Pulmonary Anatomy and Physiology
Basic Principles

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Functions of the Respiratory System

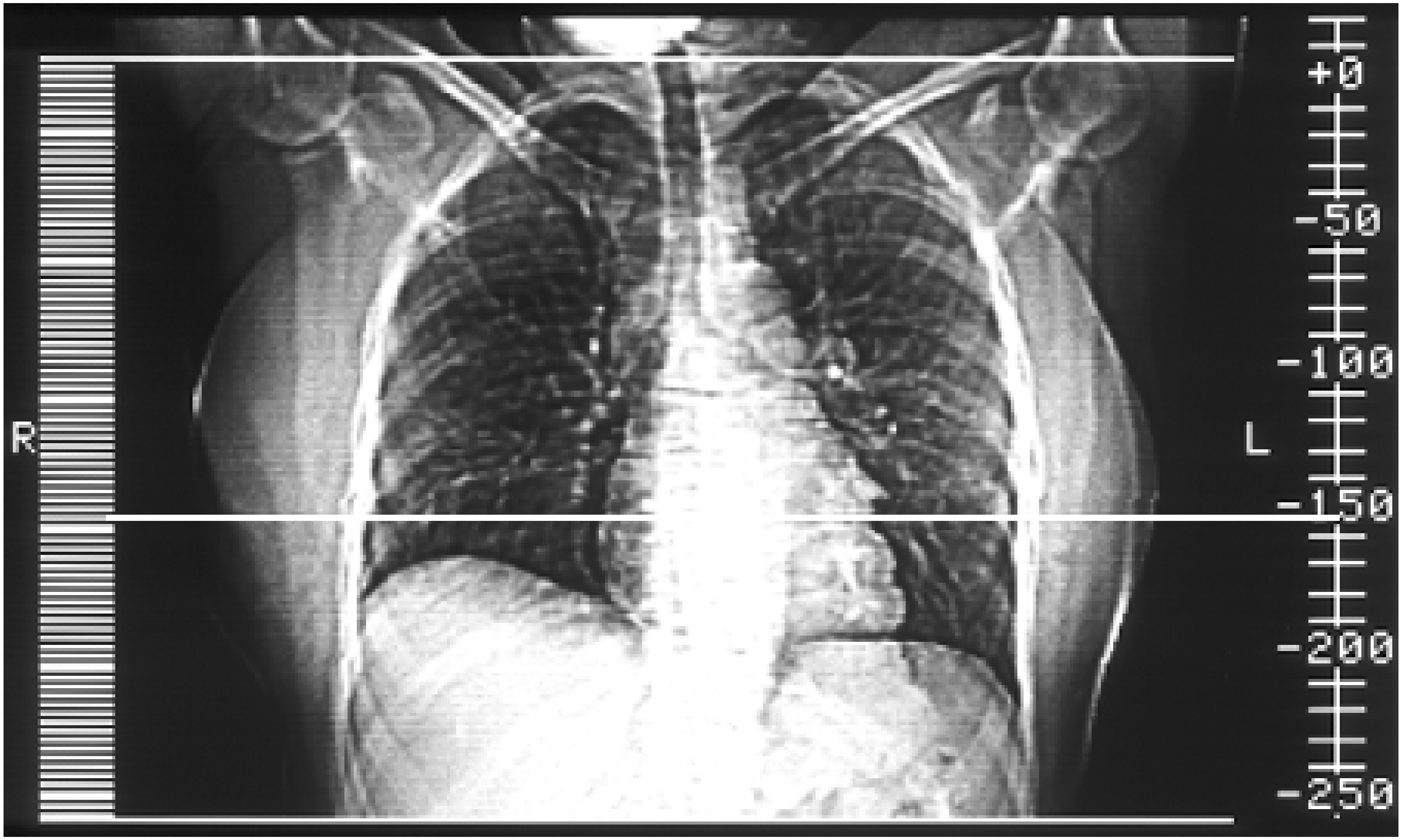
- Gas Exchange
  - O_2 and CO_2
- Acid-base balance
  - $CO_2 + H_2O \longleftrightarrow H_2CO_3 \longleftrightarrow H^+ + HCO_3^-$
- Phonation
- Pulmonary defense (air conditioning & filtering)
- Pulmonary metabolism and handing of bioactive materials

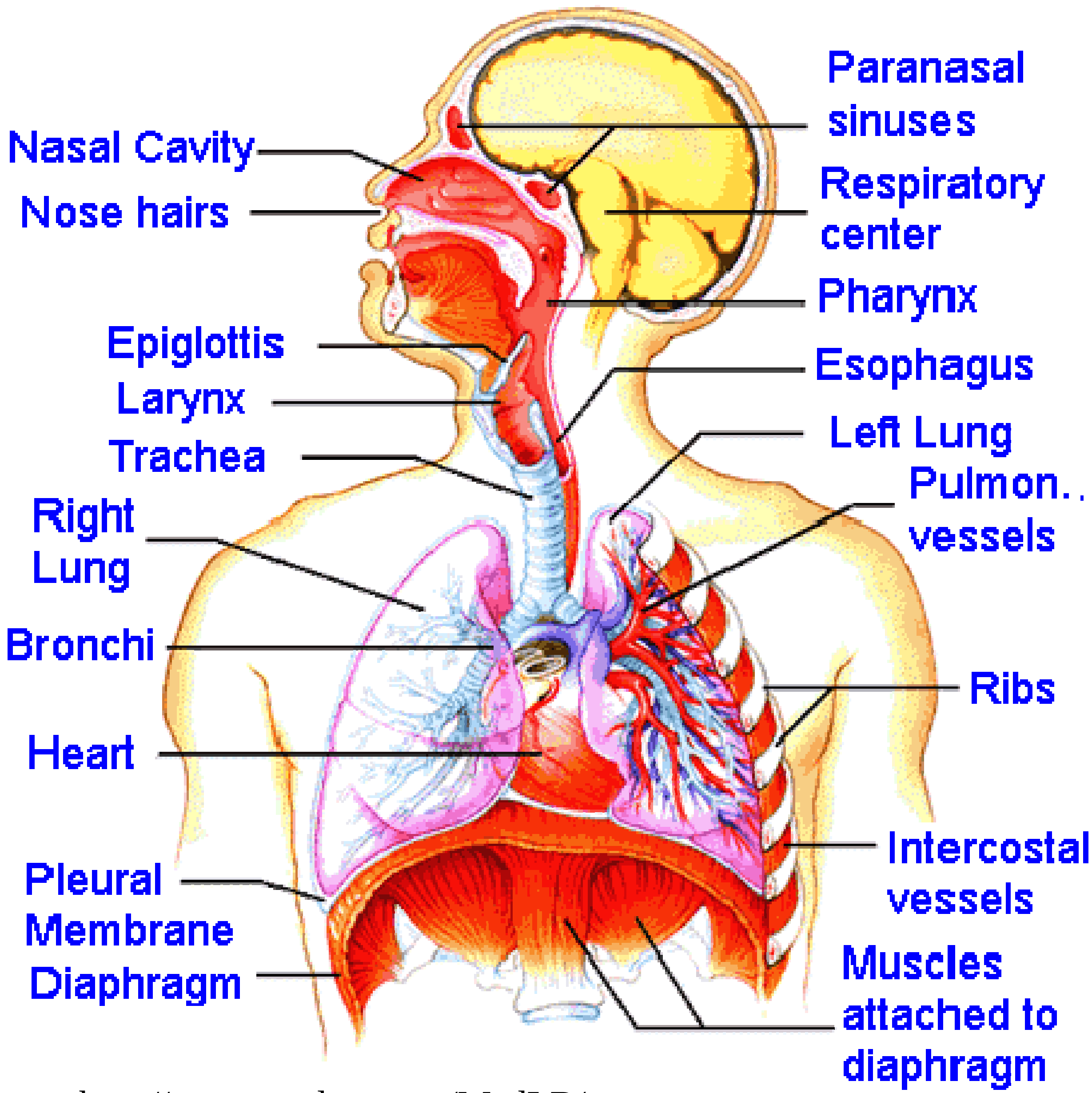
Additional Reasons to Study the Lungs

Alveolar blood-air interface: “window” into the body.

- Non-invasive drug delivery
- Non-invasive measurement of health
- Variety of physics, chemistry, math

Chest X-ray





http://www.medem.com/MedLB/a

Surface Markings of the Lung & Pleura – Anterior View

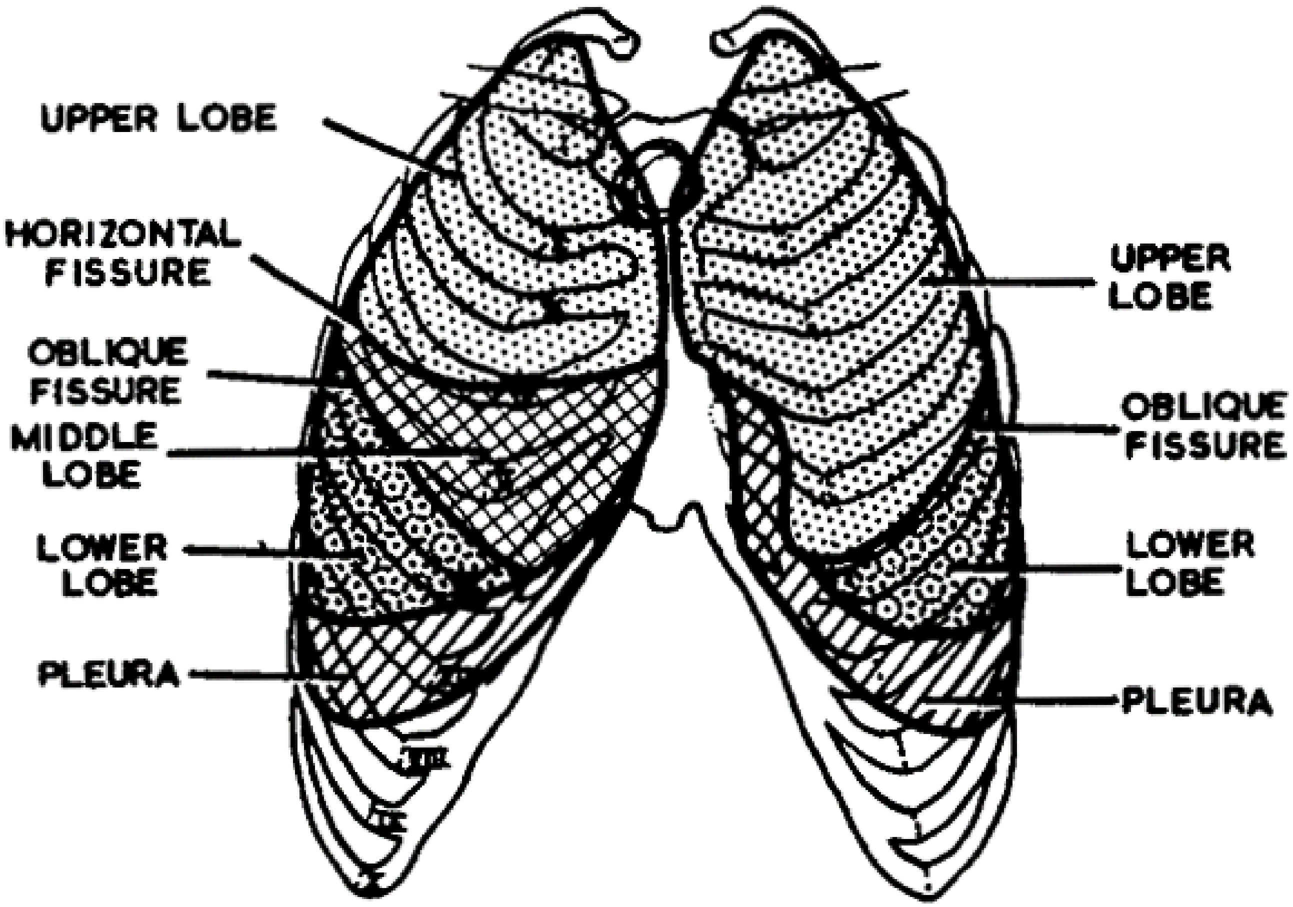
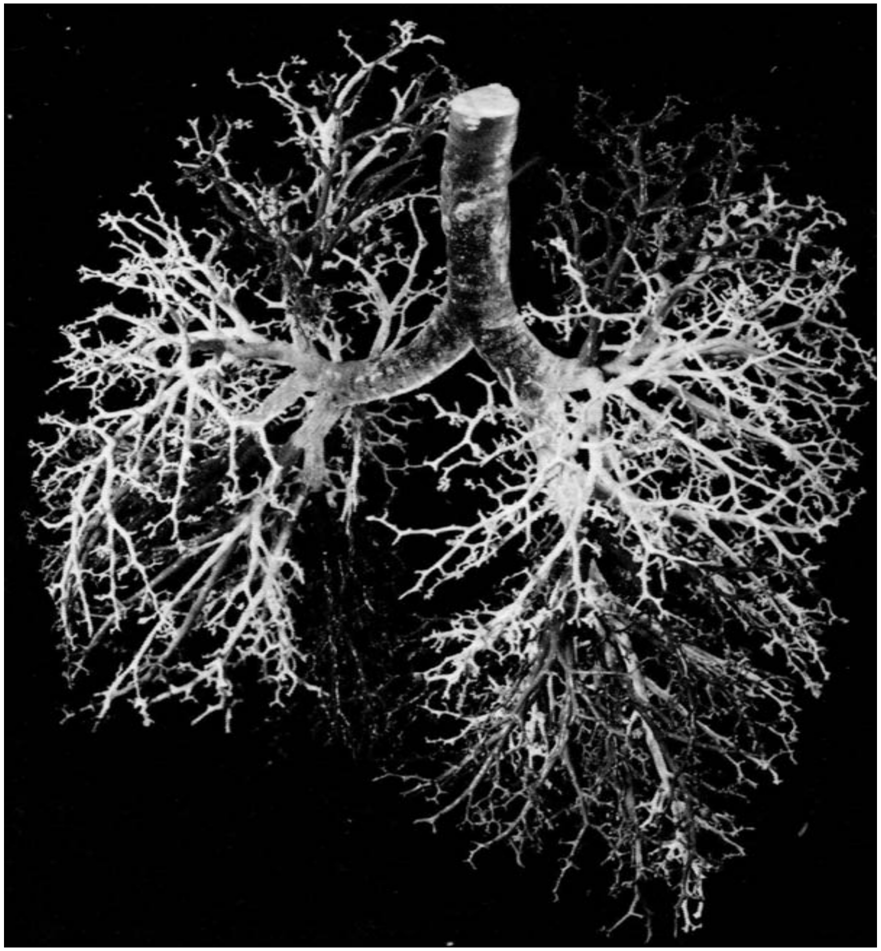


FIG. 2
The surface markings of the lungs and pleura—anterior view.

