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The Relationship Between Oxygen Administration and Airway Resistance: Clinical Considerations

RICHARD KONRAD, BA, REMT-P

The goal of oxygen therapy is the maintenance of adequate arterial oxygen tension by insuring the necessary concentration of oxygen in the inspired gas. When sufficient oxygen is present, metabolism of glucose provides adequate energy for all body processes—including active transport, protein synthesis, and muscle contraction. The level of energy production when sufficient oxygen is not available is markedly different. In anaerobic metabolism energy production drops nearly twenty-fold. This remarkable and disastrous decrease in energy available for all body processes is a hallmark of any situation in which hypoxemia or poor tissue perfusion occurs (1).

The relationship of oxygen availability and energy production for muscle contraction has a direct bearing on the provision of supplemental oxygen therapy. Many patients who receive supplemental oxygen are already hypoxic or in states of widespread inadequate perfusion. Any increased work for these patients represents a demand for energy which they are in poor condition to meet. In the normal course of treatment, the activities of these patients are restricted and demands on their limited energy reserves are limited (they are not allowed to move about actively or to become hypothermic and shiver). A review of anatomy and physiology as they affect oxygen therapy reveals that the way in which oxygen is provided may have a deleterious effect on the level of work required of the patient.

While the available energy for work is dependent on the level of oxygen available to the tissues, the work required for breathing depends on three factors: the compliance of the lungs (their propensity to collapse or recoil from the chest wall) along with the resistance of the chest wall to expansion; the resistance to expansion of the lung tissue itself; and, the resistance to the flow of gas through the airways. Any situation which decreases the compliance of the lungs (making them resist expansion), increases the viscosity of the lung tissue, or increases the resistance to airflow through the airways will increase the work of breathing. Some conditions requiring provision of supplemental oxygen increase the patient's work of breathing by causing hypoventilation which stiffens the lungs or interstitial pulmonary edema which increases tissue viscosity. Some disease states like asthma or chronic obstructive lung disease increase the work of overcoming airway resistance. The level of work necessary to overcome airway resistance is also affected by supplemental oxygen therapy.

The resistance to the flow of gas through a tube is determined largely by the cross-sectional area of the lumen of the tube according to Poiseuille's law which is demonstrated in the following equation:

$$R(resistance) = 8 \; x \; viscosity \; x \; length \; / \; \pi \; x \; r(radius)4$$

Thus, resistance varies directly with viscosity of the gas and length of the tube, but inversely by an exponent of four with changes in the radius of the cross-sectional area of the lumen of the tube. Small decreases in this radius produce large changes in the resistance to the flow of gas and hence the work required to move gas through the tube. The cross-sectional area of the entire length of the tube lumen need not be decreased in area in order for resistance to be increased; any cross-sectional plane which has a narrowed area will produce this effect. Research by Mertz and his associates has demonstrated that airway resistance is altered in exercise induced hypercapnia by increased cross- sectional area of the nasal passage lumen in such a way that resistance decreases with an attendant increase in gas flow rates. This decreased resistance, which also decreases the work necessary to move a volume of gas, is consistent with increasing ventilation and lowering CO_2 levels (2). All oxygen administration devices applied to a patient's face alter the cross-sectional area of the patient's airway at its origin. Only two sources of inspired gas exist for the patient wearing an oxygen administration appliance: the gas within the mask (or supplied through the cannula prongs) and gas outside the mask (or available to the cannula wearer in the atmosphere). The gas reservoir within the mask is replenished at a constant rate by the flow meter. While the inspiratory work to overcome compliance and tissue resistance produce a nearly linear development of the relationship of lung volume to intrapleural pressure, the work necessary to overcome airway resistance produces a markedly uneven development of this relationship. In other words, the work of overcoming airway resistance is much higher in the middle of inspiration and less at the beginning and end. Flow meters cannot alter rate of gas flow to match these physiological changes. The only way for a mask wearer to inspire the gas outside the mask is to draw it through openings in the mask which usually consist of small exhalation holes arranged in a tight circle and breaks in the seal of the mask at

Lieutenant, Pinellas Park Fire Department, Pinellas County EMS; Contributing Editor, Tampa Bay EMS Journal; Odessa, Florida

the patient's face. Whether the patient needs to inspire gas through these small openings depends on his or her minute respiratory volume as compared with the oxygen volume supplied by the flow meter.

