Numerical study of liquid plugs in an airway reopening model

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The two-layer coating plug propagation and rupture are studied computationally as a model for airway reopening for the eighth-to-tenth generations of a typical adult lung. The computational model incorporates the bi-layer structure of the serous–mucus liquid film lining the rigid tube, where the inner serous layer is treated as a Newtonian fluid, while the outer mucus layer is modeled as an elastoviscoplastic fluid governed by the Saramito–Herschel–Bulkley model. To isolate rheological influences, the effects of viscoelasticity, viscoplasticity, and elastoviscoplasticity are firstly evaluated using the one-layer model. A novel elastically driven supercritical regime is identified, governed exclusively by the Weissenberg number (Wi). Under supercritical conditions, a resonance phenomenon emerges, amplifying extra-stress oscillations within the trailing film and increasing the risk of epithelial injury. Within the EVP framework, viscoelasticity was found to promote rupture, whereas viscoplasticity exerted an inhibitory effect. Furthermore, surfactant-mediated surface tension variations confirmed the mechanical robustness of the identified resonance mechanism. Compared to the one-layer plugs: (i) the two-layer plugs necessitate a higher driving pressure for rupture and exhibit a longer propagation distance, both of which increase the risk of failed airway reopening; (ii) both the wall shear stress and the wall shear stress gradient exhibit a significant reduction of approximately 75% in the two-layer plugs; (iii) the two-layer liquid film cannot be modeled using a one-layer plug model by simply applying the Navier boundary conditions. The critical mechanism due to dynamic elastic stretching persists for the two-layer plug. The serous layer appears to limit the transmission of elastic resonance to the airway wall, which underscores the protective role of the serous layer. The shear stress and shear stress gradient increase with increasing Weissenberg number. At low Weissenberg numbers, rupture time increases as a result of an increase in the Bingham number and a decrease in the power-law index; at high Weissenberg numbers, viscoelastic effects dominate the elastoviscoplastic airway reopening. These distinct two-layer phenomena offer crucial insights for developing more physiologically accurate models of airway fluid mechanics.

Key words: Pulmonary fluid mechanics, Interfacial Flows, Non-Newtonian Flows.

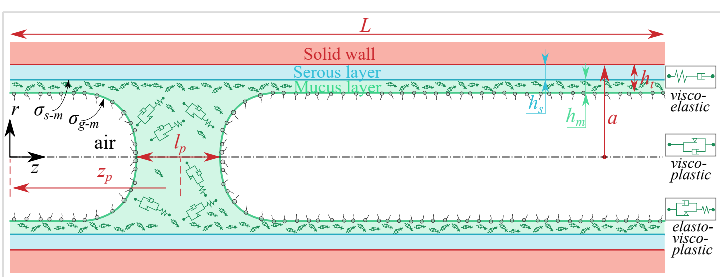

Figure 1. Schematic of the non-Newtonian two-layer airway reopening model with insoluble interfacial surfactant.

Jury

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