Clinical Anatomy, Ellis, 5th Ed., 1971

Branching Structure of Airways

- Dichotomous branching
- ~23 generations
- Can we describe this?
- Can we model this?



Trachea and Main Bronchi – Anterior View

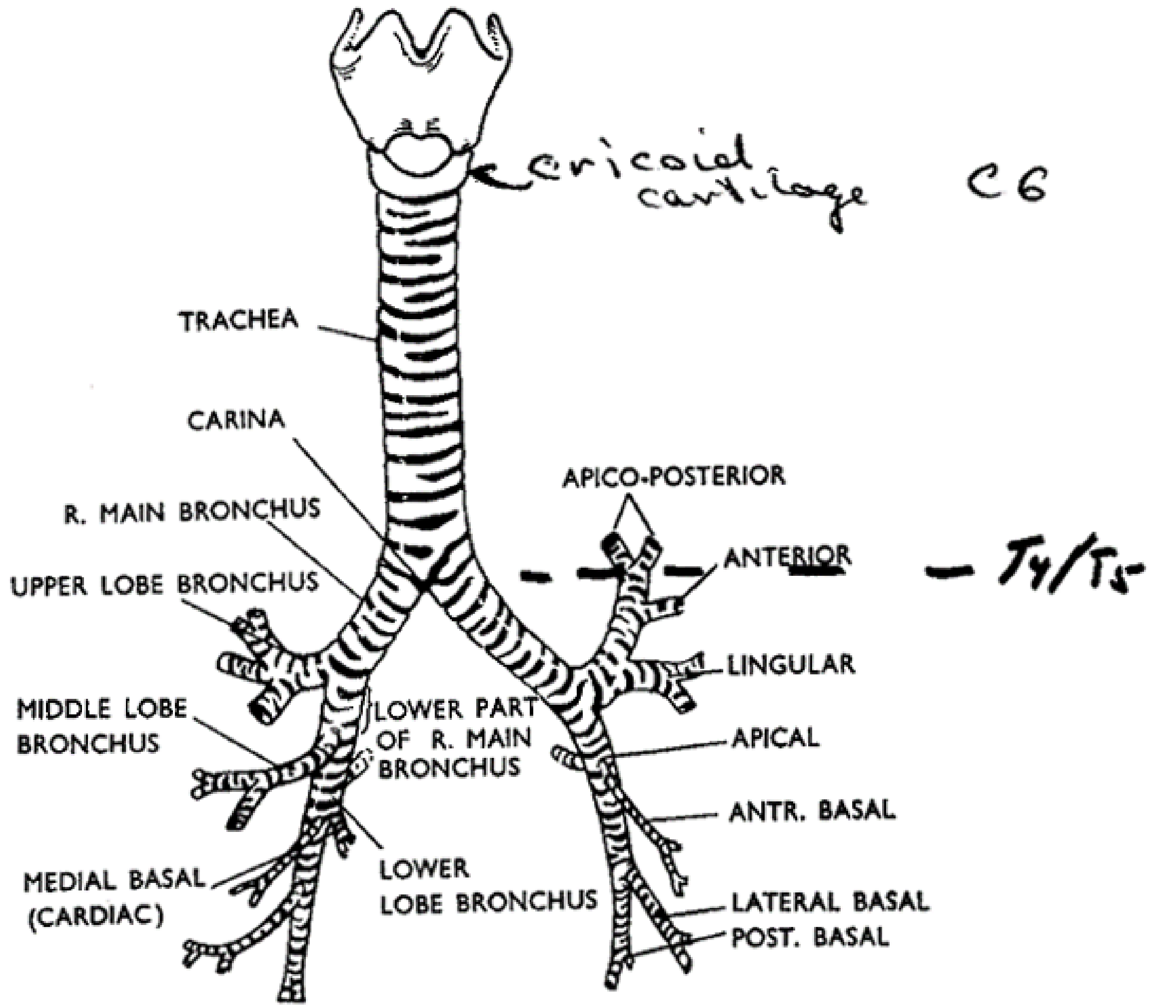
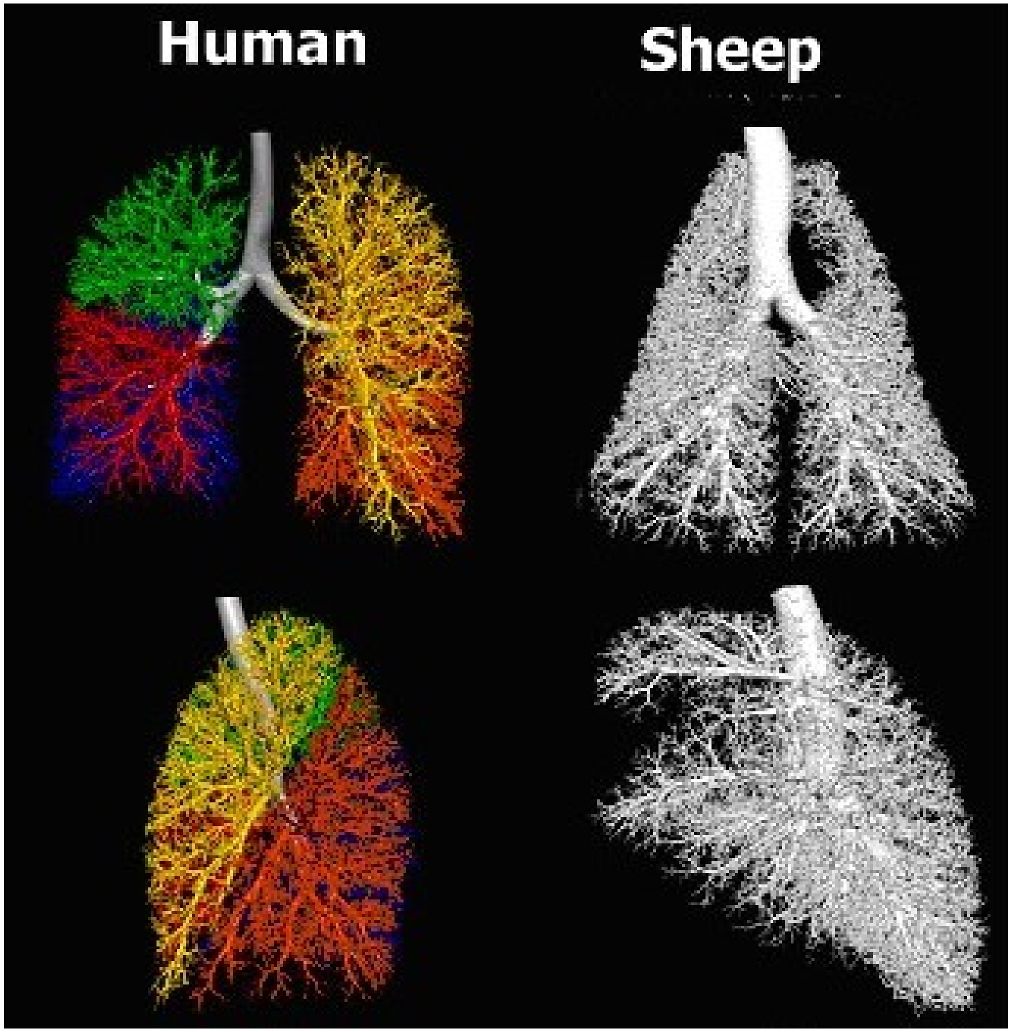


FIG. 13B

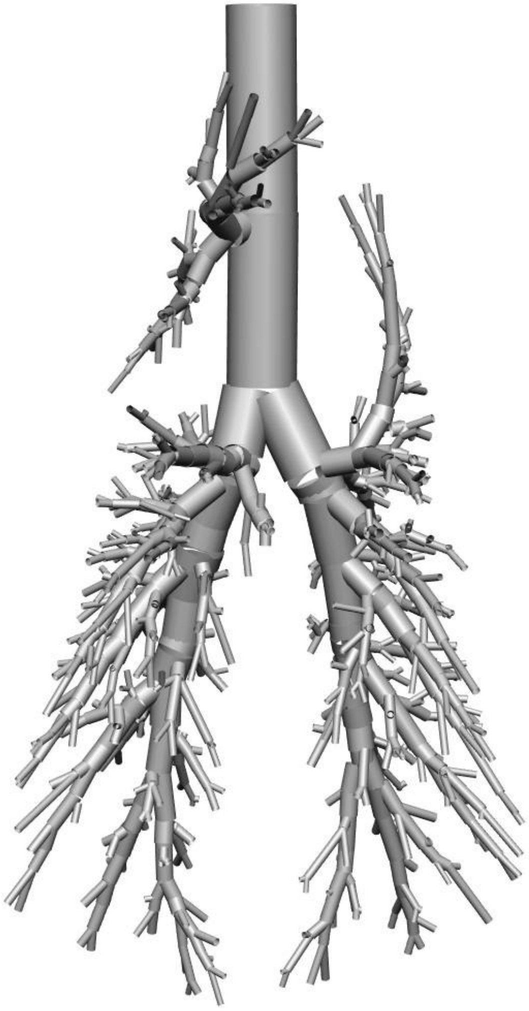
The trachea and main bronchi viewed from the front.

Clinical Anatomy, Ellis, 5th Ed., 1971

Monopodial vs. Bifurcating Airways



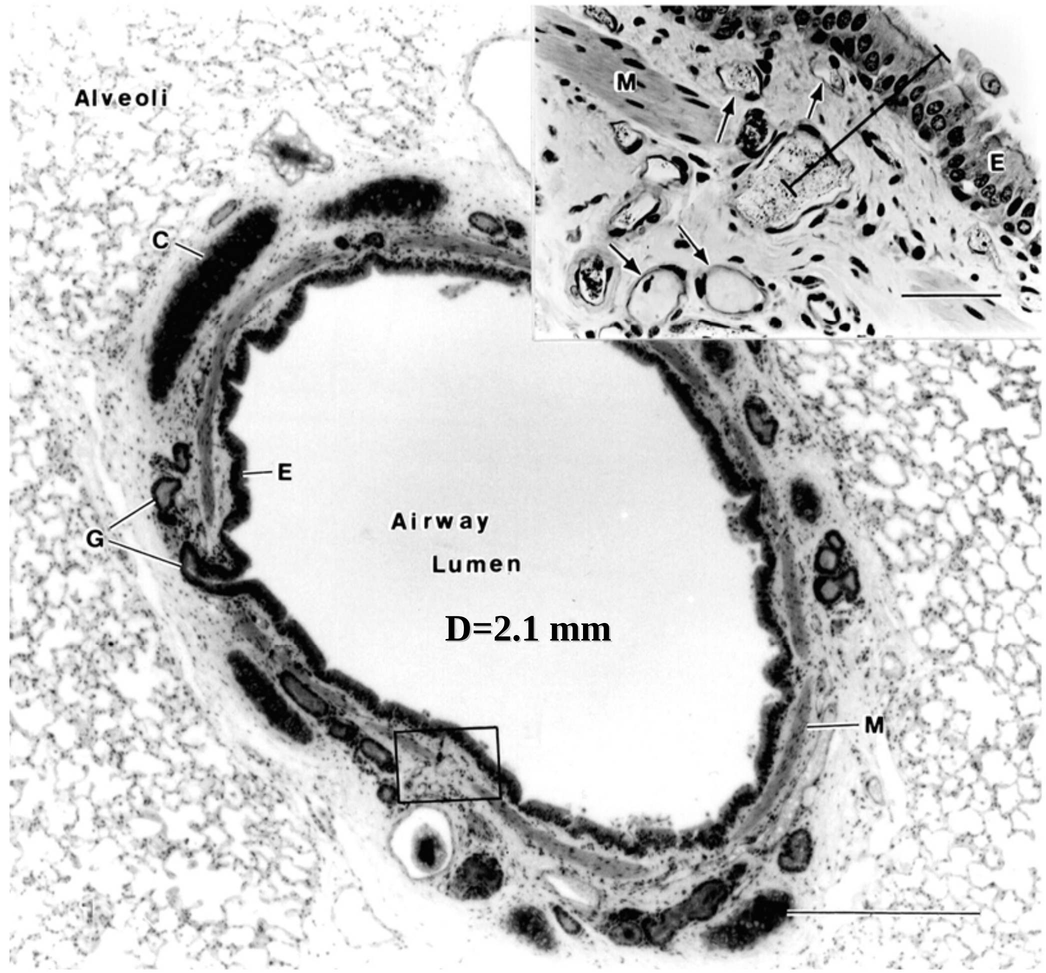
From the U. of Iowa



Monopodial structure of sheep airways

Conducting Airways

- Trachea, bronchi, small bronchi
- Cartilage
  - C-shaped in trachea
  - Irregular plates
- Cilia
- Goblet cells



Anderson 1998 (Courtesy of Dan Luchtel)

Airway Diameter vs Generation

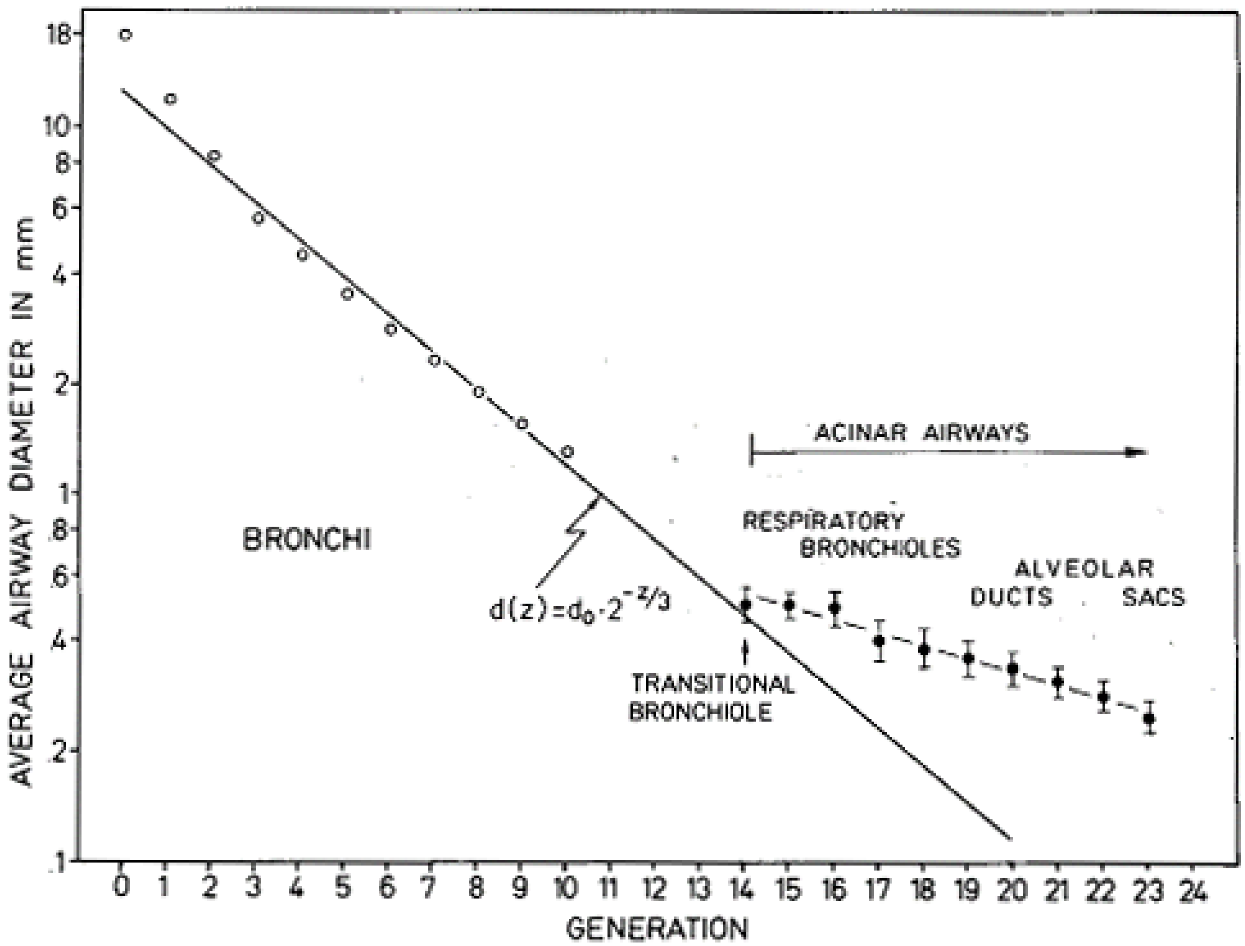


FIG. 6. Semilogarithmic plot of mean airway diameter versus generation. (From ref. 9.)

