RESISTANCE TO VENTILATION - PART I

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OThis article is the first of a two-part review of resistance to ventilation. Part I will provide an overview of the total resistance to ventilation, and the partitioning of airway resistance. Part II will discuss series and parallel resistances, airway resistance through large and small airways, and clinical implications of the partitioning of airway resistance.

Air flows from the atmosphere into the lungs in response to external forces. During normal, resting inspiration, these external forces are generated by the external intercostal muscles and the diaphragm. Contraction of the external intercostal muscles accounts for the increase in the antero-posterior and transverse diameters of the chest wall. At the same time, contraction of the diaphragm causes the vertical dimension of the thorax to enlarge.

During the act of breathing, the respiratory system experiences three types of resistance. They are (1) inertial resistance, (2) elastic or viscous resistance, and (3) airway or airflow resistance.

Inertial Resistance

Inertial resistance to ventilation reflects the tendency of the respiratory system to resist a change in motion. In other words, at the end of a normal exhalation, the respiratory system assumes a motionless state. At that point during the ventilatory cycle, no air is flowing through the lungs. Therefore, the inertia of the respiratory apparatus tends to maintain the lungs in this motionless state. However, energy expended by the muscles of ventilation, that is, the diaphragm and the external intercostal muscles, does the mechanical work necessary to overcome this inertial resistance by developing a greater subatmospheric intrapleural pressure. The drop in subatmospheric pressure in the pleural space immediately changes the pressure in the alveoli by the same magnitude; thus, establishing a pressure gradient between the mouth and the alveoli, thereby initiating inspiration. The inertial resistance to ventilation contributes an insignificant portion to the total resistance to ventilation. Consequently, inertial resistance is generally considered negligible because it contributes little to a person's work of breathing.

Elastic Resistance

The elastic properties of the lungs and chest wall constitute the elastic, or viscous, component of resistance. This particular component of the respiratory system accounts for approximately 20% of the total resistance to ventilation in a healthy person. Elastic resistance is not influenced by airflow. In fact, the elastic properties of the ventilatory system are measured under static conditions, that is, when air has ceased flowing through the airways of the lungs.

These elastic properties are commonly known as compliance and elastance. Compliance, which is defined as a change in volume divided by a change in pressure (change in volume/change in pressure), bears the units ml/cm H2O. Compliance is measured when airflow through the tracheobronchial tree is zero. Airflow through the lungs becomes zero at two points in the ventilatory cycle – end-inspiration and end-exhalation. Elastance is the reciprocal of compliance, and is equal to a change in pressure divided by a change in volume, i.e., change in pressure/change in volume). Elastance, the reciprocal of compliance, has the units cm H2O/ml, and, like compliance, is measured under static conditions.

Elastic resistance of the respiratory system increases when compliance decreases because the lungs simply become more stiff, and are more difficult to inflate. At the same time, elastance increases, causing the lungs to empty more rapidly. The converse is also true.

The work done to overcome the elastic resistance of the lungs during inspiration is stored in the lung parenchyma. This stored work accounts for the passive nature of a normal exhalation. In other words, a significant amount of the work done to accomplish inspiration (flowing of air into the lungs) is used to perform the ensuing exhalation. In this sense, the lungs are analogous to a spring that is stretched. After a spring has been stretched, the spring possesses potential energy. After work has been done by the respiratory muscles, the lungs have been stretched, and possess potential energy. When the stretched spring is released, its elastic properties cause the spring to shorten and recoil. After the lungs have been inflated to the required tidal volume, the elastic properties of the lungs cause the lungs to recoil. Therefore, normal, resting exhalation is essentially accomplished through the passive recoil of the lung tissue that was stretched during inspiration.

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Airway Resistance

The third component of the total resistance to ventilation is airway, or airflow, resistance. Airway resistance contributes the remaining 80% of the total ventilatory resistance and manifests itself when any fluid flows through a conducting system. This form of resistance results from (1) the interaction among the molecules of the flowing fluid, and (2) the interaction between the molecules of the fluid and the walls of the conducting system.

Contrary to elastic resistance, airway resistance is measured under dynamic conditions. Dynamic conditions occur when a fluid is flowing. Therefore, when air flows through the airways of the tracheobronchial tree, airway resistance develops. Airway resistance is defined as a change in pressure divided by the flow rate. The formula for calculating airway resistance is as follows:

$$R_{aw} = \frac{\Delta P}{\dot{V}} = \frac{P_{atmosphere} - P_{alveoli}}{\dot{V}}$$

where, R_{aw} is the airway resistance, change in P is the pressure gradient, and V is the flow rate. One can see that when the numerator, or pressure gradient between the atmosphere and the alveoli, equals zero, the airway resistance equals zero. The units for airway resistance are cm H2O/L/sec.

A pressure gradient must exist for flow to develop. Without a change in pressure, or a change in P, flow will be non-existent. The muscles of inspiration are responsible for generating a subatmospheric pressure in the alveoli, thereby creating a pressure gradient between the atmosphere and the alveoli (Patmosphere – Palveoli). This pressure gradient is called the transairway pressure because it represents the pressure difference across the entire tracheobronchial tree. When the transairway pressure gradient is established, air flows into the mouth or nose and through the airways of the lungs. As air flows through the lungs to the alveoli, airway resistance is encountered.

At end-inspiration and at end-exhalation, the pressure gradient between the atmosphere and the alveoli is zero (Patmosphere – Palveoli = 0 cm H2O). Because no pressure gradient exists at those points in the ventilatory cycle, air is not flowing through the airways. Consequently, because no airflow is occurring, airway resistance equals zero at end-inspiration and at end-exhalation. Airway resistance cannot be measured at those points in the ventilatory cycle because these points represent static conditions. The measurement of airway resistance requires a flowing fluid, i.e., dynamic conditions.

Partitioning of Airway Resistance

Airway resistance accounts for 80% of the total resistance to ventilation, and the elastic resistance contributes the remaining 20%. Recall that the inertial resistance is considered negligible. The amount or contribution of the elastic resistance to the total resistance remains relatively stable. In other words, its contribution to the total resistance is essentially the same in the apices as in the bases. However, the airway resistance varies throughout the tracheobronchial tree. For example, a greater resistance to airflow occurs as air flows through the larynx, compared to the resistance that develops as air flows through a respiratory bronchiole.

Partitioning of airway resistance across the lungs is viewed two ways. First, partitioning can be considered from the airway opening at the mouth to the alveoli. Second, segmenting airway resistance can be viewed from the trachea to the alveoli. When considering airway resistance from the mouth to the alveoli, 50% of the airway resistance is encountered as air flows from the mouth to trachea. The remaining 50% of the airway resistance occurs as air flows from the trachea to the alveoli.

When partitioning airway resistance from the trachea to the alveoli, an analogy is sometimes made between the tracheobronchial tree and an inverted funnel. The opening or neck of the funnel represents the trachea. The gradual widening of the inverted funnel represents successive large airway generations, and a progressive increase in the cross-sectional area within the lungs. Ultimately, the widest portion of the funnel is analogous to the small airways, specifically generations 9 through 23, inclusively. With this model, the large airways contribute 90% of the airway resistance, and the small airways render the remaining 10%.

This partitioning of the airway resistance through the anatomic dead space and gas exchange regions of the lungs has physiologic and clinical ramifications that will be explored in Part II of this review of respiratory system resistance.

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