PULMONARY ALVEOLUS' MODEL INCLUDING SURFACE TENSION EFFECTS

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Abstract. *Mathematical models of the pulmonary tissue are required to investigate recruitment maneuvers for collapsed lung tissue. The lungs have water droplets in alveoli corners. In the small cavities of alveoli, the surface tension of the fluid-gas interface plays an important role on the structural stability of the alveoli. Current models for pulmonary tissue don't consider fluid's surface tension in brochioles and alveoli and, therefore, do not represent properly recruitment and collapse of the alveoli. The present work develops mechanical models, based on the finite element method, taking into account fluid droplets in alveolar corners and their surface tension. The model is capable to represent the collapse and the sudden opening of an alveolus. The results are generated by numerical simulations.*

Keywords*: alveolus model, tissue model, surface tension, finite element method.*

1. INTRODUCTION

Many patients in intensive care units are unable to breathe spontaneously and, therefore, can survive only by mechanical ventilation. The mechanical ventilation doesn’t work as spontaneous ventilation, it pumps a positive pressure inside the lung that inflates, instead of a lung that is expanded inside the chest, generating negative pressure and thus sucking air in. Many times their health condition debilitates their lungs and the physicist must chose a ventilation maneuver or another procedure that better helps the patient’s recovery. The knowledge of the physical and physiological phenomena involved in pulmonary dynamics shall be very useful in developing new maneuvers for lung care.

The pulmonary structure is very complex and its dynamics is nonlinear. The airway has many ramifications, with different diameters and stiffness (Leff and Schumacker, 1993). That means that both airway’s resistance and compliance are neither constant during the respiratory cycle nor along the airway, from the trachea to the alveoli. In the alveoli, where most of the gas exchange occurs, there is water diffusion from the blood vessels to the interstitial space of the alveoli. In some cases, this water can cause the closure of the alveoli due surface tension effects. In most alveolar models, the physics of interaction between air and fluid is displayed in the same way as a bubble. This conception is being contested, as in recently works of Hills (1999) and Prange (2003). They both believe that the liquid stays in the corners of alveoli’s walls, between the tissue folds.

The alveoli are interconnected in clusters resembling honeycombs, called acini. The walls are corrugated surfaces resembling soaking wrinkles. These corrugations are blood capillaries vibrating in heart frequency (Hills, 1999). The walls stretch and fold as the acinus is filled and emptied with air.

The surface tension appears in the interface between two chemical phases, as a result of uneven molecular forces in the different phases. This results in a rather rigid liquid surface due to the fact that surface molecules are pulled more to the substrate and sideways (by other molecules of same kind) than to the interface. In curved interfaces, as capillary meniscus, the Law of Young-Laplace, represented in Eq. (1) and Fig. 1, relates the meniscus radius (R), the surface tension (γ), contact angle with solid surface (θ) and the difference of pressure between the two sides of the interface (Δp) (Adamson and Gast, 1997). The contact angle measures the capacity of the liquid phase to adhere to the solid phase.

$$\Delta p = \frac{\gamma}{R}\cos\theta \qquad (1)$$

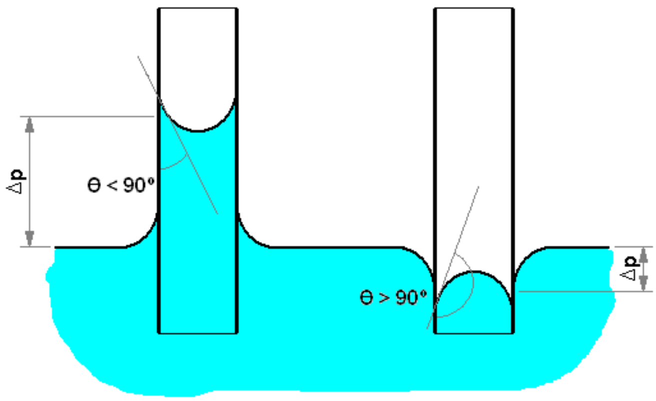

Figure 1. Relationship between contact angle and differential pressure.

To avoid the collapse of the alveoli and decrease the alveolar hysteresis, some lung cells secrete a surfactant solution. The surfactant decreases the surface tension, because it is a substance that has chemical affinity with both liquid and gaseous phases. The efficiency of the surfactant depends strongly on its surface concentration. As in recent work by Hills (1999), the surface area of the water droplets inside the alveoli changes during the respiratory cycle. As a result, the surface tension of interstitial liquid changes too. The surface tension decreases with the increase of surface area in inspiratory phase, and increases again in expiratory phase. Thus, the surfactant helps to avoid collapse during the expiration and protects against tissue damage in inspiration.