The Lung: Scientific Foundations,
Weibel, 1991

Airway Path: Weibel Model

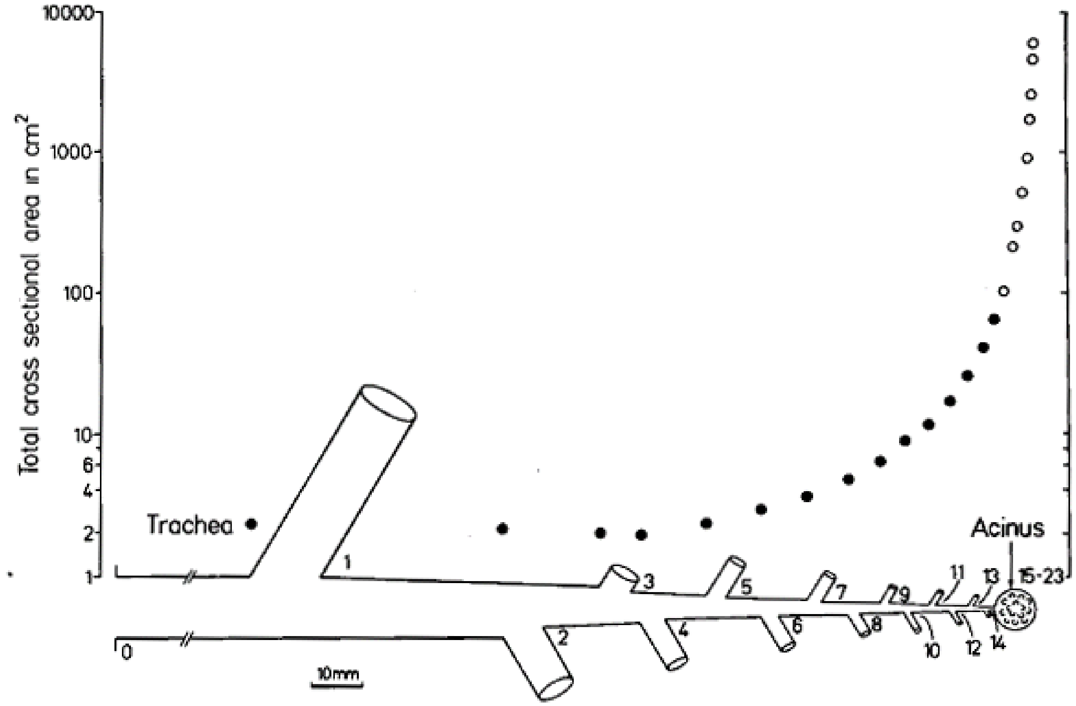
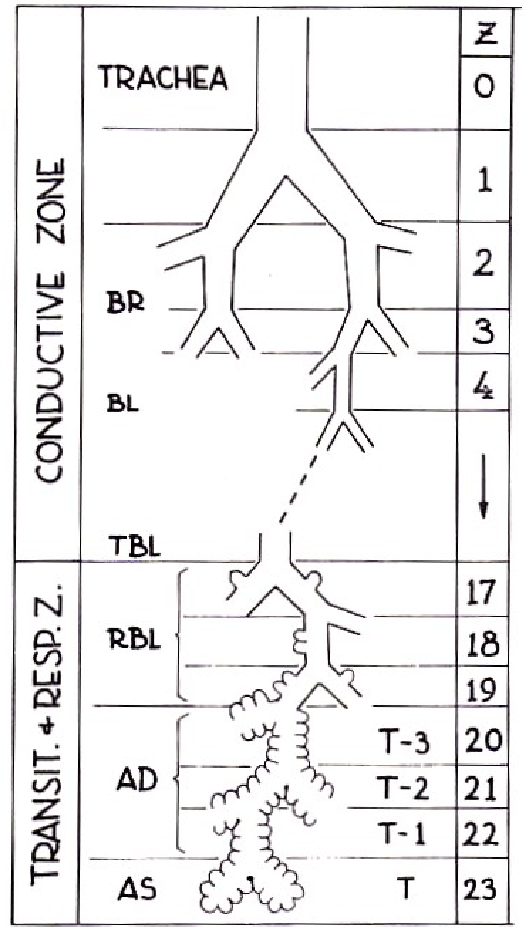
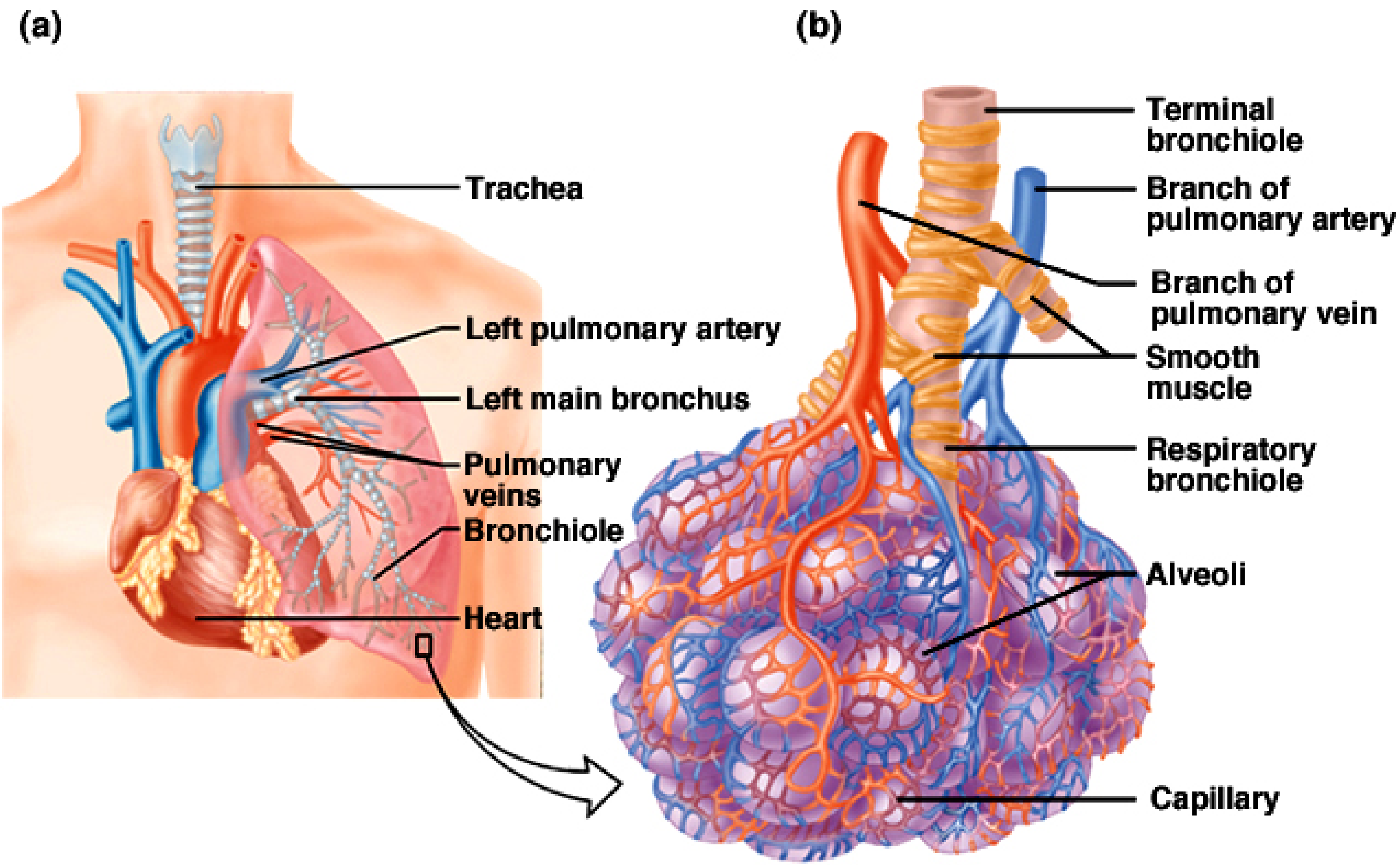


FIG. 7. Symmetric typical path model drawn to scale along abscissa, with increase of total airway cross-sectional area shown on logarithmic ordinate. Filled circles represent conducting airways, and unfilled circles represent acinar airways.



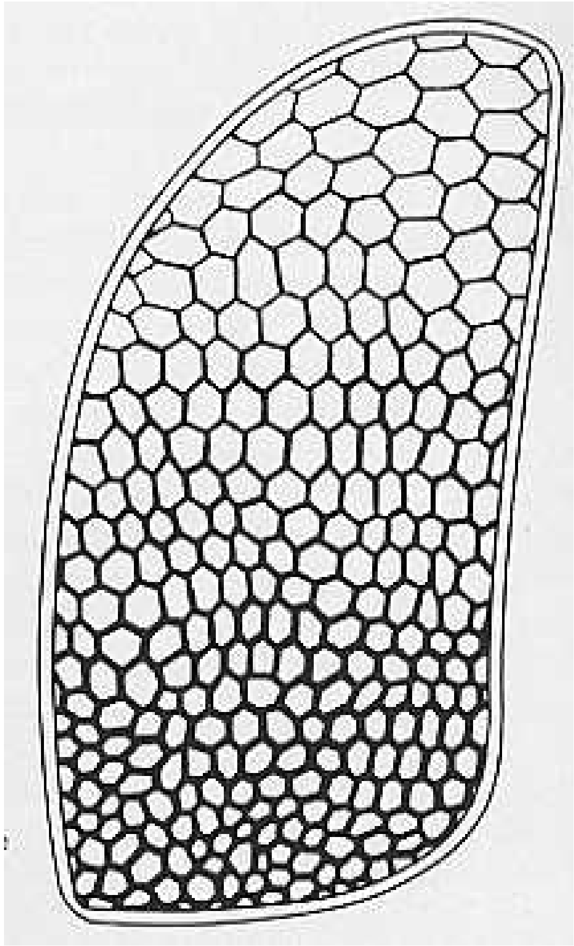
The Lung: Scientific Foundations,
Weibel, 1991

Respiratory Unit



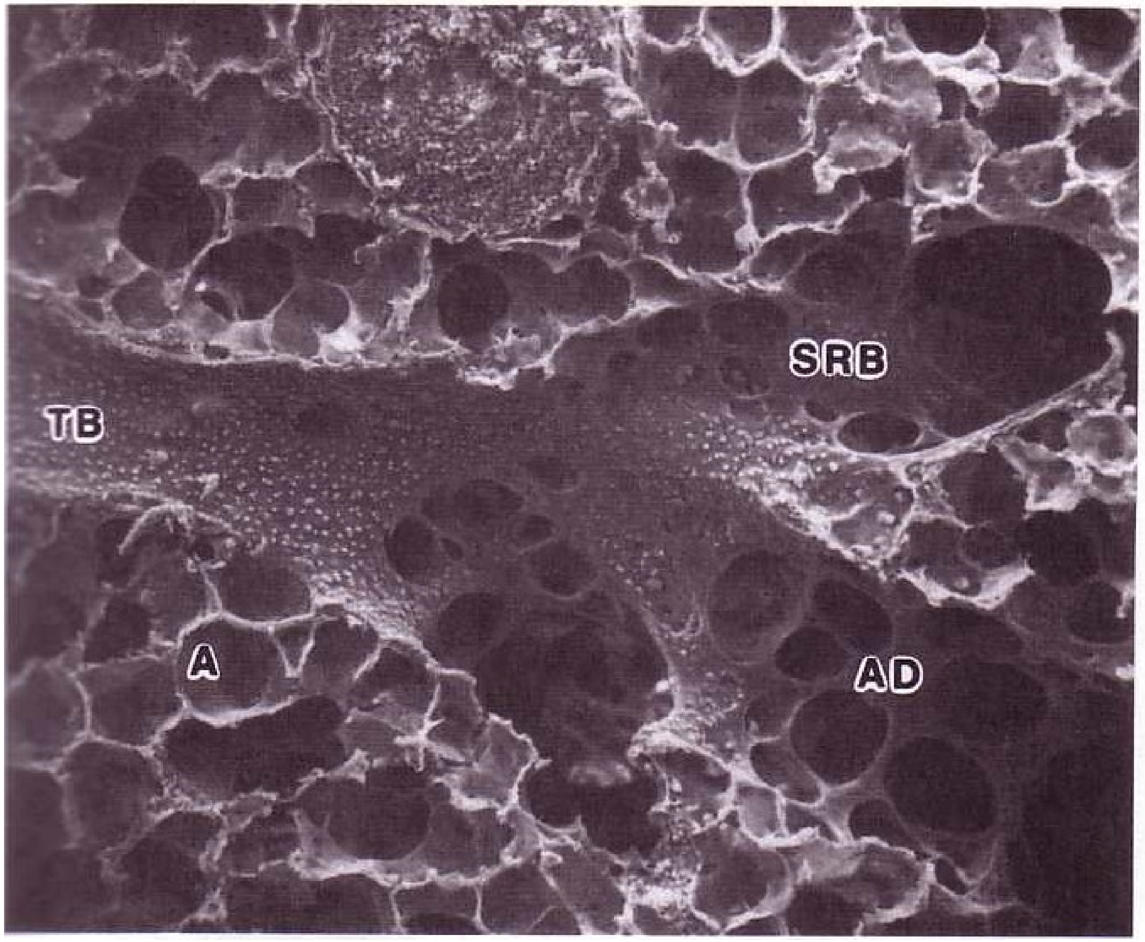
Static Lung Volumes

- Lung is easily extensible
- Alveoli in non-dependent regions tend to be larger than in dependent regions
- Lung is tethered



