3D Airway Closure: A Non-Axisymmetric, Fluid-Elastic Instability

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The gas-conducting airways of the lung are flexible tubes lined with a thin liquid film. The film is susceptible to a capillary instability, analogous to the classical Plateau–Rayleigh instability, provided that the length of the airway is greater than the circumference of the air-liquid interface.
The instability causes an initially-uniform film to develop a series of axisymmetric peaks and troughs. The fluid pressure is low in the regions of increased film height, the lobes, and the compressive load on the airway walls is locally elevated in these regions. If the surface tension of the liquid is sufficiently high, relative to the bending stiffness of the tube, the altered loading can lead to a secondary, non-axisymmetric, buckling instability of the elastic tube. Under certain conditions, the subsequent evolution of the system leads to complete occlusion of the gas core by the liquid — airway closure.
We study the time-evolution of an idealised airway and the development of any instabilities using a fully-coupled, three-dimensional finite-element method. The deformations of the airway wall are modelled using Kirchhoff–Love, thin-shell theory and the dynamics of the liquid film are described by the Navier–Stokes equations. The most unstable axial wavelength of the initial instability is $\approx 2\sqrt{2}\pi R$, where R is the radius of the gas core, which leads to preferential buckling in a three-lobed mode, see Figure 1.

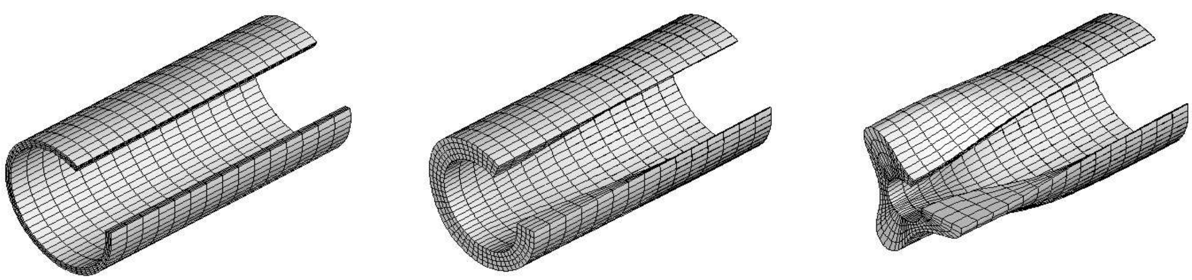

Figure 1: An initially-uniform liquid film undergoes an axisymmetric capillary instability causing fluid to drain into a lobe. The additional compressive load in the region of the lobe causes the elastic tube to buckle non-axisymmetrically and, ultimately leads to airway closure. Time increases from left to right and the liquid is shown as a shaded volume. In the simulation, symmetry conditions are imposed at both ends of the tube and hence only one half of the developing lobe is shown.