2. ANALYTIC MODEL OF AIRWAY MECHANICS

The numerical model of alveolar collapse developed in this work, using finite element method (FEM), was based on the analytic model of Hill *et al.* (1997) for small airways mechanics. Although the model presented here was based on the model of Hill et al., it doesn't work in the same way, some assumptions and simplifications are different. They assumed the airway as a membrane tube, inelastic to stretch, but able to bend. The airway has a liquid film on the inside wall. The tube may buckle when there was negative pressure inside. The buckle of a cylinder wall makes folds, which became filled with fluid in the model. The liquid in the folds had capillarity effects. The radius of liquid surface becomes proportional to the distance between the fold sides. The Young-Laplace's Law, Eq. (1), generates a negative pressure that pulls the folds' walls more inward. As the folds are bent, the fluid is squeezed and the radius decreases even more until obstruction of the airway occurs. A higher air pressure is required to open the airway than to maintain it opened, because the negative pressure created by the surface tension is much higher as well.

3. METHODS

To simulate alveolar collapse, a routine in Matlab was developed using the FEM. The program's used 2D beam and spring elements, as described by Logan (2001). The mesh was created with Gmsh (Geuzaine and Remacle, 2006), an open source Computer Aided Design (CAD) software.

Some simplifications were taken, in order to have a first approach to the phenomenon and not an exact solution that would require a very complex model. The main goal of this work was to simulate the collapse of a tubular structure due to surface tension effects.

The geometry of this model is a simple 2D linear-elastic beam structure fixed by four spring elements, as seen in Fig. 2. The springs are very stiff and represent the collagen fibers that sustain the lung tissues. In order to approximate wall mechanics of an alveolus, it were used beam elements with relatively high axial stiffness (high sectional area) and low bending stiffness (low second moment of area).

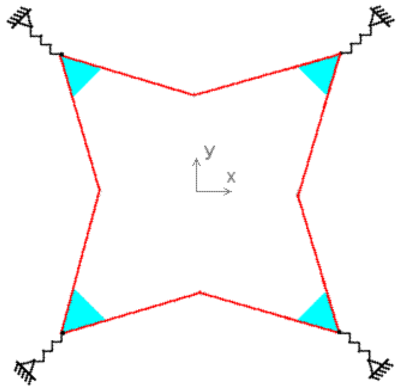

Figure 2. Geometry and border conditions. The beam elements are in red. Each corner is fixed by a spring element and has a constant volume of liquid (blue area).

There is a constant volume of liquid in each corner of the alveolus. The position of each liquid-gas interface relative to the structure is determined by imposing that the liquid volume is constant, and the position is found when a numerical integration equals the adopted volume. To simplify, the interface's approximate radius is the distance between the first node of the mesh after the interface and the symmetry line, on Fig. 3. The wetted elements are loaded with a distributed load Δp, according to Eq. (1).

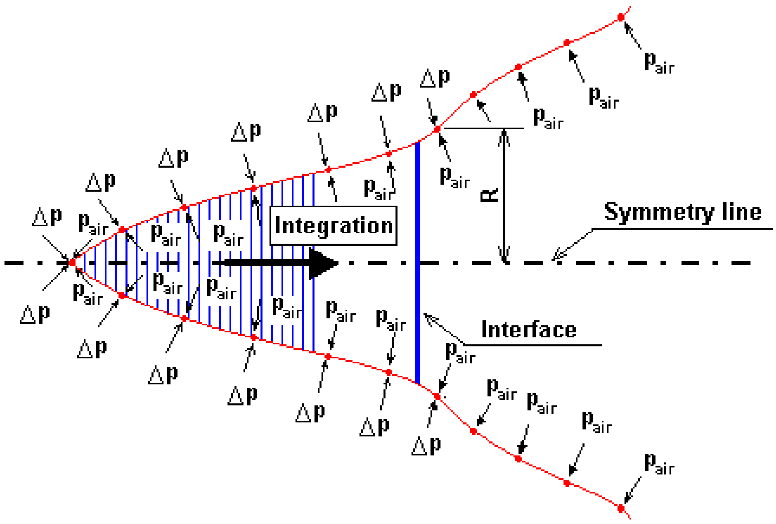

Figure 3. Integration of volume until the adopted volume, where the interface is found.

