Inflation and Atelectasis in a Topographical Model of the Lung*

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Introduction

Instability and atelectasis of the lung are discussed in this article. The word instability, like the word disease, has no unique meaning. Here I mean the tendency of a system toward returning to the initial state after an arbitrary infinitesimal perturbation: A system is stable if it would return, unstable if the return is not guaranteed.

The term atelectasis may also mean different things to different people. Here I mean the existence of some groups of completely collapsed alveoli in which there is no ventilation. In contrast, Wilson (1982) considered the pressure-volume curves (PV) of the lung and used positiveness of the bulk modulus of the parenchyma as a criterion for stability. Stamenovic (1986) generalized this concept and defined atelectasis as a coexistence of different phases of expansion, with each phase having a uniform volume expansion ratio. While their investigations threw new light on the phenomenon, their definitions are different from what follows in this paper.

Thus defined, atelectasis and instability are not the same thing. A lung which is stable with respect to small perturbations may become atelectatic by a "large" deformation. On the other hand, an atelectatic lung may be quite stable in the atelectatic state. However, it is most likely that atelectasis follows instability. Hence we investigate them both: the initial tendency toward instability and the persistent atelectatic plaque.

Atelectasis is often seen in surgery, trauma, disease, airway obstruction, high oxygen breathing, high acceleration, etc. To a patient or a physician, the most important question is how to reinflate the collapsed region. A related question is the inflation of a new born baby's liquid-filled lung. The answers are discussed below.

Physical Principles of Stability Analysis

Figure 1 shows the common concepts of equilibrium and stability. A ball in a dish will rest at the bottom and is stable there. Turn the dish over, the ball will

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be in equilibrium at the top but unstable there. This concept is expressed mathematically by saying that the potential energy of the ball is at a relative minimum at the stable equilibrium position and at a relative maximum at the unstable equilibrium position. The potential energy of the ball, derived from gravitation, is equal to the product of the mass of the ball and the height. The relative maximum or minimum is examined against variation of the radial distance from the equilibrium position.

This concept can be generalized to an elastic system by the method of calculus of variation (see, for example, Fung 1965, Chap. 10). One examines the variation of the potential energy of the system against all possible strains. If the first variation of the potential energy function is zero at a certain state of strain, then that state is in equilibrium. If the second variation of the potential energy is positive at the equilibrium state, then that state is stable. If the second variation of the potential energy is negative, then that state of equilibrium is unstable. This is illustrated in the lower half of Fig. 1. In this generalization, the slope of the dish is replaced by the first variation and the curvature of the dish is replaced by the second variation of the potential energy.

From the general theory of thermodynamics we recognize the existence of internal energy. For the lung, the internal energy per unit volume is designated as \( \rho_0 W \), and it consists of two parts: (1) the strain energy in the tissue and (2) the surface energies of the liquid-gas interfaces of the alveolar walls. As to the external forces acting on the lung, some, like gravity, are conservative and have a potential function; others, like aerodynamic forces in airways and viscous shear forces in blood vessels, are nonconservative. All external forces multiplied by the corresponding displacements are equal to the work done, which has the same dimension as energy. When the lung deforms a little in an arbitrary way, the displacement of the lung can be described by a continuous vector field \( \delta u \). This displacement causes a change of strain \( \delta E_{ij} \), a change of stress \( \delta S_{ij} \), a change of internal energy per unit volume \( \delta (\rho_0 W) \), a work done by body force \( X_i \) equal to \( X_i \times \delta u_i \), and work done by surface force \( T_i \) equal to \( T_i \times \delta u_i \). Then a rigorous