THE EFFECT OF GRAVITY ON LIQUID PLUG TRANSPORT IN A BIFURCATING AIRWAY MODEL

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Introduction

Liquid boli are instilled into the pulmonary airways during medical procedures such as surfactant replacement therapy, partial liquid ventilation and pulmonary drug delivery. These liquid boli form air-blown plugs that are subsequently transported through a network of bifurcating airways. The final liquid distribution throughout the lung depends on how the plug divides at each airway branch. The splitting of a plug between daughter branches following a bifurcation depends on many factors including liquid viscosity, surface tension, density, velocity and orientation of the parent and daughter branches in the gravitational field. In this study, we examine how these factors effect the distribution of liquid in airways following a bifurcation.

Methods

These effects are studied using a physical model of a realistic airway bifurcation, shown in Figure 1. The parent diameter is 5/32", the two daughter diameters are each 1/8", giving an area increase from parent to combined daughters of $2A_{dau}/A_{par}=1.28$ which is physiologic. The daughters branch at a 30° angle from the midline. The test section is made from two clear 4" x 6" polycarbonate plates, 1/4" thick. These plates can be positioned at different orientations with respect to gravity. The angles θ and ϕ (Fig. 1) can range from 0° to 180° as measured from the z-axis.

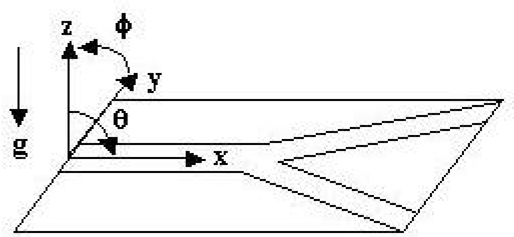

Figure 1. The bifurcating tube model with a spatial orientation corresponding to q**=90° and** f**=0°.**

The test section was attached to a positive displacement pump via flexible tubing and placed under a video camera attached to a computer (Fig. 2). Plug fluid (LB-400X, Union Carbide Chemical) is manually injected into the tubing from syringe 1. Subsequently, air is driven into the tube by the pump pushing syringe 2. A camera records plug movement through the test section. Images are captured at 15 frames/s and saved to the computer hard drive for off-line analysis.

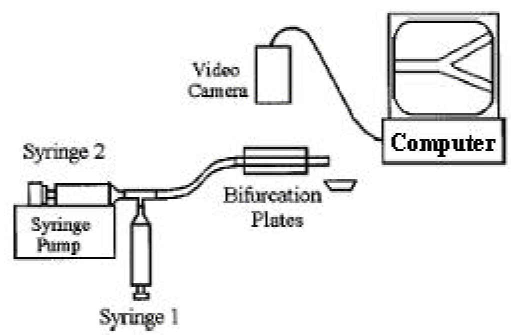

Figure 2. Schematic of the experimental setup for liquid plug flow visualization and measurements.

The physical properties of the plug fluid are the surface tension, σ, density, ρ, and viscosity, μ. The plug and a single tube have additional parameters: plug volume, V_p, tube radius, a, gravity constant, g, and plug velocity, U. These seven parameters were combined into four non-dimensional groups: Capillary number ($Ca=\mu U/\sigma$), Bond number ($Bo=\rho g a^2/\sigma$), Reynolds number ($Re=\rho Ua/\mu$), and a dimensionless plug volume ($V=V_p/a^3$). The experiments modeled the clinical ranges of these non-dimensional variables for small airways where $Re<<1$.

For the experiments, the test section was oriented at predetermined angles θ and ϕ. A plug of LB-400X lubricating oil was pumped through the test section at plug velocity, U, in the parent tube. The airway bifurcation was cleaned with deionized water, isopropyl alcohol and dry air. For a given airway orientation, this procedure was repeated at different parent velocities, U. From each experimental trial, a mass split ratio, R_s, was calculated and defined as the volume of liquid in daughter tube B divided by the volume of mass in daughter tube A (Fig. 3). The volume of liquid in each daughter was measured at the time immediately after the trailing meniscus of the plug moved beyond the carina.