From Levitzky, Fig 5-5

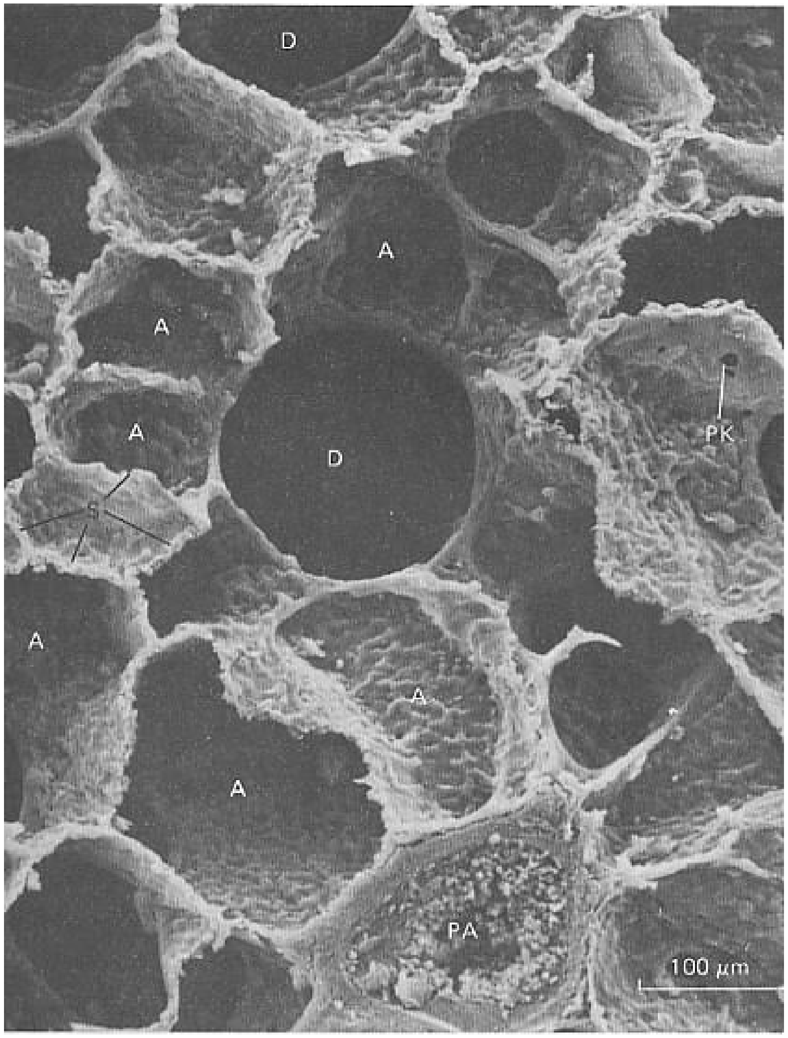
Respiratory Zone



Hlastala & Berger, Fig. 1-4

Airspace Microstructure

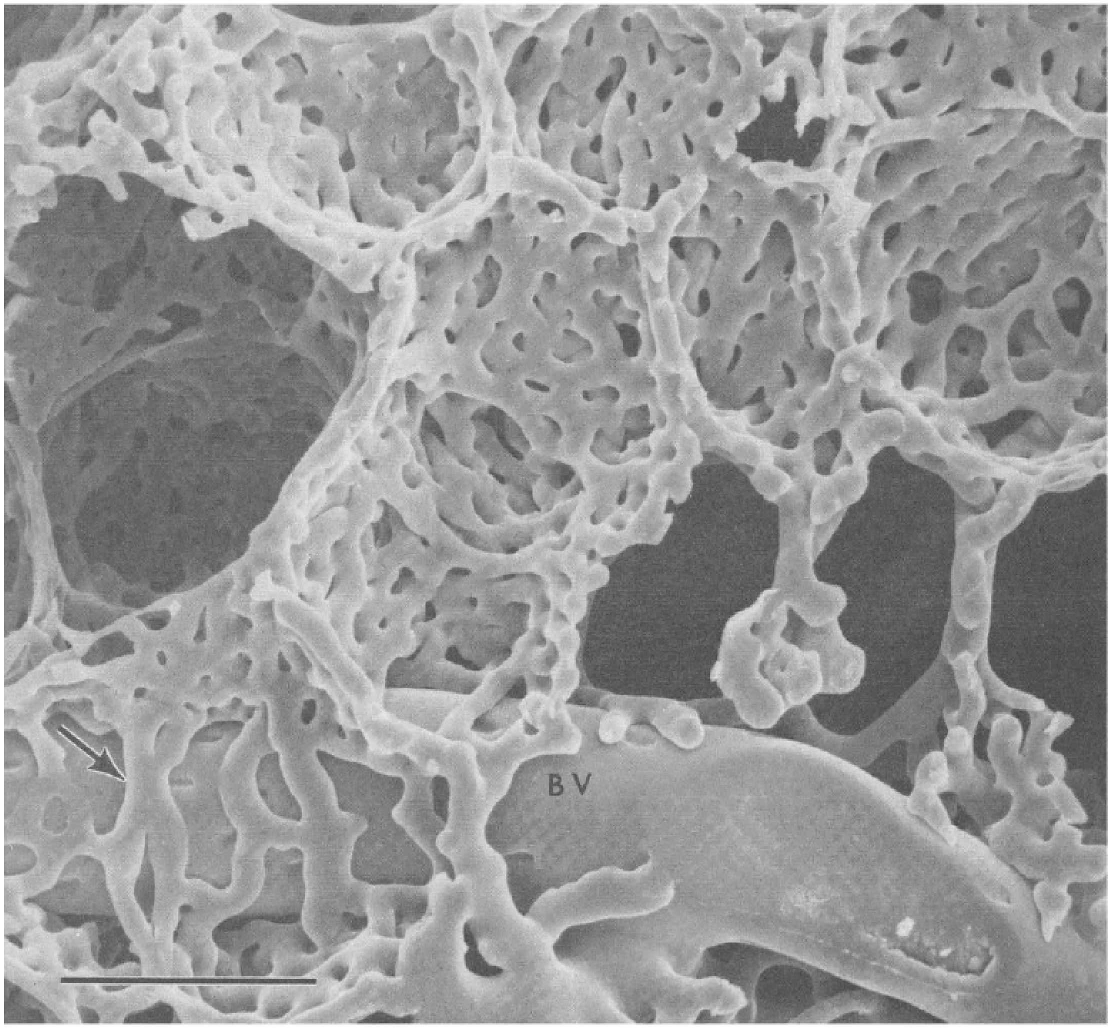
- Alveoli
- Alveolar ducts
- Pores of Kohn
- Liquid lining layer



Levitzky, Fig 1-2

Pulmonary Microcirculation Network

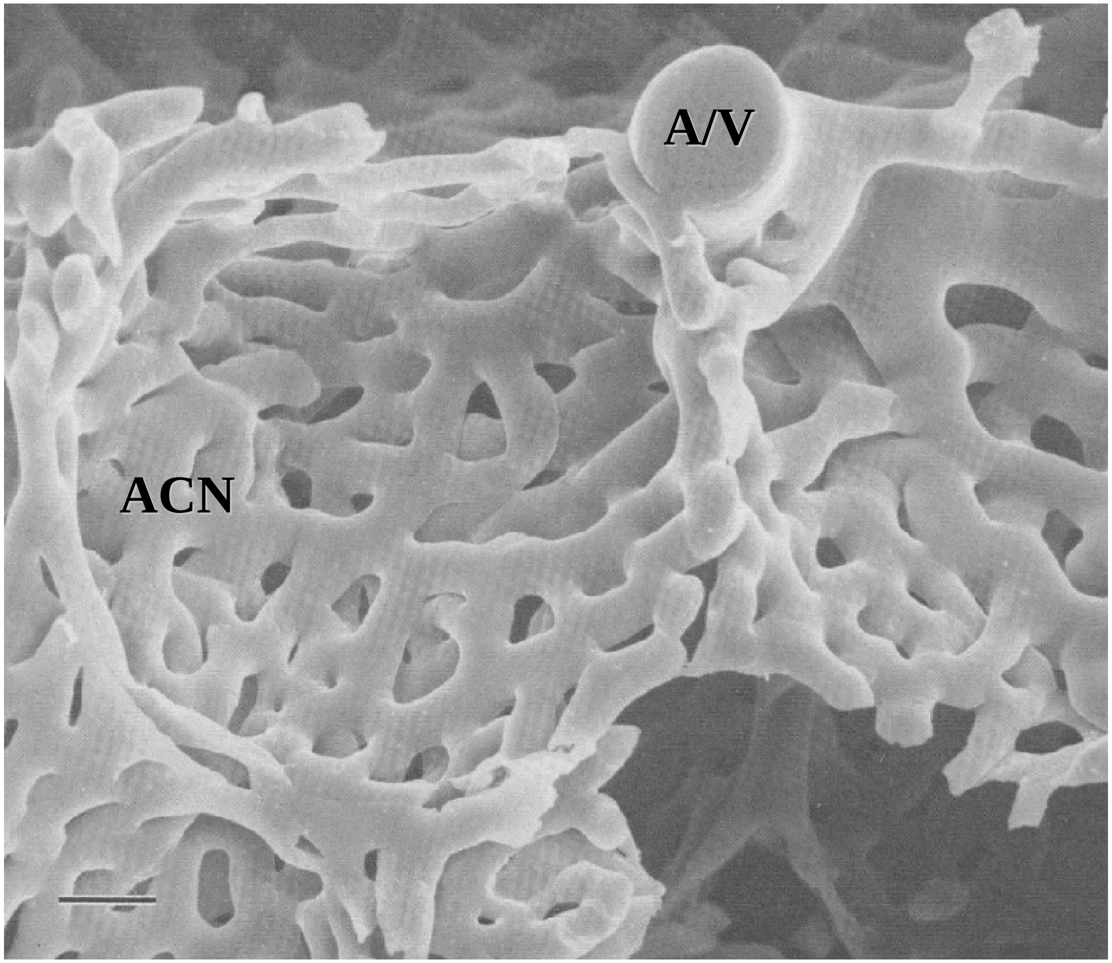
- Pulmonary capillaries encapsulate alveoli



