Chapter 11
Deposition of Submicron Particles by Chaotic Mixing in the Pulmonary Acinus:
Acinar Chaotic Mixing

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ABSTRACT

In this review, the authors outline the evidence that emerged some 30 years ago that the mechanisms thought responsible for the deposition of submicron particles in the respiratory region of the lung were inadequate to explain the measured rate of deposition. They then discuss the background and theory of what is believed to be the missing mechanism, namely chaotic mixing. Specifically, they outline how that the recirculating flow in the alveoli has a range of frequencies of oscillation and some of these resonate with the breathing frequency. If the system is perturbed, the resonating frequencies break into chaos, and they discuss a number of practical ways in which the system can be disturbed. The perturbation of fluid particle trajectories results in Hamiltonian chaos, which produces qualitative changes in those trajectories. They end the review with a discussion of the effects of chaotic mixing on the deposition of inhaled particles in the respiratory region of the lung.

INTRODUCTION

The primary purpose of the lung is gas exchange. Oxygen-rich air is drawn into the lung by the diaphragm and intercostal muscles, and carbon dioxide and other gasses are rejected with the outgoing air when the muscles relax. This rhythmic, in-and-out, motion of the lungs happens twelve times a minute on average (Weibel, 1984).

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The anatomy of the lung may be divided into three regions: upper airways (nasal pharynx area), conducting airways (trachea to terminal bronchioles) and the pulmonary acinus (respiratory bronchioles to terminal alveolar ducts). Each region has its own unique anatomy and flow regime (West, 2012). Despite these differences in anatomy and flow type, particles are carried from the mouth to the lung periphery.

For a particle to deposit on the surface of the alveolar blood-air barrier, two things have to occur. First, the particle has to travel with the ambient air through a network of ducts and end up close to the alveolar surface. Second, if the particle is close enough, short-distance forces acting on the particle (e.g., the van der Waals force, electrostatic force, Brownian force, etc. [Friedlander, 1977]) will be sufficient to bring it to the surface.

In the lung physiology literature (e.g., West, 2012; Oberdörster et al. 2007), three mechanisms are typically defined as contributing to particle deposition. These are inertial impaction, gravitational sedimentation, and Brownian motion.

Inertial impaction: describes the situation in which a particle with relatively large mass (typically a relatively large particle, since mass is proportional to the cube of the particle's diameter) cannot follow the curvilinear airflow patterns faithfully; and as a result, it deviates from the airflow streamlines and the particle's own inertia carries it to the surface (Friedlander, 1977). This phenomenon is significant when airflow velocity (U) is large, and thus it occurs predominantly in the upper/large airways. A particle's inertia is consider significant when the Stokes number, $Stk > 1$. The Stokes number, $Stk = \rho_p d^2 U / 18\eta L$, where ρ_p is the particle density, d is the particle diameter, η is the air viscosity, and L is the characteristic length scale.

Sedimentation: particles with large mass are also subject to the external gravitational force, which makes the particles deposit in the direction of gravity (Tsuda et al. 2013). This phenomenon becomes significant when the particle sedimentation velocity (expressed in terms of the terminal velocity $v_s = \rho_p d^2 g / 18\eta$, where g = gravitational acceleration) becomes comparable to, or more than, the airflow velocity. Deposition by sedimentation occurs primarily in the large airways and at the beginning of the acinus.

Brownian motion: the potential for particles to cross flow streamlines and deposit due to Brownian-motion is characterized by the Péclet number, $Pe = UL / D$. A balance between thermal effects and viscous drag exerted on the particle determines the magnitude of the diffusivity, D. Particles with small Péclet numbers are more likely to deposit due to Brownian motion. Particles of very small size (diameters < 0.005 μm) may deposit in the upper/large airways because those small particles have an extremely high diffusivity, and low Péclet numbers. Particles with small mass, which can follow the curvilinear airflow patterns with little inertia/gravitational effects, can enter the pulmonary acinus with the airflow. In this review, we focus on the deposition of particles in the pulmonary acinus, which occupies more than 95% of the lungs in volume (Weibel 1984). We concentrate on particles in the diameter range 0.005 μm to 0.5 μm because particles in this range have been found to deposit preferentially in the acinus (Tsuda et al. 2013). Such particles have diffusivities that are small enough to prevent them from depositing before reaching the acinus but are also light enough to exclude deposition through inertial impaction or sedimentation.