \cdot 10^{-5} Pa.s$. We will focus our study here on low flow regimes, assuming that the viscous part of the fluid is dominant. This is an approximation, most particularly in the proximal parts of the lung where inertia is known to play a role on flow distribution [9], and hence on shear stress distribution. This first order approximation hypothesis will however allow us to reach already rich qualitative behavior for shear stresses. In this study, we focus on expiration.

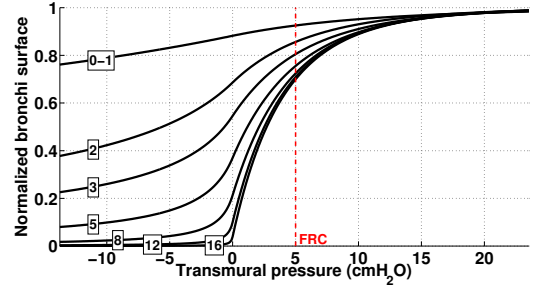


Figure 2: Lambert et al's bronchi deformation model [5]: the curves represent the bronchi section surface area versus the transmural pressure for a subset of generations (indexes are indicated by numbers in squares).

SHEAR STRESSES IN A RIGID AIRWAY TREE

A model with rigid bronchi will be used in this section. This hypothesis is a good first approximation for proximal bronchi that are quite rigid as they are partly cartilaginous. We will start with the lung modeled as a quasi-fractal tree with N generations. We assume that the fluid mechanics in a bronchi in generation i is stationary, axisymmetric and does not depend on the axial position z in the tube. Fluid mechanics equations depend only on the radial position r in the branch and are reduced to

$$-\frac{1}{r} \frac{\partial}{\partial r} (r \Sigma_{zr,i}) + \frac{\partial p_i}{\partial z} = 0$$

with $\Sigma_{zr,i}$ the shear stress in z, r directions and p_i the pressure in the branch. Consequently,

$$\Sigma_{zr,i} = \frac{\partial p_i}{\partial z} \frac{r}{2} \quad (1)$$

If the mucus thickness is small relatively to bronchus diameter [3], the boundary condition on the bronchus wall and the higher mucus viscosity allow to neglect the effect of mucus on air. In this case, the previous system of equations lead to a parabolic profile along r for air velocity, and the amplitude of shear stress at air-mucus interface can be evaluated at bronchus wall: $\Sigma_{a/m,i} = \frac{\mu_a \Phi_{a,i}}{\pi r_{b,i}^3}$ with $\Phi_{a,i}$ the air flow in the bronchus. Using the scaling property of the tree and mass conservation of air in the tree bifurcations ($\Phi_{a,i} = 2\Phi_{a,i+1}$) allow to compute the (non signed) shear stress at air/mucus interface $\Sigma_{a/m,i}$ in generation i ,

$$\Sigma_{a/m,i} = \Sigma_{a/m,0} \left(\frac{1}{2h^3} \right)^i \quad \text{with} \quad \Sigma_{a/m,0} = \frac{\mu_a \Phi_{a,0}}{\pi r_{b,0}^3}$$

Hence the behavior of shear stresses along the tree generations depends on the tree scaling parameter h and its relative position to $h_c = \left(\frac{1}{2}\right)^{\frac{1}{3}} \sim 0.79$. For $h < h_c$, shear stress is increasing along the tree generations; for $h = h_c$ shear stress is constant all along the tree; for $h > h_c$, shear stress is decreasing along the generations.

Estimation of h in the lungs is very complex, and published values for h showed that it might be slightly larger than

h_c , typically $h \sim 0.82$ [10, 13] indicating that shear stress should decrease along the tree. But a refined analysis from Lambert et al's model (FRC configuration) leads to h values being slightly below h_c in the proximal lung and slightly over h_c in the distal lung. In such a configuration, shear stress is increasing up to a threshold generation from which it is decreasing. Practically, we can estimate with Lambert et al's data that the transition occurs between generations 8 and 10, as shown on figure 3.

