Respiration: ventilation

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Abstract

Ventilation is the process by which air moves into and out of the lungs and is made available for gas exchange. Weibel's description divided the lungs into a conductive zone and a respiratory zone of 23 generations of dichotomously branching airways. Gas flow within the proximal airways is in the form of bulk movement and via diffusion in the distal airways. Resistance to gas flow in the airways is determined by a number of factors. Airway radius is the most important factor influencing resistance and gas flow changes from being turbulent proximally to laminar distally. Inspiration is an active process. The diaphragm is the main muscle of inspiration. Expiration is normally a passive process during quiet breathing but requires energy expenditure during certain actions (e.g. coughing). Ventilation is not evenly distributed throughout the lungs and distribution is related to the compliance of alveoli in different areas. Under normal circumstances, in the standing position, basal alveoli are the most compliant and are therefore preferentially ventilated. Ventilation occurs automatically in a continuous rhythmic pattern without conscious effort. It is controlled by neural and chemical inputs and is concerned with the homeostasis of oxygen and carbon dioxide and acid–base balance.

Keywords Breathing; compliance; control of ventilation; flow; resistance; respiration; ventilation

Royal College of Anaesthetists CPD Matrix: 1A01

Learning objectives

After reading this article you should be able to:

- describe the respiratory anatomy and mechanics of ventilation and the regional variations in ventilation
- describe how elastic recoil of the lungs and surfactant affect lung compliance and how this is altered in disease processes
- outline the control of ventilation and describe how ventilation maintains homeostasis of oxygen and carbon dioxide

Ventilation

The function of the lung is primarily to deliver oxygen to and excrete carbon dioxide from the pulmonary capillary blood. This is accomplished by generating a flux of air to and from the alveoli (ventilation) facilitating the absorption of oxygen into pulmonary blood and eliminating carbon dioxide from alveolar air (gas exchange) maintaining optimal oxygenation and acid–base balance.

This article provides an overview of the relevant respiratory anatomy with regards to ventilation, and the physiology, mechanics and control of ventilation below.

Respiratory anatomy

In 1963, Weibel clarified the morphological characteristics of the human airway, defined as model A, which divided the airways into 23 generations (Z) (Figure 1). Following transit via the oral and nasal cavities, larynx and trachea, air enters a series of dichotomously branching airways. The first 16 generations, bronchi to terminal bronchioles, are conducting airways (*conductive zone)*. Generations 17–19 are a *transitional zone* of respiratory bronchioles in which the non-alveolated regions do not have a respiratory function. Finally the true *respiratory zone* consists of three generations of alveolar ducts and one generation of alveolar sacs.

Calculation of the cross-sectional area of each generation of the airways demonstrates minimal change until the terminal bronchioles (generation 16). Thereafter, the enormous number of small airways produces a huge cross-sectional area for airflow (Figure 2). For example, the first seven generations contribute to 80% of resistance, whereas the remaining small airways (<2 mm diameter) contribute only 20% of resistance to airflow and during inspiration, as the lung expands, the net cross-sectional area of the alveolar ducts doubles, reducing resistance to airflow further.

The nature of gas flow in the airways up to the terminal bronchioles is *convective* (bulk movement), but due to the sudden increase in cross-sectional area, forward velocity suddenly decreases and *diffusive* (diffusion) gas flow becomes dominant mode of transport around generation 16.

Mechanics of breathing

Two elastic structures, the lungs and chest wall determine the respiratory mechanics of breathing controlling the forces required for delivery of air to the lungs. At end-expiration, the inward recoil of the lungs is balanced by the outward recoil of the chest wall (equilibrium position – at functional residual capacity (FRC)) (Figure 3).

Inspiratory muscles provide the energy (active process) to stretch the lungs beyond equilibrium, lowering intra pleural pressure and subsequently the intra-alveolar pressure. Once alveolar pressure becomes sub-atmospheric, air flows to the alveoli via the airways. The diaphragm is the primary muscle of inspiration. Others include the external intercostal, scalene and sternocleidomastoid muscles.

