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RESPIRATORY PHYSIOLOGY

On a fundamental level, respiratory physiology is geared toward gas exchange with oxygen moving from the alveolus to the vascular space and carbon dioxide diffusing from the vascular to alveolar space. However, there are many components to respiration, including blood flow, ventilation, muscular activity, and gas exchange, which all must operate in concert to create effective respiratory function.

In order to effectively move air into the lungs, negative pressure relative to the atmosphere must be generated (in natural circumstances; while intubated, positive pressure ventilation can increase the pressure in the lungs above the atmospheric pressure). This change is accomplished partly by the diaphragmatic motion and partly by intercostal muscle activity. The diaphragm moves caudally during inspiration while the intercostal muscles abduct the ribs and pull the ribs cranially. Both activities serve to expand the chest cavity, which (presuming at rest the lungs were at atmospheric pressure) creates a pressure below atmospheric pressure. These motions cause inspiration to be an active process in dogs and cats. Expiration, however, is a passive process when at rest and largely relies on recoil of the respiratory muscles. During some respiratory illness, activity/exercise, coughing, or sneezing, expiration is an active process and can generate more force. Active inspiration versus passive expiration leads to a longer time in expiration; the ratio of inspiratory time to expiratory time typically between 1:2 and 1:3.

In addition to muscular control, the autonomic nervous system plays a critical role in the respiratory system. Parasympathetic stimulation leads to both bronchoconstriction and an increase in respiratory secretions. There tends to be a degree of underlying parasympathetic tone to the respiratory system, which can lead to pathology as some irritants or stimulation can lead to parasympathetically-mediated reflex constriction (e.g. feline asthma). Sympathetic stimulation, through β2 receptors, has an opposite effect leading to both bronchodilation and a decrease in respiratory secretions. Complementing the autonomic nervous system is the local response to the partial pressures of oxygen and carbon dioxide – a decrease in the oxygen partial pressure (PO_2) or an increase in the carbon dioxide partial pressure (PCO_2) lead to airway dilation.

Pulmonary blood flow encompasses two regions. The bronchial circulation is the arterial supply of the tracheobronchial tree down to the level of the terminal bronchioles. The pulmonary circulation serves as the site of gas exchange between alveolar air and capillary blood. Pulmonary vessels are far more distensible than their systemic counterparts and therefore have a far lower vascular resistance (~10% of systemic vascular resistance). The greater pressure generated systemically does increase the metabolic demand of the left ventricle, but it also allows for greater regulation and distribution of the cardiac output through various vascular beds. The pulmonary circulation is therefore far more dependent on extravascular factors to maintain blood flow. The smaller alveolar vessels are stretched and compressed during lung (and alveolar) expansion, while the larger extra-alveolar vessels are exposed to intrapleural pressure and are pulled open during inspiration. The opposite effect is then seen during expiration. PO_2 can also effect flow and resistance as hypoxia causes constriction of the pulmonary vascular smooth muscle.

Oxygen and carbon dioxide diffuse across the endothelium and alveolar epithelium to complete gas exchange. Pulmonary surfactant, produced by the type 2 alveolar cells, is critical to reducing surface tension and preventing alveolar collapse. Gas must cross the layer of pulmonary surfactant, the alveolar epithelium, the interstitium, the capillary endothelium, and the plasma. Additionally, oxygen must traverse the red blood cell membrane to bind hemoglobin. Fick's Law states that diffusion (gas flow) is proportional to the area, diffusivity of the gas, and the partial pressure gradient. Diffusion is inversely proportional to thickness. Diffusivity is proportional to the solubility of the gas and inversely proportional to the square root of the molecular weight:

$$Diffusivity \propto \frac{Solubility}{\sqrt{Molecular\ weight}}$$

Carbon dioxide diffuses ~20% slower than oxygen because of its larger molecular weight but ~24 times faster because of its greater solubility. This leads to carbon dioxide having an overall diffusivity ~20 times that of oxygen. The pressure gradient for oxygen is ~60 mmHg while the pressure gradient for carbon dioxide is ~5 mmHg; therefore, the pressure gradient has a stronger effect on oxygen gas exchange. Taking all factors together, the time for oxygen and carbon dioxide gas exchange is typically quite similar.

The concept behind ventilation-perfusion matching is that optimal gas exchange occurs in the lung when ventilation and perfusion are matched. Local airway responses and pulmonary vasoconstriction in response to hypoxia help achieve this matching. Ventilation-perfusion matching leads to the following partial pressures at different sites:

	Inspired Air	Entering Capillary	Exiting Capillary
PO2	150 mmHg	40 mmHg	100 mmHg
PCO2	0 mmHg	45 mmHg	40 mmHg

Low ventilation-perfusion ratio means poor ventilation relative to circulation and may be noted in cases of airway obstruction or atelectasis. High ventilation-perfusion ratio means poor/no perfusion relative to ventilation and leads to alveolar dead space (i.e. alveoli which are ventilated but no gas exchange occurs).

The pulmonary system also serves several functions which are not directly related to gas exchange. The upper airway is necessary for olfaction and air conditioning in which the air passed to the alveoli is humidified and warmed or cooled appropriately. The airway also serves to filter particles – dependent on the size of the particle, different regions of the respiratory tract may serve as the filter. Particles >10 µm are almost entirely removed by the nasal turbinates. Particles between 2-10 µm tend to settle in the mucous of the trachea, bronchi, or bronchioles. Particles between 0.3-2 µm usually reach the alveoli. Particles <0.3 µm tend to remain as aerosols and are expired. Particles can be removed via sneezing or coughing as well as via cilia which propel mucous and particles to the pharynx. Alveolar macrophages can engulf particles in the alveolus as well as play some role in bacterial killing.

References

– Dye JA, Costa DL. Pulmonary mechanics. In: King, LG. ed. Textbook of Respiratory Disease in Dogs and Cats. St Louis: Saunders, 2004; 157-75.