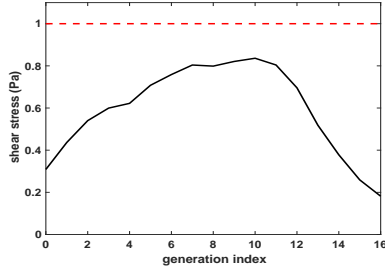


Figure 3: Predictions of shear stress distribution along the generations of an airway tree whose geometry is based on Lambert et al's model at FRC configuration, i.e. with transmural pressure equals $5 \text{ cmH}_2\text{O}$. Flow is 10 L/s in the root of the tree. The red curve represents a typical value for mucus' yield stress [4].

Typical values for shear stresses using the previous model are $\Sigma_{a/m,0} \sim 2.10^{-3} \text{ Pa}$ at rest, and can reach up to 0.9 Pa when mimicking cough. In order for thin layers of mucus to be motioned, shear stress has however to overcome the yield stresses whose order of magnitude is about $0.1 - 1 \text{ Pa}$. Our rigid tree models predict that yield stress might not always be overcome, even with flow rates as high as 10 L/s .

INFLUENCE OF BRANCHES DEFORMATION

In the previous section, we determined how shear stress behaves in a rigid tree. In a fractal tree, the shear stress has a monotonous behavior along the generations, but we saw that more realistic models, such as Lambert's show that the shear stress can exhibit a bell-like shape along the generations, with, in our case, a maximum reached near the 9th generation. Bronchi deformation might however affect how shear stress is distributed into the tree and its amplitude: actually, when air pressure increases strongly in a bronchus, it can relax the hydrodynamic resistance by dilating the bronchus. During expiration, this would occur more particularly in the distal part of the bronchial tree where bronchi are smoother and pressures higher. In order to improve our predictions, we computed stationary shear stresses along a deformable tree using Lambert et al's mechanical model shown on figure 2. Although this is an approximation, because of tissue heterogeneity, gravity, etc., we made the hypothesis that tissue pressure was homogeneous everywhere in our model of the lung.

As for rigid trees, the deformable model also predicts bell-like profiles of shear stress along the generations. However, the amplitude of shear stress is now larger, mainly because

the surrounding tissue pushes on the bronchi, which cannot be fully closed however, thanks to the opposing air pressure induced by the air flow. Also, the location of the shear stress maximum depends on the amount of air flow and on the tissue pressure. The generation where the maximal shear stress occurs shifts upward the tree when air flow is increased. Air pressure is actually saturating in the deepest part of the tree where the bronchi are very dilated; this induces that lower pressure drops are needed for maintaining the flow at these locations. Consequently the pressure drops and velocities in the distal tree are low and shear stress decreases. Pressure saturation starts at the generation where shear stress is maximal. This phenomena was induced by the geometry in the case of rigid trees, it is now still induced by the geometry but the geometry is the resultant of the trade-off between tissue and air pressure.

Shear stress distributions in several configurations are plotted on figure 4. This model indicates that at rest ventilation (low flow and low tissue pressure), air flow cannot overcome mucus yield stress. In order to start mobilizing mucus, tissue pressure has to be increased and mucus mobilization starts in the deepest parts of the lung. Pressure increase plays only a small role on the localisation of the maximum of shear stress. In order to reach more proximal parts of the tree, flow has to be increased. These results suggest that tuning of air flow and tissue pressure -related to choice of lung volume and applied pressure amplitude during chest physiotherapy's manipulations- might allow to select the region treated.

The previous phenomena will also occur in the case of a constricted bronchus: at a given expiratory flow rate, pressure will increase upstream the bronchus, and upstream bronchi will be dilated. Maximal shear rate will then be located exactly at the constricted bronchus. If constriction is due to mucus accumulation, the high shear stress will help moving the extra mucus downstream. Consequently mucus motion induces a decrease of the airway tree's hydrodynamic resistance. This behavior was previously observed in [11] using a more complex, but less tractable model of air-mucus interaction. An example of this previous model is shown on figure 5 where we mimicked the effect of chest physiotherapy on an airway tree with mucus excess. These results indicate that hydrodynamic resistance decrease is a direct consequence of the geometry and its influence on shear stress distribution; it might be a de facto effect of chest physiotherapy and should probably be a criterion for analysing chest physiotherapy efficiency.