Guntheroth et al. J. Appl. Physiol., 1982

Alveolar Capillary Network

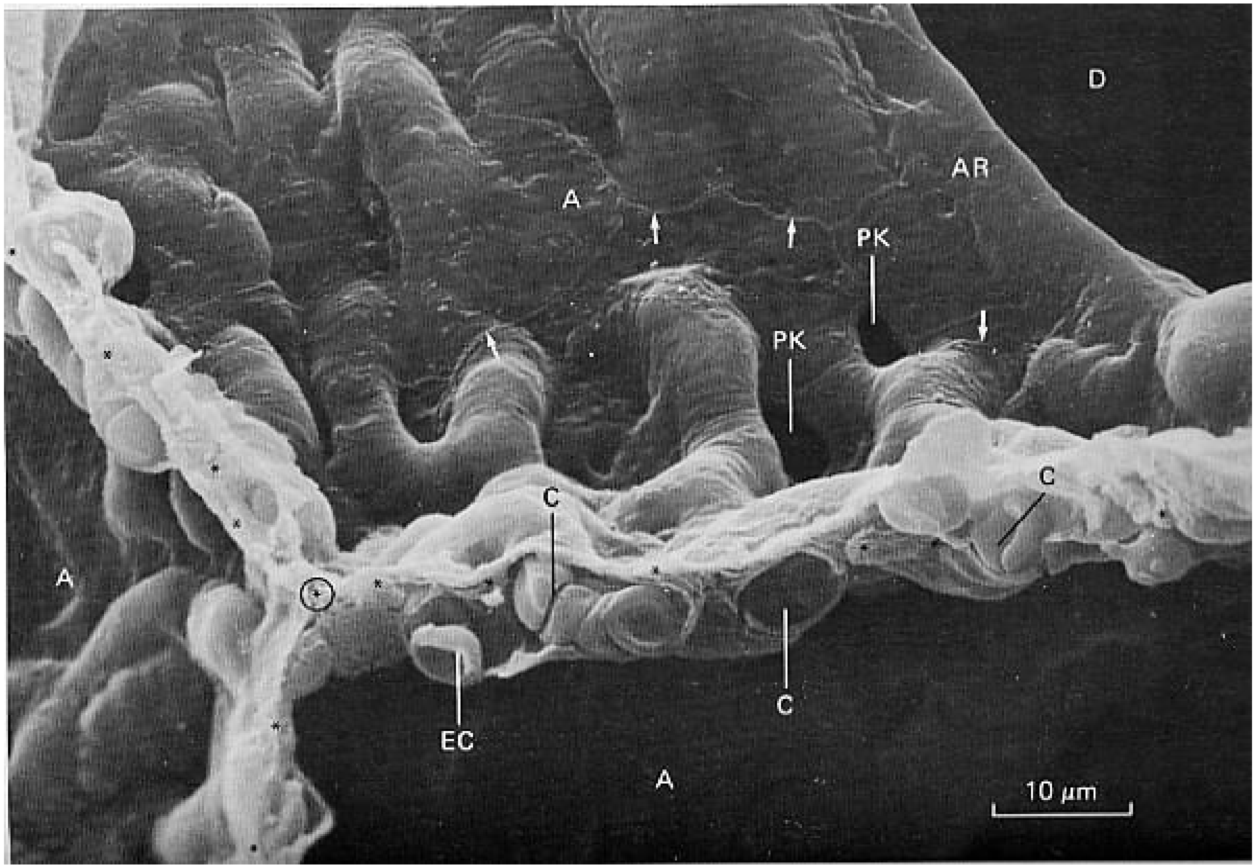
- Forms continuous sheet of blood



Guntheroth et al. J. Appl. Physiol., 1982

Cross-section of Microcirculation

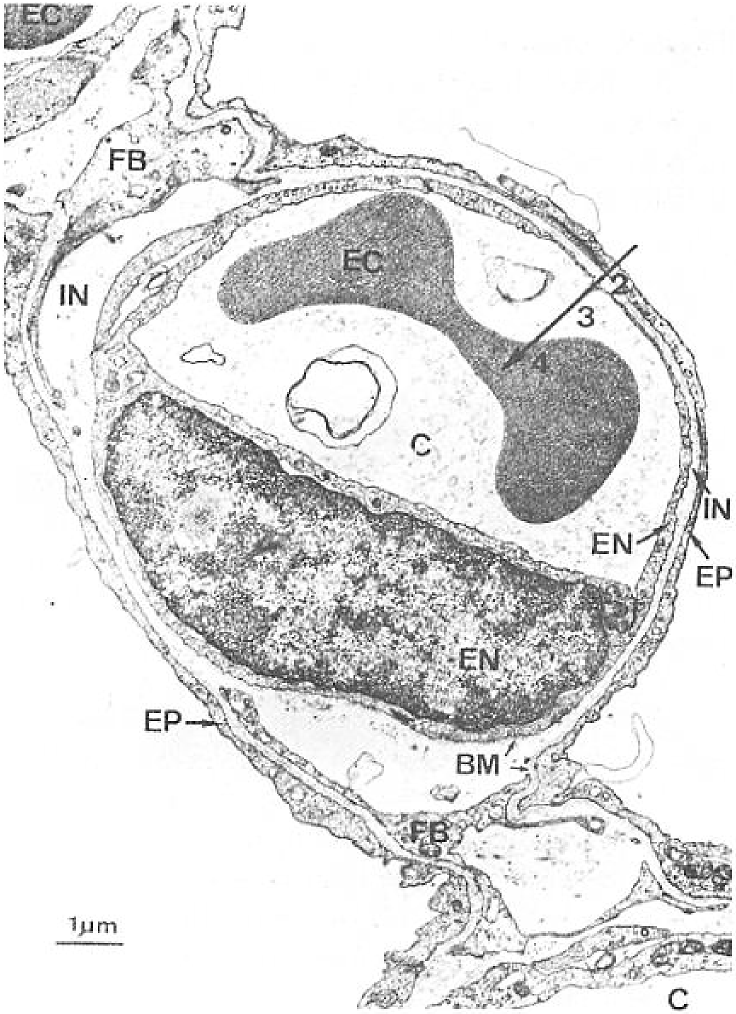
- Capillaries surround alveoli
- Sheet flow of blood



