FLOW AND SURFACTANT TRANSPORT IN AN ALVEOLUS PARTIALLY FILLED WITH LIQUID

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INTRODUCTION

Alveoli are major units responsible for gas exchange in the lung. They are either directly connected to airways, or form an alveolar cluster at the terminal end of an airway. A typical size of an alveolus is about 200μm. A normal lung produces surfactants to reduce the surface tension in the alveoli making the lung more compliant to aid in breathing. A liquid layer usually coats the internal wall of alveoli and contains surfactants produced by alveolar. During partial liquid ventilation (PLV), surfactant replacement therapy (SRT), congestive heart failure (CHF), and respiratory distress syndrome (RDS), the liquid film can become thick and occupy an appreciable fraction of the alveolar volume, thus forming a diffusion barrier to transport. The transport of gases, surfactants, cellular materials and other substances for such an alveolus is, consequently, will depend on convection due to alveolar breathing motions.

Most previous investigations for alveolar flows are focused on the dynamics of a thin alveolar liquid lining as occurred in a normal lung. In this aspect, Podgorski and Gradon [1] have modeled the flow for the alveolus directly connected to airways. Wei *et al*. [2] recently have explored the flow occurring in an alveolar cluster. These studies suggest that for a sufficiently low tension the fluid motion is favored to flow towards the alveolar opening, which could assist in cleansing processes. For clinical applications such as PLV, SRT, CHF and RDS, however, the thickness of the liquid layer could be thick or comparable to the size of an alveolus. The corresponding flow and transport could be significantly different from the previous *thin-layer* model. In the present work, we propose a *thick-layer* alveolar flow model to understand the underlying fluid transport mechanisms.

APPROACH

Figure 1 shows our thick-layer, two-dimensional model. The fluid layer is partially filled in an alveolus and is pinned at the alveolar opening. The air-liquid interface contains insoluble surfactants. We assume a sufficiently strong surface tension and a small surfactant activity. This suggests that the deformation of the interface only responds to the conservation of the fluid mass. That is, the interface remains circular at all times. The breathing motion is assumed to be self-similar, i.e., the opening angle α is fixed during breathing. As such, we utilize the bipolar coordinates [3] and combine analytic and numerical techniques to solve the Stokes flow and the surfactant distribution.

Since the flow field couples to the surfactant conservation, we thus involve the following solution procedures. For a given surfactant concentration distribution Γ at a time *t*, we can calculate the surface tension gradient (i.e., Marangoni stress) along the interface. We then can calculate the corresponding flow field using the stream function formulation in the bipolar coordinates. This flow field is applied to update Γ at $t+\Delta t$ by solving the surfactant transport equation numerically. The implicit Euler method is employed to discretize the time derivative. To discretize the spatial derivatives, the upwind and central difference schemes are performed for the first and second spatial derivatives, respectively. Initially, we start with a uniform Γ and conduct simulations until reaching steady, oscillatory states. In the present work, we are particularly interested in time-averaged flow patterns and results are presented as below.

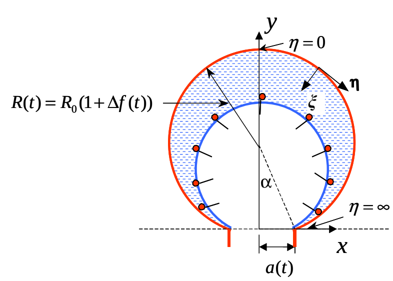

Figure 1. A thick-layer alveolar flow model

RESULTS AND DISCUSSIONS

First of all, one should notice that in the absence of surfactants, there is no steady streaming. This is because the Stokes flow of our system is reversible unless the interfacial deformation deviates from a circular shape. Figures 2 shows time-averaged flow patterns for various inspiratory to respiratory period ratios (I:E). We only display results in a half of the alveolus due to the symmetry. For I:E=1:1 as shown in Figure 2(a), the time-averaged streamlines show two vortices. This is a result of a non-zero time-averaged surfactant concentration distribution $\overline{\Gamma}$, and the Marangoni stress tends to drive the flow from lower tensions (higher $\overline{\Gamma}$) for higher tension (lower $\overline{\Gamma}$). Since the minimum surface tension occurs at about the middle of the interface, it drives a surface flow toward the midline and the alveolar opening (higher tension regions). For a longer expiratory period I:E =1:2 as in Figure 2(b), the resulting time-averaged flow pattern only exhibits a single vortex with counterclockwise flow direction. In particular, I:E = 1:2 is more physiologically relevant. Figure 2(b) suggests that the surfactant tends to flow out of the alveolus, which is consistent with the previous thin-layer model [1], even though the interface is pinned. However for I:E=2:1 as in Figure 2 (c), the flow pattern displays a primary vortex with an opposite flow direction in contrast to Figure 2(b).