CONCLUSIONS

Our results show that both the geometry of the bronchial tree and its mechanical response to transmural pressures are crucial in understanding how mucus can be motioned by air, as in exercise, cough or chest physiotherapy. Our model suggests that shear stress exhibits a maximum in the bronchial tree whose location depends on the tissue pressure and amount of air flow in the lung. We also showed that air shear stress distribution at expiration tends to motion mucus from an encumbered bronchi upward the tree, by thus decreasing the global

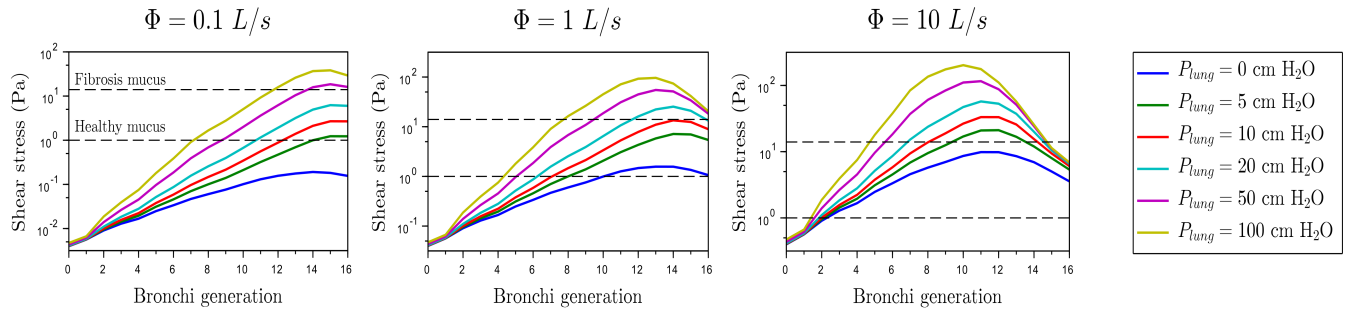


Figure 4: Shear stress distribution in a deformable tree. Shear stress is increasing in the proximal lung and decreasing in the distal lung. The higher the air flow, the deeper the maximum shear rate is located. Dashed lines correspond to typical mucus yield stress for two patient configurations.

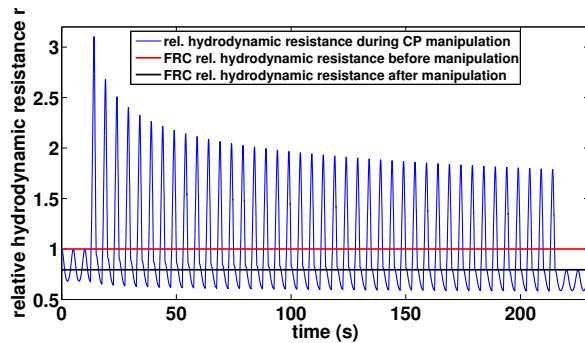


Figure 5: Mucus motion induced by its interaction with air flow tends to decrease the airway tree hydrodynamic resistance. Here, we mimicked successive manipulations of chest physiotherapy using the model we published in [11].

hydrodynamic resistance of the airway tree. This raises the question on the link between chest physiotherapy efficiency and hydrodynamic resistance before and after the manipulation, even if no mucus has been expectorated.

These results have however to be interpreted in the frame of the model's hypotheses in term of lung geometry, lung's mechanics and mucus rheology. Other physical phenomena, such as inertial effects, turbulence, surface tension, etc. have also to be investigated to confirm and improve our understanding and predictions of air-mucus interactions. Moreover, to reach more quantitative predictions, it would be necessary to account for patient specificities in term of lung's geometry and mechanics and in term of mucus properties.

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