Expiration during normal quiet breathing is achieved by passive recoil of the respiratory system creating a positive alveolar pressure until the equilibrium positions of the lungs and chest wall are established and alveolar and atmospheric pressure are equal. Expiratory flows can be augmented during coughing or exercise by recruitment of expiratory muscles (internal intercostal and abdominal muscles).

Compliance

To inflate the respiratory system during inspiration, lung and chest wall elastic forces and resistance to airflow must be

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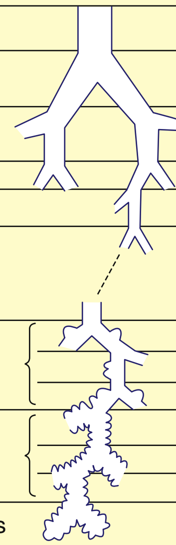
Weibel's model A, generations of airway branches



Zone	Generation		Diameter, cm	Number	Total cross-sectional area, cm^2
Conducting zone	Trachea	0	1.80	1	2.54
	Bronchi	1	1.22	2	2.33
	↓	2	0.83	4	2.13
		3	0.56	8	2.00
	Bronchioles	4	0.45	16	2.48
	↓ Terminal bronchioles	5 ↓ 16	0.35 ↓ 0.06	32 ↓ 6×10^4	3.11 ↓ 180.0
Transitional and respiratory zones	Respiratory bronchioles	17, 18, 19	↓ 0.05	↓ 5×10^5	↓ 10^3
	Alveolar ducts	20, 21, 22	↓	↓	↓
	Alveolar sacs	23	0.04	8×10^6	10^4

Adapted from *Morphometry of the Human Lung*, ER Weibel, 1963.

Figure 1

overcome. Normally, the recoil of the lungs is inwards (deflation) and the recoil of the chest wall is outwards (inflation), with equilibrium being at end-expiration or FRC. However, at high lung volumes, the chest wall also recoils inwards. The respiratory system has a tendency to resist stretch and the elastic recoil of the respiratory system is volume dependent; more difficult to stretch at volumes greater than FRC and more difficult to compress at volumes less than FRC. The lungs and chest wall have characteristic elastic recoil pressures when deflated and inflated.

The slope of the relationship between lung volume and elastic recoil pressure of each structure represents compliance and the sum of lung and chest wall compliance represent total lung compliance with compliance greatest at FRC (Figure 4).

The elastic properties of the lungs are related to two factors:

- the surface tension at the air–liquid interface within the alveoli, promoting alveolar collapse
- the behaviour of connective tissues (collagen and elastin) within the lungs parenchyma.

Surfactant, a phospholipid synthesized by type II pneumocytes, lowers the surface tension within alveoli making it easier to inflate therefore increasing compliance. Lung compliance may be reduced and the lungs difficult to inflate by certain diseases that either cause a lack of surfactant (e.g. neonatal respiratory distress syndrome) or excess collagen (e.g. pulmonary fibrosis). Increased lung compliance occurs in diseases that breakdown connective tissue reducing elastic recoil (e.g. emphysema). Chest wall compliance can be reduced by certain disease processes such as ankylosing spondylitis due to joint sclerosis following inflammation.

Resistance and flow

Airway resistance during inspiration is dependent on the airway opening-alveolar pressure difference and inspiratory flow.

The key element of airway resistance are type of flow (laminar or turbulent), radius or diameter and length of the airway, and density and viscosity of the gas. However, the major determinant is radius, as resistance increases to the fourth power as radius decreases (with laminar flow) as demonstrated by Hagen–Poiseuille's law:

$$R = 8\eta l/\pi r^4$$

R – Resistance
η – Viscosity
l – Length
r – Radius
d – Diameter
v – Velocity
ρ – Density

Resistance increases to the fifth power as radius decreases with turbulent flow. The Reynolds number (Re) can be used to predict whether gas flow within the airway will be laminar or turbulent.

$$Re = dv\rho/\eta$$

Laminar flow occurs when Re is less than 2000 and turbulent flow occurs when Re is greater than 4000. In the transitional region between 2000 and 4000, both laminar and turbulent flows

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