Levitzky, Fig 1-3

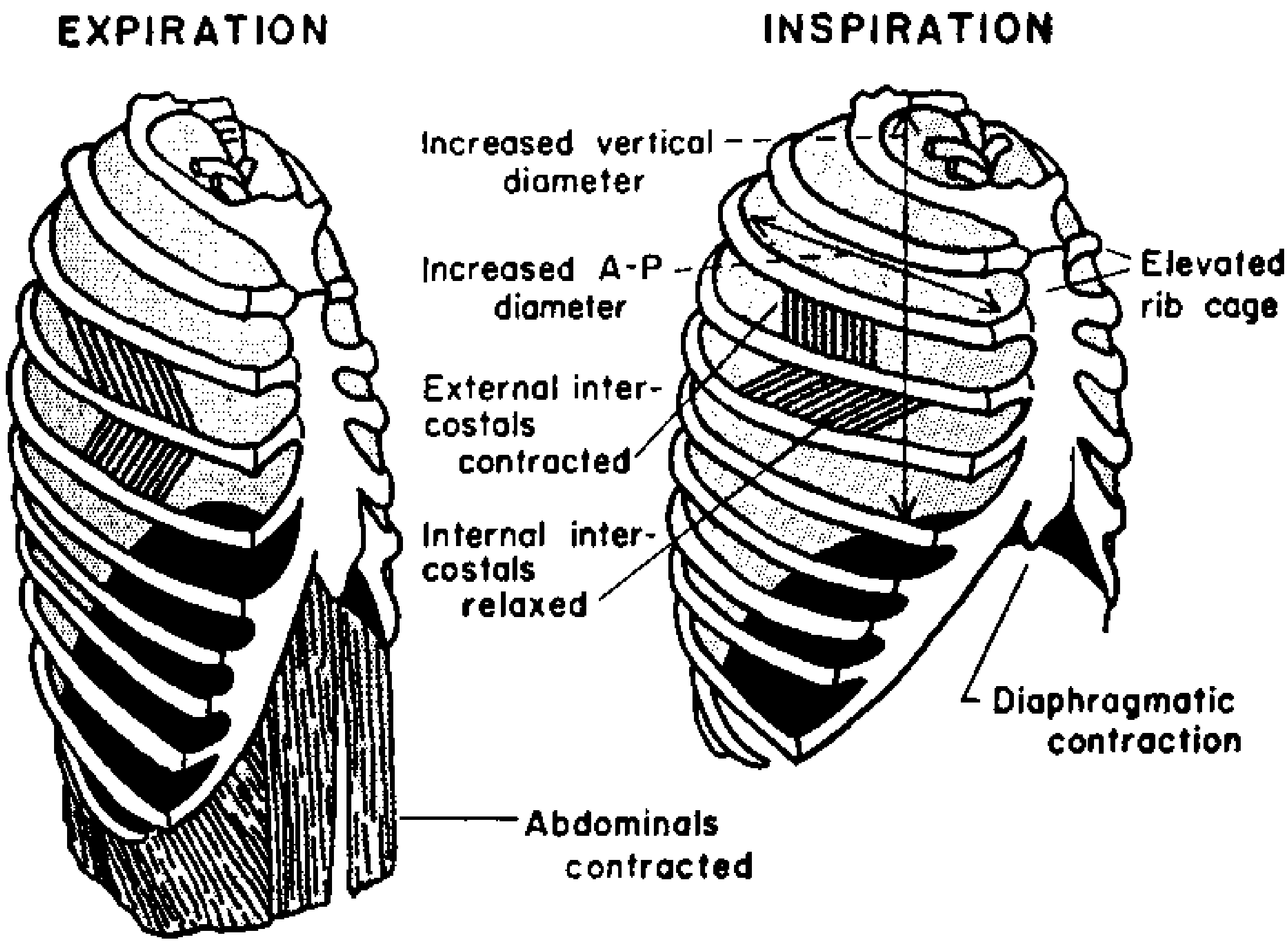
Diffusion Barrier

- Capillary cross-section
- Diffusion barrier
  - ~0.2-0.5 μm



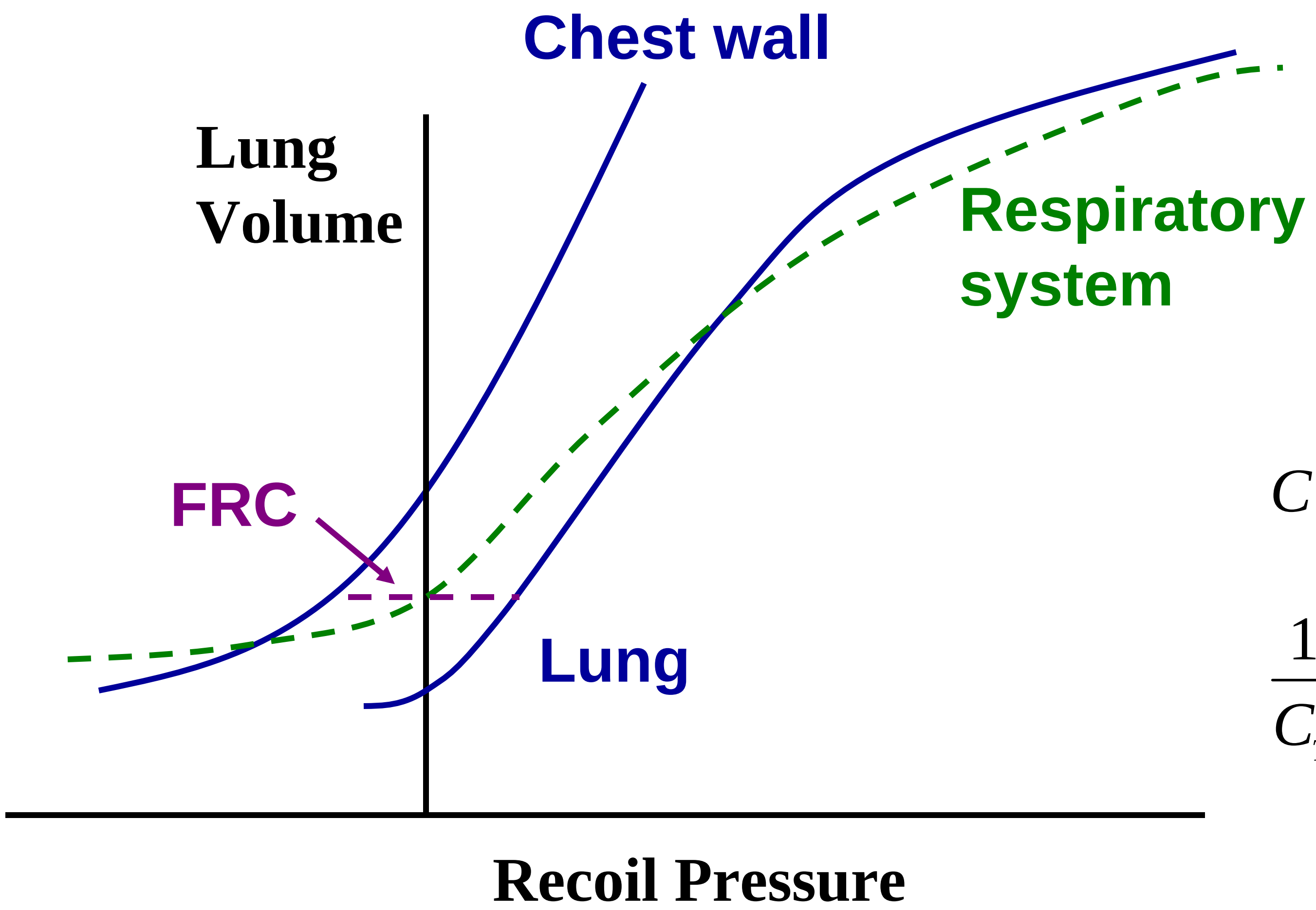
Levitzky, Fig 1-4

Rib Cage, Diaphragm and Lung



Textbook of Medical Physiology, Guyton, 4th Ed., 1971

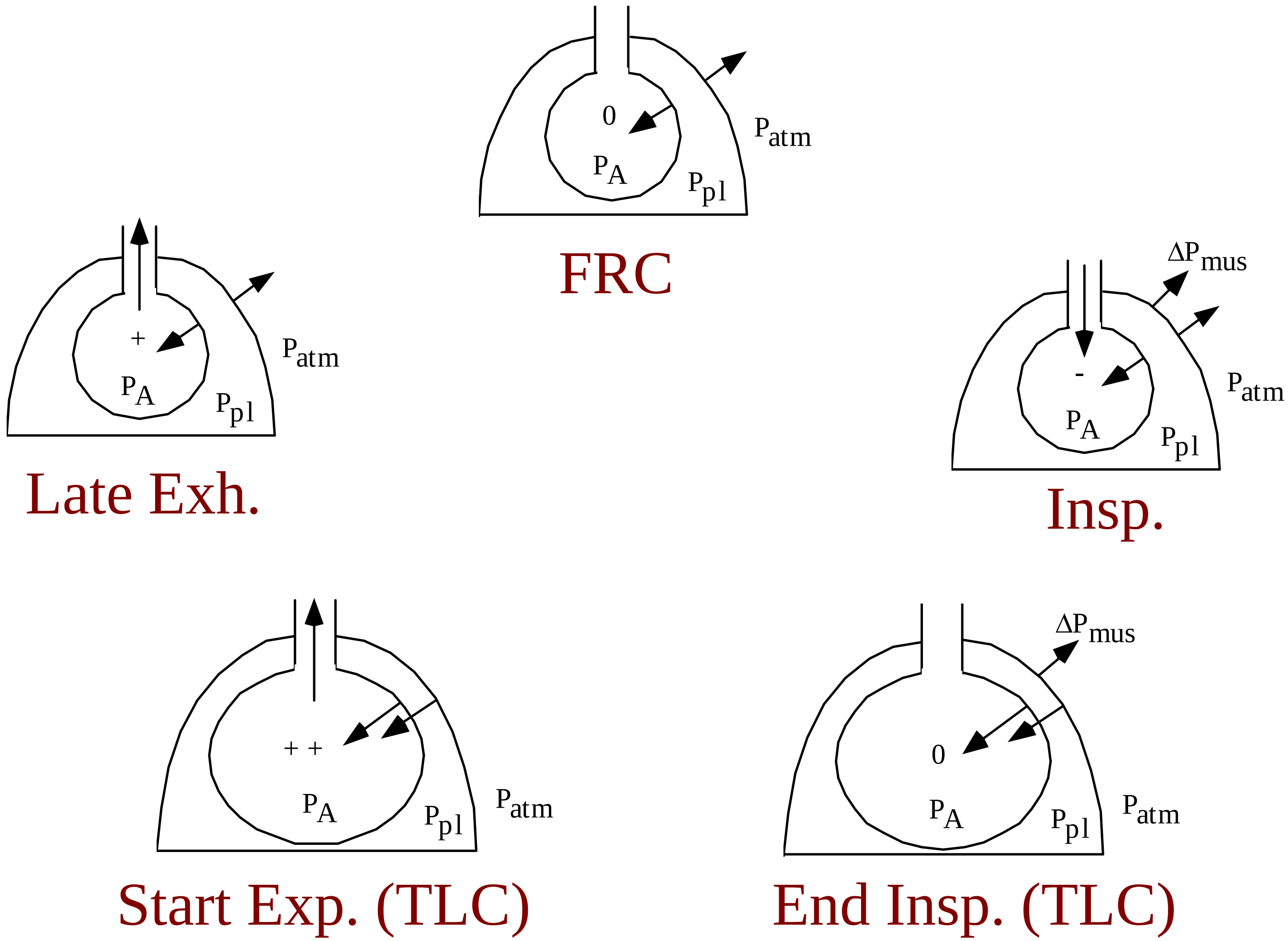
Lung and Chest Wall



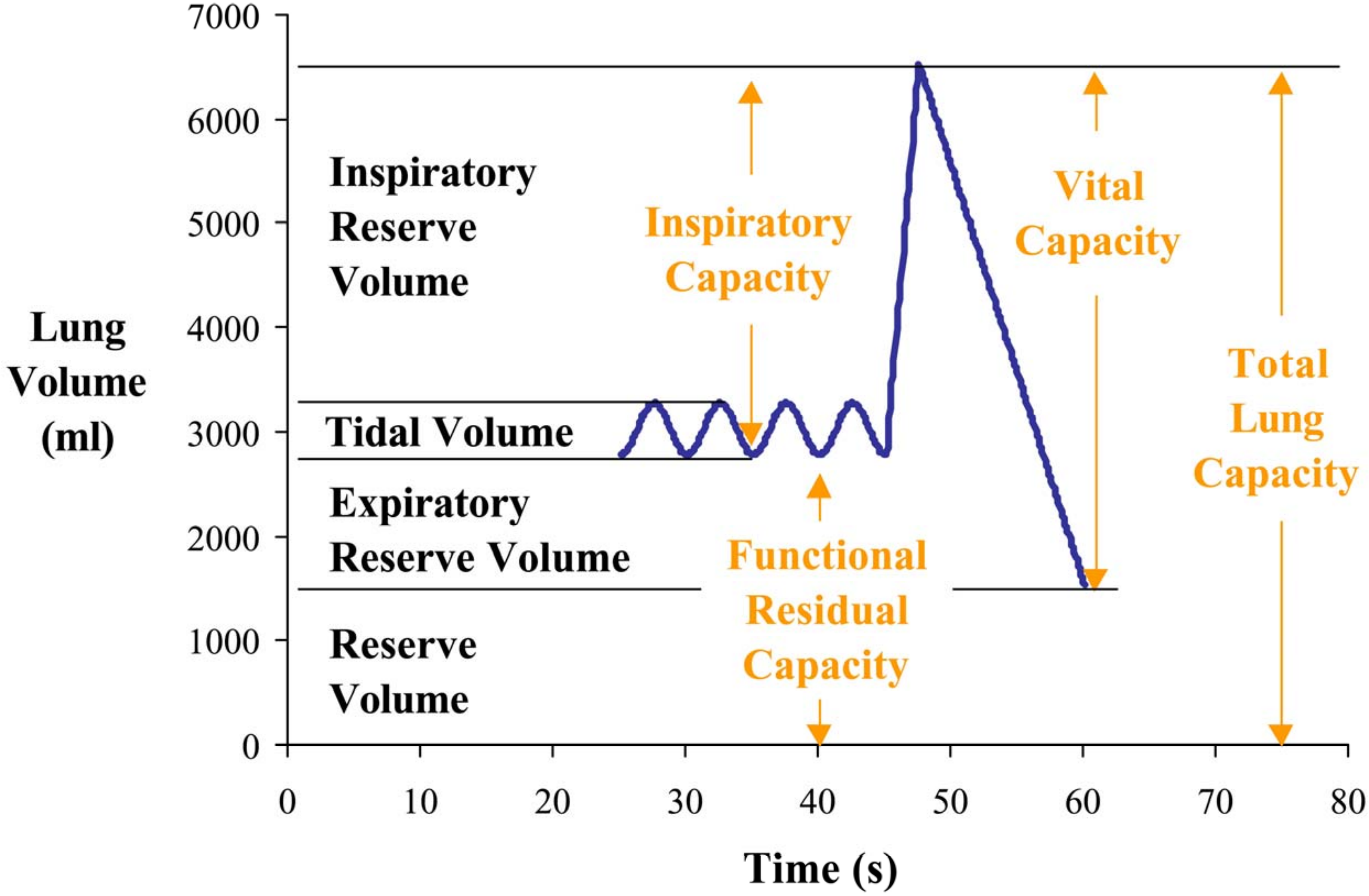
$$C = \frac{\Delta V}{\Delta P}$$

$$\frac{1}{C_T} = \frac{1}{C_L} + \frac{1}{C_{CW}}$$

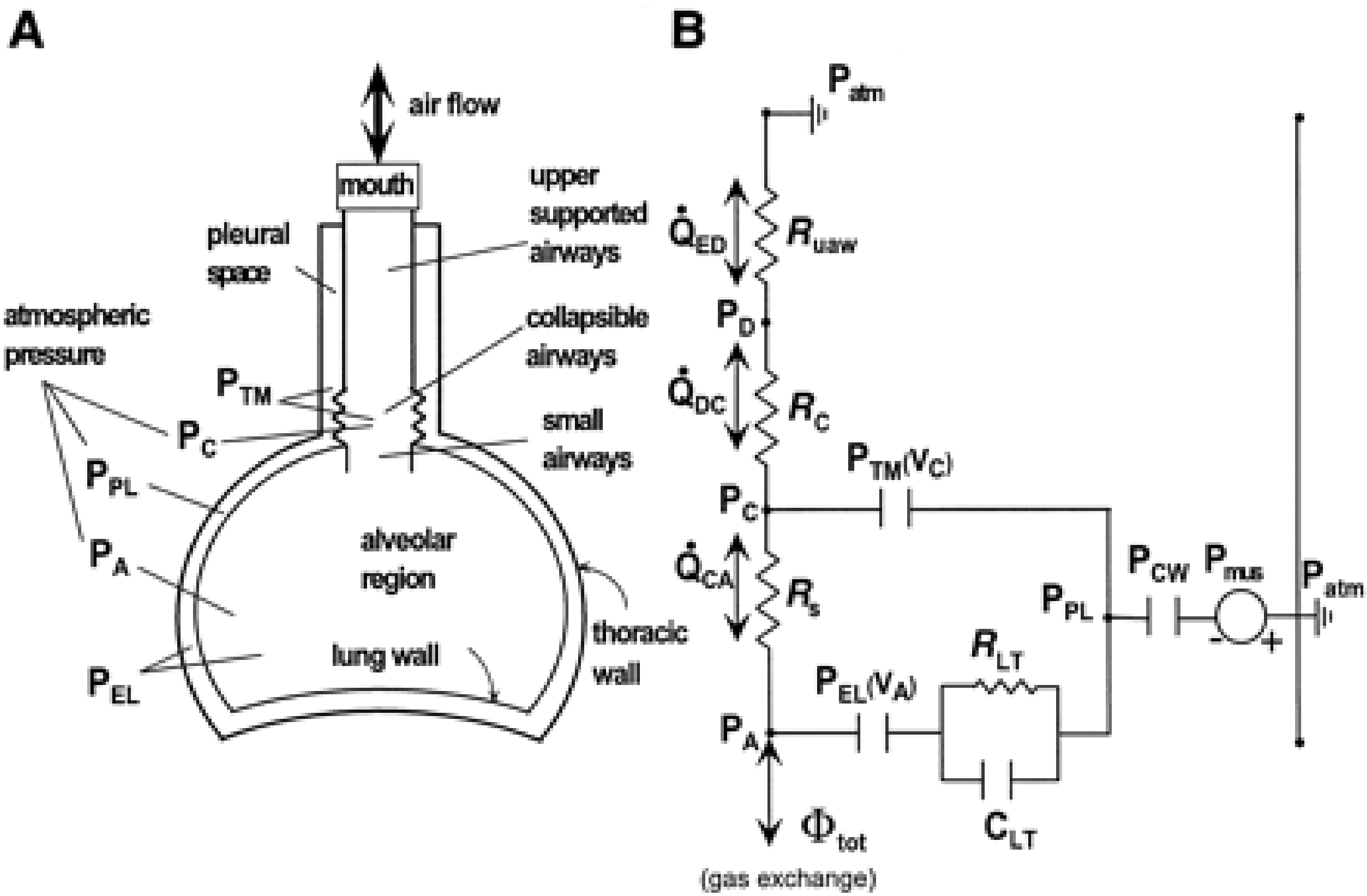
Relative Pressures of the Breathing Cycle



Lung Volumes

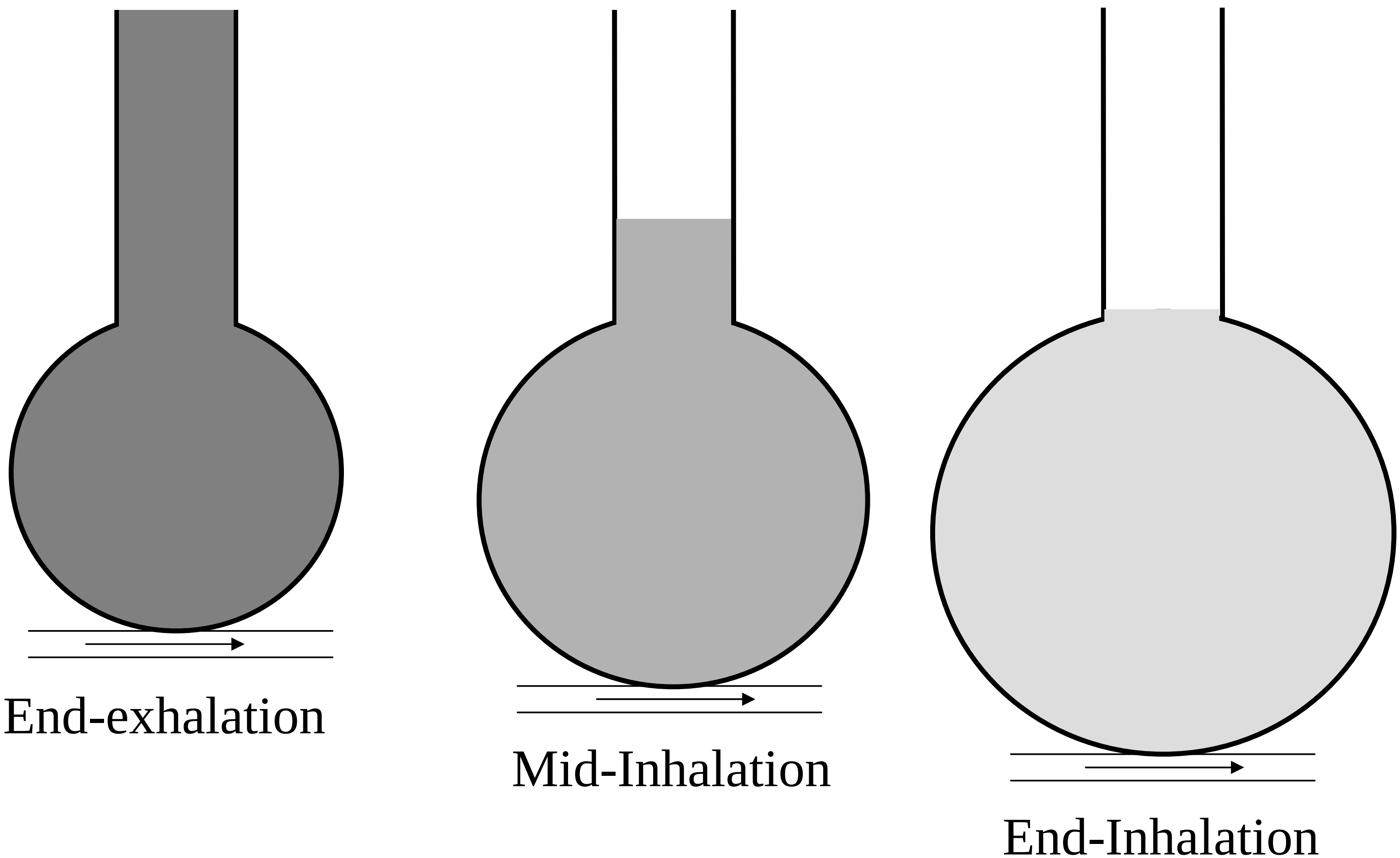


A Lumped Parameter Analogue



Lu, APJ Heart, 2001

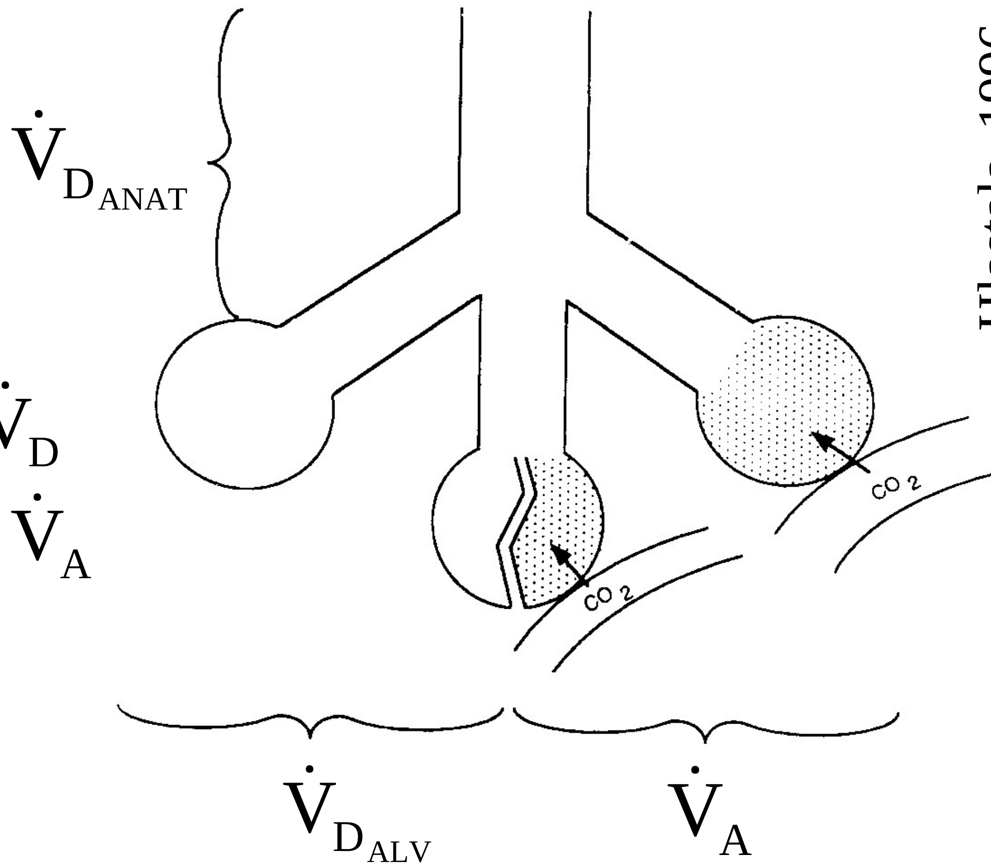
Airways and Ventilation



Dead Space

- Dead space: V_D
- Wasted Ventilation: $\dot{V}_D$
- Alveolar Ventilation: $\dot{V}_A$