The model is also able to be loaded by the air pressure. The air pressure loads all elements of the structure, see figure 3. The air pressure is transmitted through the water towards the wall of the alveolus. Only the surface tension pressure pulls exclusively the wetted region. Equation (2) shows the load of the structure on wet and dry surface.

$$p_{load} = \begin{cases} p_{air} - \Delta p, wet \\ p_{air} \qquad , dry \end{cases} \tag{2}$$

No gas compressibility model was applied. When the alveolus shrinks, the air pressure stays constant. Another simplification is a constant surface tension, the surfactant surface concentration is considered constant.

This non linear structural model must be solved iteratively. After the finite element deformation results, another volume iteration is performed. Usually the interface moves, so the interface radius and the pressure of the wetted region change. When the interface line passes through an element node, the next element is loaded. The logic of the routine can be seen in Fig. 4.

Sometimes, as the model's walls are approaching each other, they could transpose themselves, resulting in divergent results. So this model needs a special boundary condition, because FEM isn't able to determine if a solid surface touches or goes through another. Thus, when the program detects that one node has a negative distance from the symmetry line (see Fig. 3), it adds a force to this node and its opposer, simulating a contact force. At each iteration, which results in transposed nodes, this opposition force is applied to the node of more negative displacement. The value of the contact force is incremented until the displacement becomes positive.

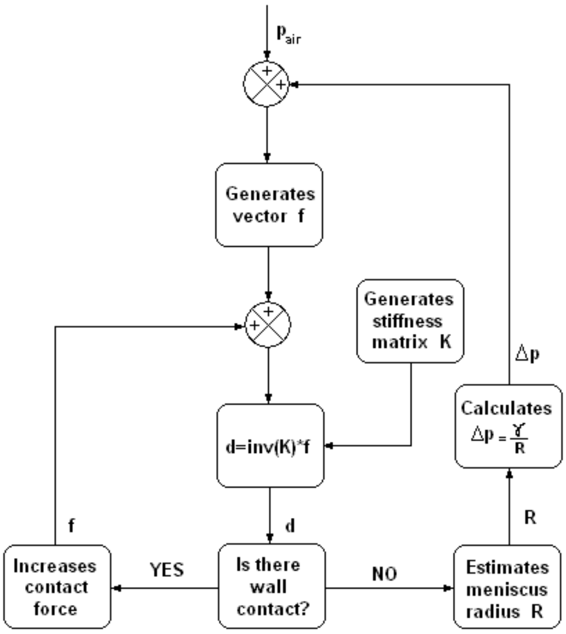

Figure 4. Routine's block diagram.

The alveolus model will be investigated under two different initial conditions. First, the alveolus is open and the air pressure is kept constant until equilibrium is reached, for discrete values of air pressure, from 30 to 0 Pa. Second, the alveolus is collapsed and the air pressure is kept constant until equilibrium is reached, for discrete values of air pressure, from 0 to 30 Pa. The model is intended to have only qualitative value and can show the phenomenon of collapse.

4. RESULTS

The shape of the collapsed alveolus structure can be seen in Fig. 5. The blue dashed line shows the position of the air-water interface after the deformation of the structure. The program stops when the interface reaches the last node. At this moment the radius of the bubble is small enough to continue the deformation of the structure.

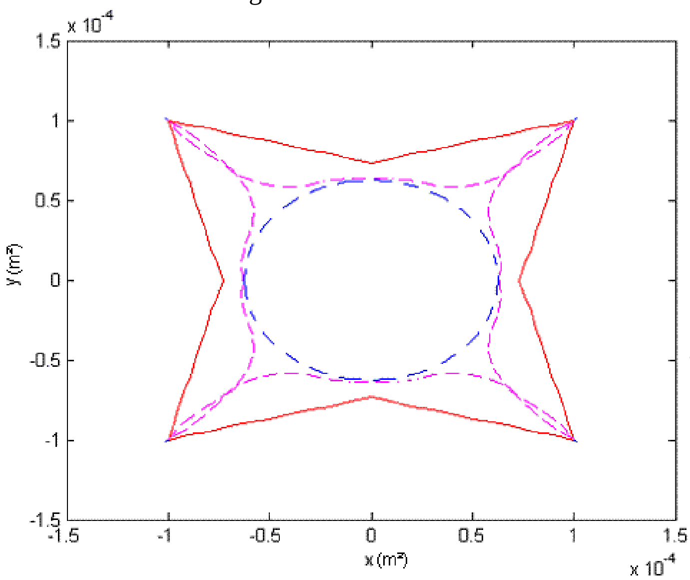

Figure 5. Collapsed alveolus. Red solid lines form the beam mesh before applying the loading; blue lines in the tips are spring elements, magenta dashed lines show the deformed mesh and the blue dashed line show the air-water interface after deformation.