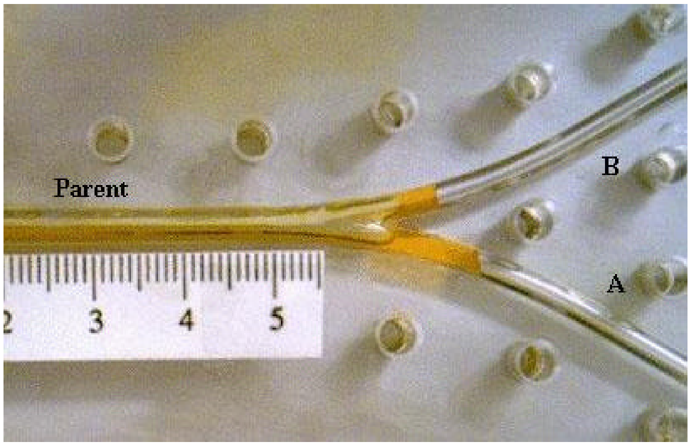

Figure 3. Image of the bifurcating tube model after plug division into daugters A and B.

We plotted the splitting ratio versus capillary number, Ca, for a range of orientations of the airways bifurcation. Shown in Figure 4 is an example of this data.

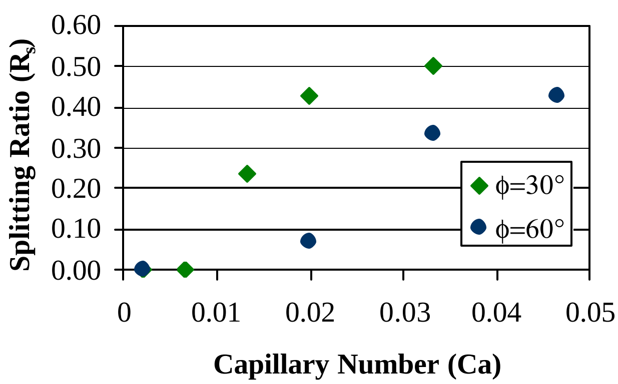

Figure 4. The bifurcating tube model with a spatial orientation corresponding to Bo=1.24, V=32 and q=90° with f =30° (diamonds) or f =60° (circles).

For symmetrical splitting of the plug between the two daughters, R_s=1. For these two orientations, there is a minimum capillary number below which all of the plug in the parent tube is transported into the gravity dependent daughter tube, in this case daughter A. This minimum Ca seems to depend on the orientation of angle ϕ with gravity. The splitting ratio increases with increasing capillary number for the orientations shown. The splitting ratio decreases with increasing ϕ at a particular Ca.

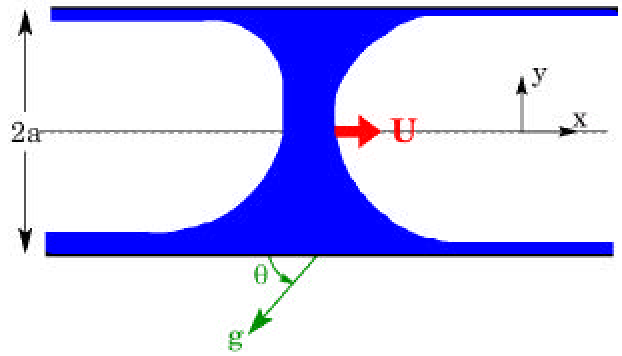

Figure 5. Schematic of the two-dimensional pre-bifurcation airway model.

We also use a simplified two-dimensional theoretical model to examine gravitational effects in the parent tube prior to bifurcation. The model describes the quasi-steady pressure driven motion of a liquid plug through a two-dimensional channel oriented at an angle θ with respect to gravity. A matched asymptotic expansion is used in the limit of small capillary numbers to determine the shape of the plug. The shape of the front and rear air-liquid interfaces close to the body of the plug are governed by fluid statics with the pressure drop being balanced by surface tension and gravitational forces. These regions smoothly connect with the uniform thin film regions at the front and rear of the plug through intermediate transition regions where the viscous, surface tension and pressure forces balance. A pre-bifurcation splitting ratio defined as the ratio of the liquid volumes above and below the centerline of the channel is calculated. For θ =90°, Ca = 0.045, Bo = 1.24 and V = 32 the theory predicts a pre-bifurcation splitting ratio of 0.7. The experimentally determined trans-bifurcation value the same set of parameters with ϕ = 60° is 0.43, indicating that a significant portion of the asymmetric splitting is a result of the dynamics at the bifurcation.

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