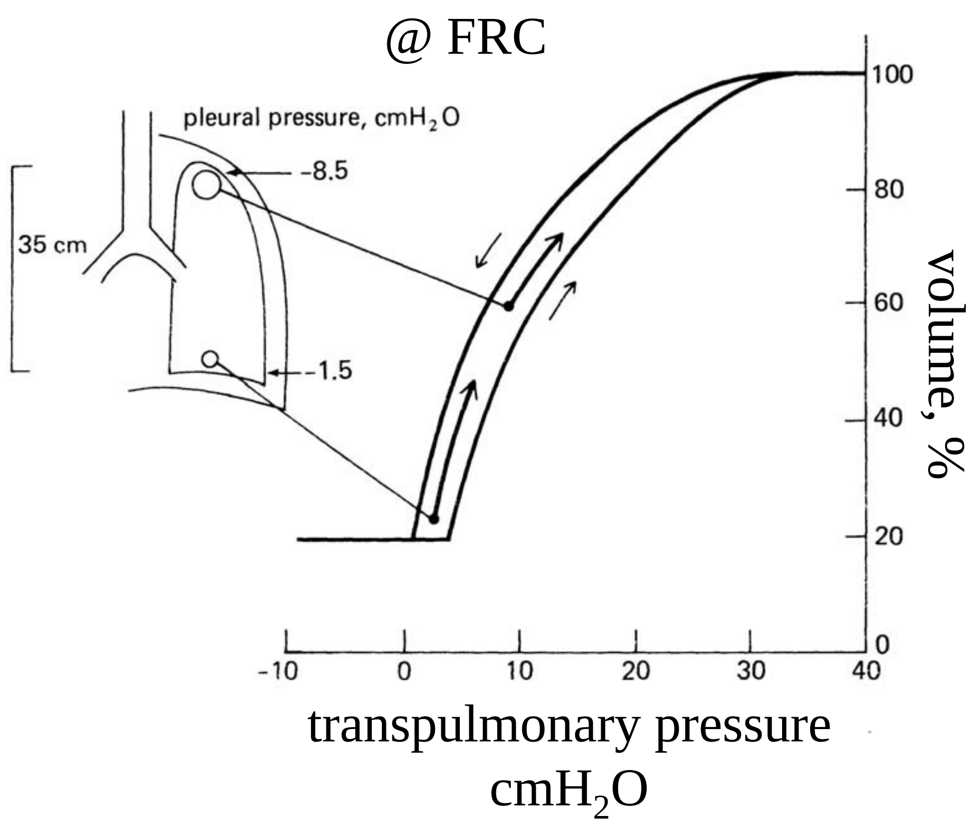
$$V_{D_{physiol}} = V_{D_{anat}} + V_{D_{alv}}$$



Hlastala, 1996

Ventilation Heterogeneity

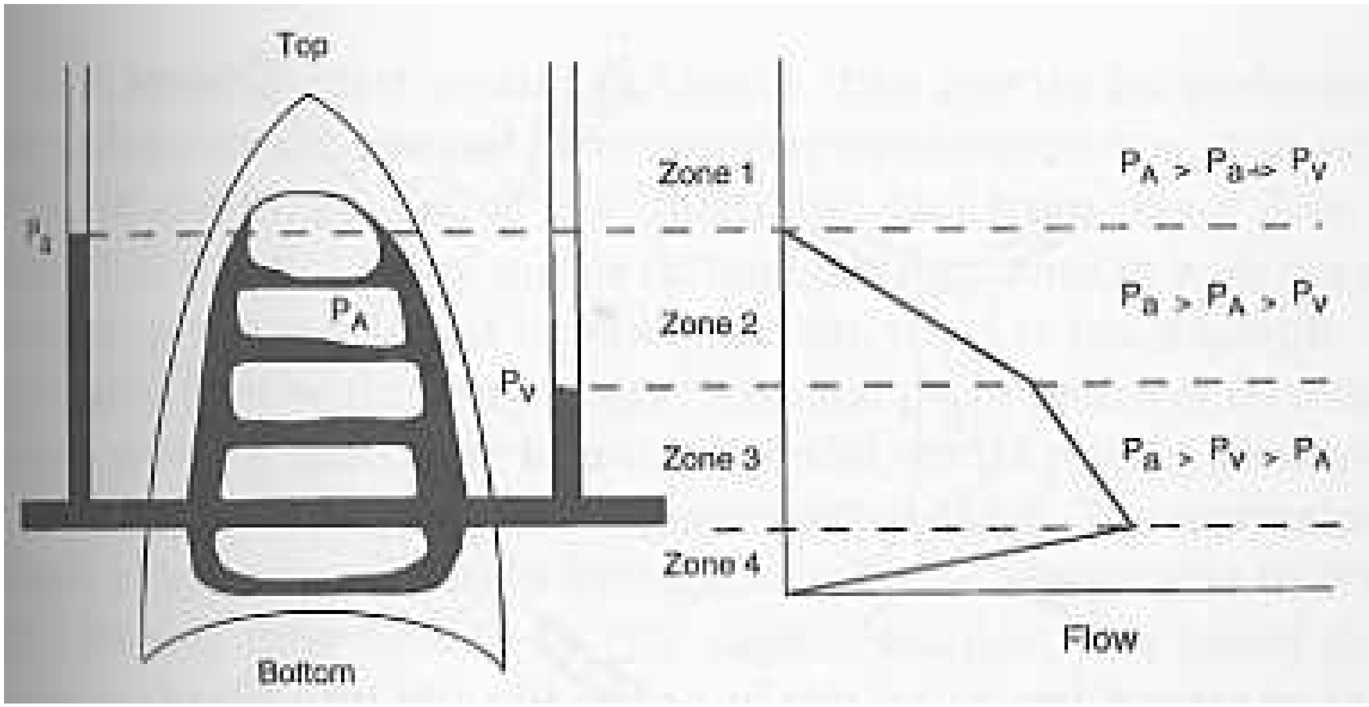
- Gradient in intrapleural pressure (~0.2 cmH_2O/cm)
- Larger transpulmonary pressures in non-dependent regions