If the initial condition is an open alveolus, the routine iterates to find the equilibrium, the routine iterates to find an equilibrium condition, given an air pressure. Figure 6 is a graph of area inside the structure as a function of the air pressure. There are two kinds of solution: one with lower pressures and collapsed alveolus and another with higher pressures and recruited alveolus. There is no intermediate solution possible.

If the initial condition is a collapsed alveolus and the air pressure is incremented, a sudden opening of the alveolus happens. This sudden opening represents the recruitment of the alveolus and Fig. 7 shows the graph of alveolus inner area as function of the air pressure.

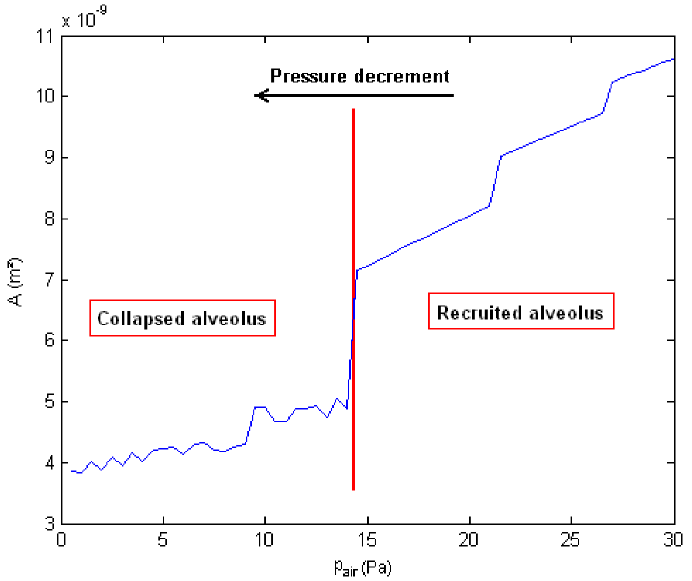

Figure 6. Sudden collapse of alveolus represented by the area inside the beam mesh.

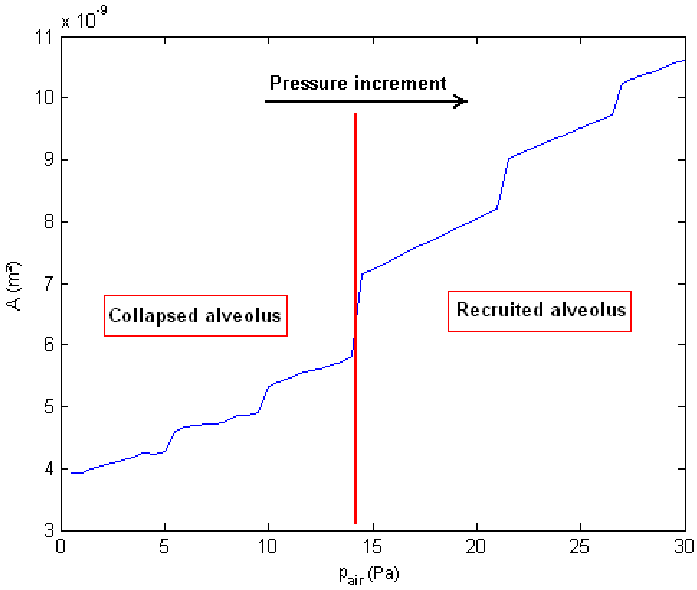

Figure 7. Sudden opening of alveolus represented by the area inside the beam mesh.

5. DISCUSSION

Although the surfactant concentration is kept constant, the geometry that is represented is pipe shaped instead of ball shaped, the amount of interstitial liquid is kept constant and some of the structural properties were adopted qualitatively to represent a structure that has high axial stiffness and low bending moment, the model is able to show how the surface tension may explain the sudden collapse and the sudden recruitment of the alveolus. Due to the lack of viscous elements in the model, the present results have shown the same critical pressure to open and to close the alveolus.

6. FINAL COMMENTS

In spite of the simplifying assumptions, the model can show the phenomenon of alveolar collapse and recruitment due to the overall geometry and surface tension. In order to improve the results, getting closer to the real phenomenon, some hypothesis taken in this work have to be changed. A 3D geometry resembling more the real alveolus shall be build using shell elements, instead of beam elements. The way to determine the radius of the gas-liquid interface shall be more realistic and the contact angle shall be better known. There shall be a way to relate the surface tension and the gas-liquid interface area. And, since, the real phenomenon has hysteresis, the model should incorporate physiological facts that bring hysteresis to the overall model.

7. ACKNOWLEDGEMENTS

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