Different time-averaged flow patterns by manipulating I:E ratios can be realized by examining the surfactant transport equation:

$$\Gamma_t + \nabla_s \cdot (\boldsymbol{u}_s \Gamma) + \Gamma(\nabla_s \cdot \boldsymbol{n})(\mathbf{v} \cdot \boldsymbol{n}) - 1/Pe_s \nabla^2 \Gamma = 0,$$

where $\boldsymbol{n}$ is the unit normal of the interface and Pe_s is the surface Peclet number. $\boldsymbol{u}_s$ is the surface velocity tangential to the interface. As we check for a system during the mid-inspiration, the expanding motion of the alveolus results in two competing effects on the surfactant transport. On the one hand, the surface velocity (the second term) tends to sweep surfactants from the alveolar opening toward the midline; on the other hand, the expansion of the surface area (the third term) tends to diminish the surfactant concentration near the midline. The competition leads to lower Γ near the midline toward which the surface flow thus favorably acts. Similarly, the mid-expiration causes higher Γ near the midline from which the surface flow acts away. Since the flow tendency during inspiration or respiration has its own preference, the resulting time-averaged flow strongly depends on the I:E ratio. For example, longer expiration favors flow toward the alveolar opening, and the time-averaged flow pattern should be dominated by a counterclockwise vortex structure just demonstrated as in Figure 2(b).

We estimate steady velocity $u^* \sim 10^{-4}$cm/s. The corresponding Peclet number Pe = $u^* a_0/D_m = 10^{-7}/D_m$, where D_m is the molecular diffusivity (cm^2/s). For molecules with D_m lower than 10^{-7} cm^2/s, the fluid velocity governs the steady transport.

ACKNOWLEDGEMENTS

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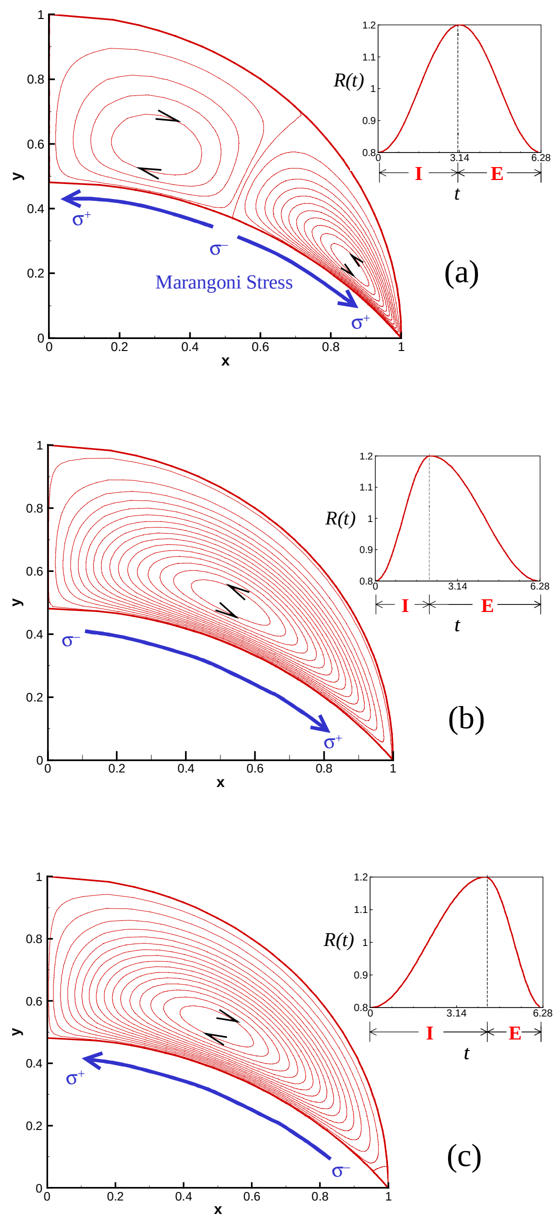

Figure 2. The time-averaged streamlines. V=0.9, Δ=0.2, Ma=4.0,Pe_s=1.0. (a) I:E=1:1 (b) I:E=1:2 (c) I:E=2:1.