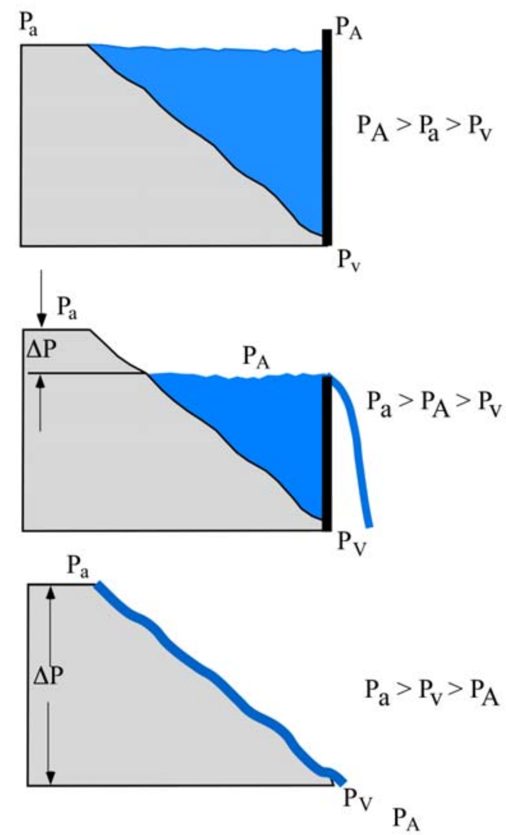


Levitzky, 1991

Pulmonary Perfusion: Zone Model

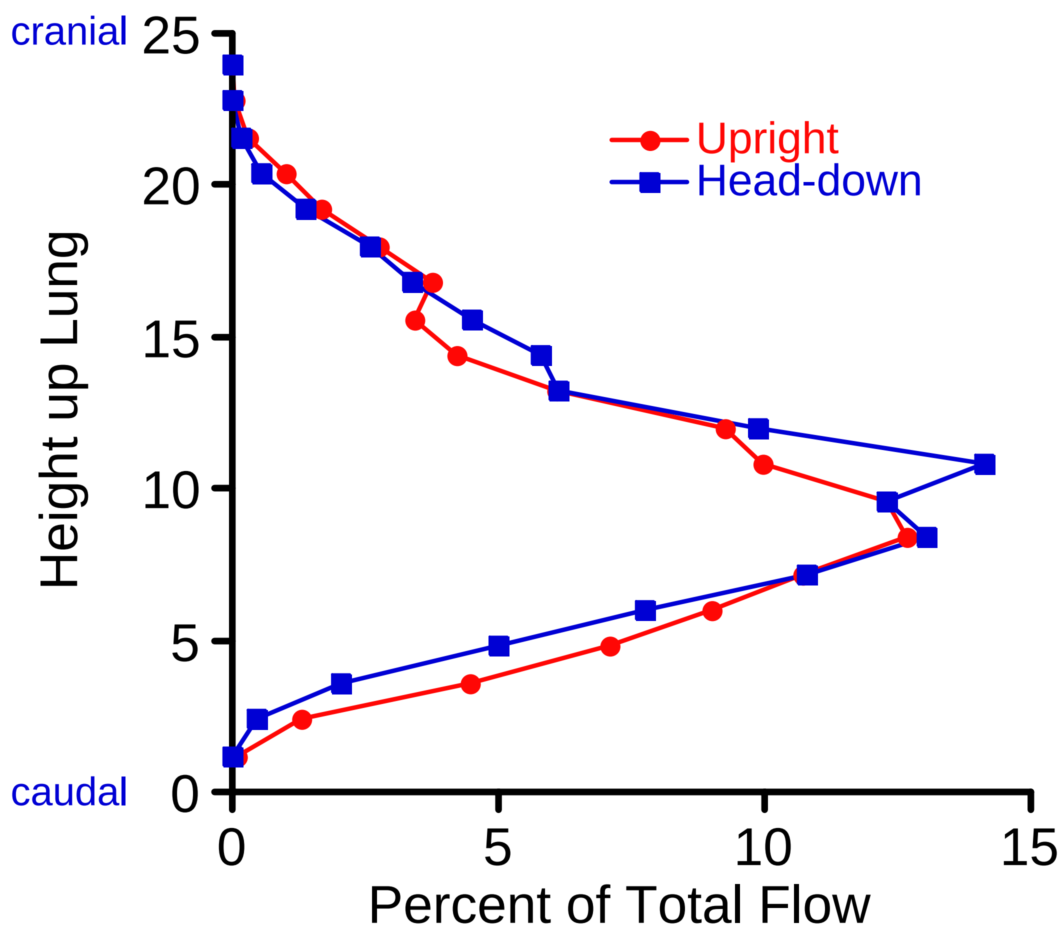
Hlastala & Berger, 1996





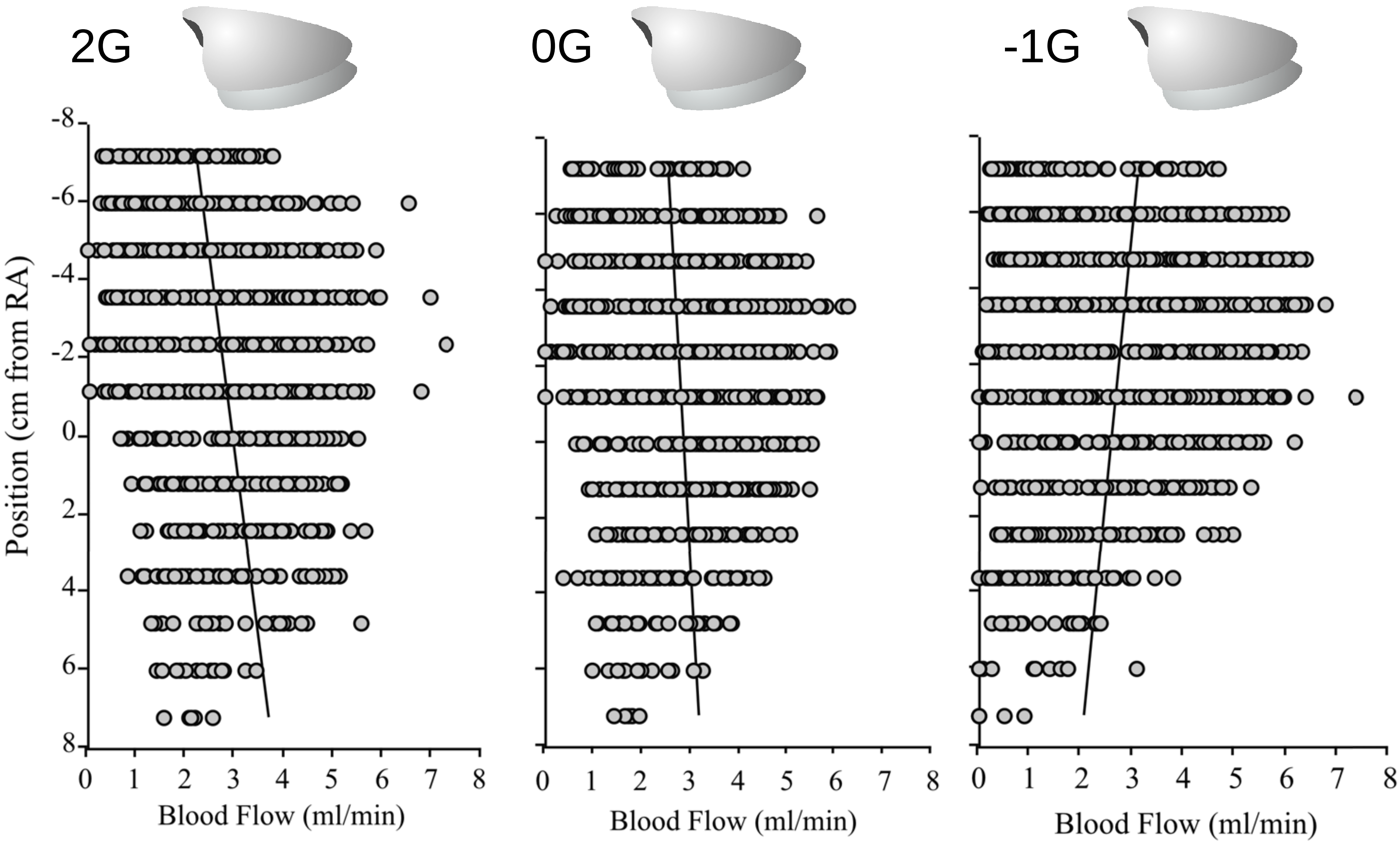
Then, there is the other point of view…

Upright vs Head-down

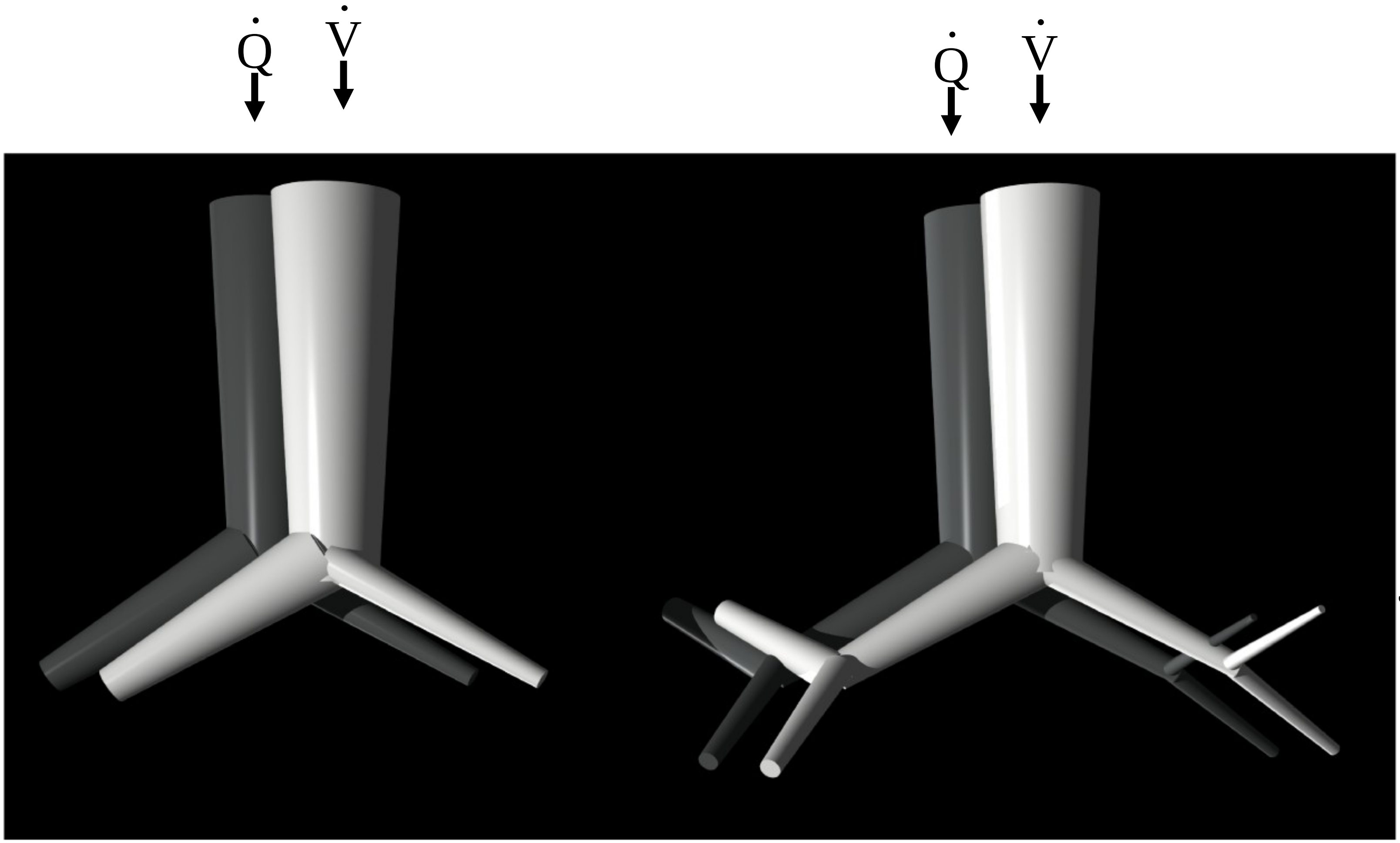


Data from Robb Glenny

Gravity Effects

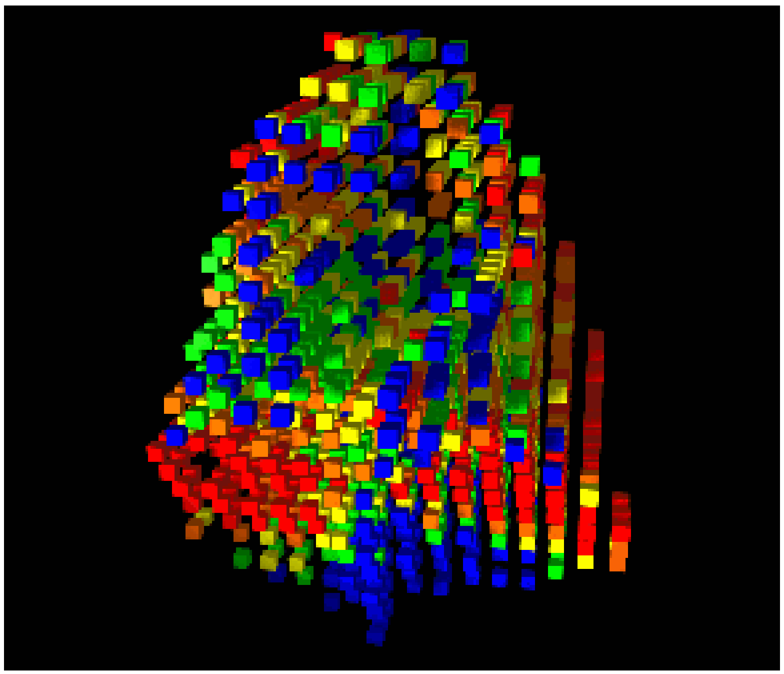


Ventilation and perfusion

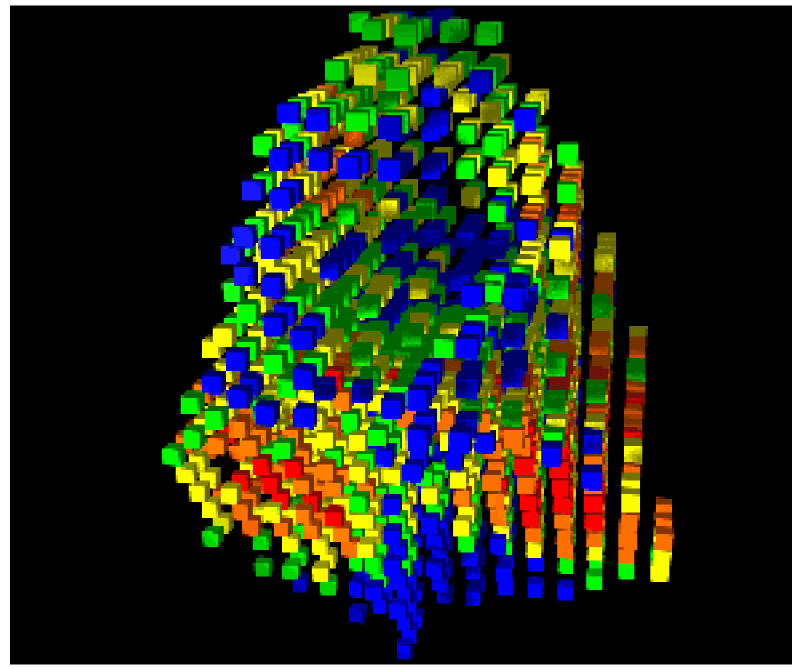


Courtesy of Dave Frazer

Ventilation/perfusion matching



V



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Courtesy of Bill Altemeier

Pulmonary Parameters

Parameter	Normal Value
Respiratory Rate	12-15 per min
Tidal Volume	500 ml
Dead space volume	150-200 ml
Compliance	200 ml/cmH_2O
Cardiac Output	100 ml/s
O_2-blood sol. (P>150)	1.18E-6 M/mmHg
O_2-blood sol. (P~40)	2.35E-5 M/mmHg
CO_2-blood solubility	3.1E-4 M/mmHg
Alveolar PO_2	100 mmHg
Alveolar PCO_2	40 mmHg

Why Model the Lung?

Summarize findings

Simplify complex system

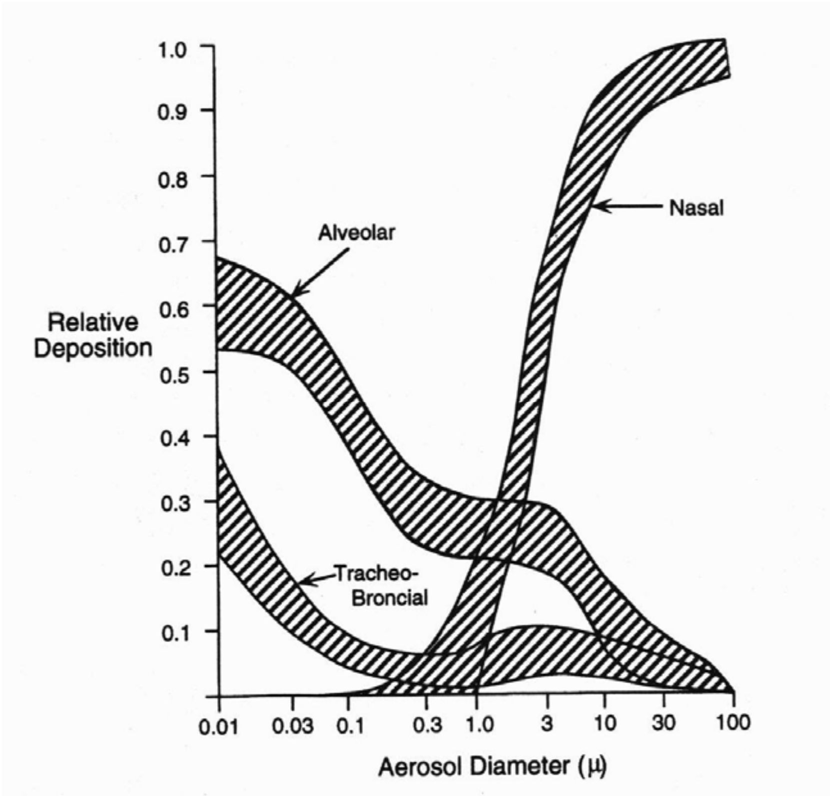
Predictions – inaccessible for measurement

Develop new research strategies

Type of Mathematical Models

Mathematical Complexity	**Description**
Algebraic	Steady state, flow-through or unidirectional flow (resp. half cycle); e.g., MIGET
Ordinary Differential Equation (ODE)	Oscillatory flow; Simple lung mechanics
Systems of ODEs	Effects of spatial and temporal heterogeneity on lung function e.g., ventilation, perfusion, and diffusion heterogeneity on gas exchange
Partial Differential Equation (PDE)	Trumpet model; Convection-diffusion; Highly reactive gas uptake in airways
Systems of PDEs	Combined physics; Mass, momentum & energy transport; aerosol transport, airway exchange

Aerosol Deposition



<u>Mechanisms</u>

- Diffusion
- Sedimentation
- Impaction

Aerosol Diameter

- Key Factor

Model Yeh et al, 1980

Aerosol Deposition Model - Inhalation

Yeh et al, 1980 and Schum et al, 1980
Weibel 1963 – Airway dimensions
Modified to single inhalation: Drug & Steam delivery

<u>Deposition Probability</u>

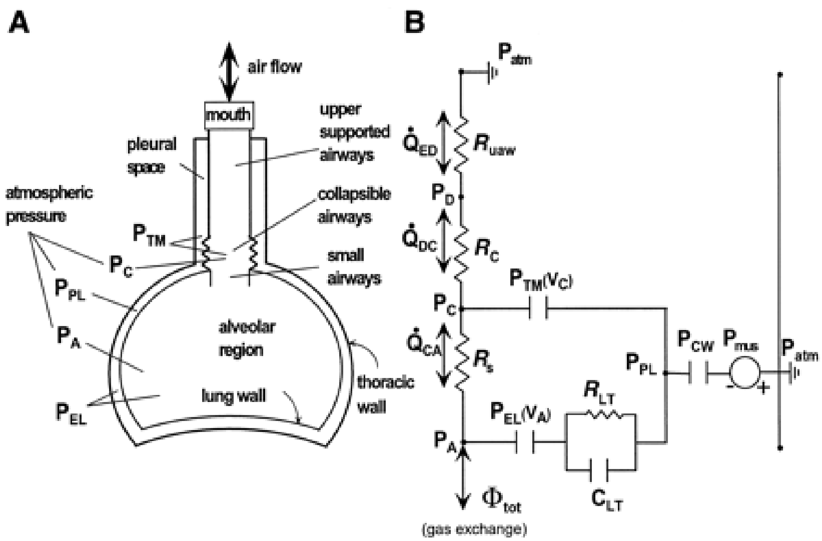
- Diffusion
- Sedimentation
- Impaction

$$P(n) = P_D + P_S + P_I - P_D P_S - P_D P_I - P_S P_I + P_D P_S P_I$$

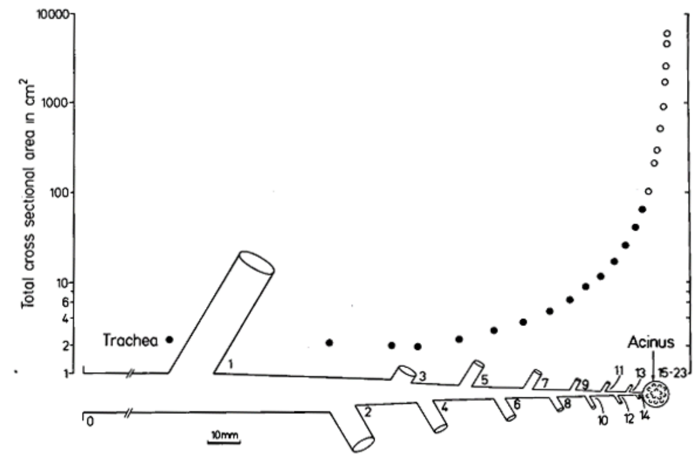
$$Xp(n) = [1 - P(n)] \cdot Xp(n-1)$$

Examples of Mathematical Models

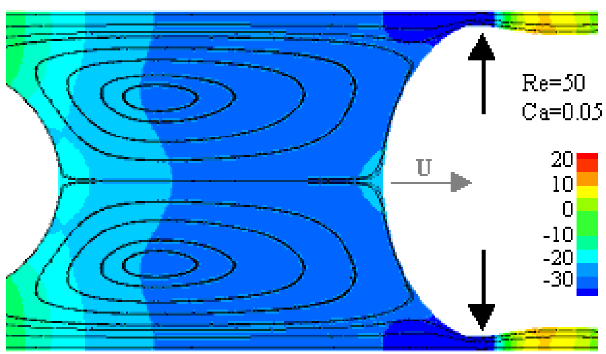
<u>Systems of ODEs</u>



<u>PDE</u>



<u>System of PDEs</u>



Lung Model Progression

Series Comp.

Parallel Comp.