An average adult male has a tidal volume (V_T) of approximately 500 ml and a respiratory rate between twelve and twenty (the limitations of the useful statistical concept of the average patient are recognized). In an adult possessing normal lungs and no disease or injury with the previously stated V_T of 500 ml and a respiratory rate of fifteen breaths per minute, a volume of 7.5 liters (500 ml x 15) of gas is breathed each minute. This figure represents the minute respiratory volume (V_M). The V_M is adjusted moment to moment in order that metabolic demands for oxygen and removal of waste products be met. Any time a patient is not able to achieve the necessary V_M, the work of respiration is increased in order to achieve the necessary volume.

Guyton points out that, if sufficient energy exists, the V_T may approach vital capacity (V_C), about 4600 ml in adult males (3). In rapid breathing, however, the V_T rarely exceeds half the vital capacity. Imagine that in response to early pulmonary edema (interstitial pulmonary edema), which increases the work of overcoming lung tissue resistance, a patient's breathing rate increases to 30 breaths per minute, accompanied by a modest increase in V_T to 750 ml. The subject's minute volume is now 22.5 liters per minute. This elevation in V_T is occasioned by increased expenditure of energy in order to perform the increased work.

If a simple face mask is placed on the above considered patient and the flow meter is set to provide 10 liters of medically pure oxygen each minute, slightly less than half the patient's minute volume is met by the reservoir of gas within the mask. This patient must draw the remainder of his minute volume, 12.5 liters, through the small holes in the mask. The cross- sectional area of the patient's airway has suddenly been markedly reduced at its origin, with an attendant rise in resistance of gas flow through the airway and increase in the work of breathing. The non-linear development of work to overcome airway resistance discussed above means that even in circumstances where the patient's minute volume is met by the reservoir of gas within the mask, at times during the inspiratory cycle the work of inspiration may increase. The discomfort of which patients receiving oxygen therapy by mask complain has often been laid at the foot of the mind, a psychological aversion or claustrophobic reaction. A physiological basis for the patient's wish to remove an obstructing object from his or her airway is just as possible in some circumstances.

These facts are not set out in order to condemn the simple face mask or to suggest that it is inappropriate in all circumstances. Each oxygen administration device must be used with an appreciation for the ways in which it affects the mechanics of breathing. The venturi mask, which mixes room air with oxygen at specific concentrations, produces a high total gas flow with fixed fractional concentration of inspired oxygen by percentage (F_iO_2). In the Hudson Multi-Vent mask, oxygen concentrations range from low (23-30%) to moderate (35-50%). Note that the simple face mask provides only 60% oxygen concentrations under ideal conditions. The construction of the venturi mask differs from that of the simple face mask in one other important regard. The exhalation port of the venturi mask is one large hole, rather than a collection of very small ones. A patient with a very high minute volume is served well by such a mask because of the high total gas flow into the mask and the relatively low resistance to the flow of gas through the large exhalation port. Considering that the F_iO_2 possible with each mask is relatively close, the least obstructive of the devices might be a wise choice in patients with high minute volume. The consideration of the relationship between the patient's minute volume and the oxygen administration device leads to the question of whether a method exists to determine the patient's minute volume at the time of treatment. Aside from spirometry, no easy method of accurately determining the minute volume exists. The minute volume may, however, be indirectly estimated with a flow meter and an oxygen mask with a reservoir bag. Either a partial rebreathing mask or a total non-rebreathing mask provide high F_iO_2. If the reservoir bag is filled prior to placing the mask on the patient, the effect of the patient's breathing on the volume of oxygen in the bag may be observed. If, at the peak of the patient's inhalation, the bag remains at least one-third filled, the minute volume being delivered through the inlet tubing of the mask should be sufficient to meet the patient's minute volume demand. If, on the other hand, the patient's inhalation collapses the reservoir bag completely, the flow meter can be adjusted to supply increased minute volume. In any event, although claustrophobia as an etiology for the discomfort patients feel with oxygen masks is entirely plausible, an understanding of the mechanics and work of breathing as affected by oxygen masks reveals that a physiologic etiology is equally plausible. Oxygen administration devices vary widely in the degree to which they obstruct the airway and increase the work of breathing. Devices such as the face tent offer no increase in airway resistance, but are incapable of supplying high F_iO_2. The nasal cannula is another low-to-moderate concentration device which has little effect on airway resistance, since the mouth remains open to the atmosphere. Almost all high concentration devices have the potential to increase airway resistance and the work of breathing. Remember, however, that the bag-valve-mask system with oxygen reservoir can act as a non-rebreathing mask for oxygen inhalation therapy. Because of the larger volume of the reservoir and the relatively large diameter of its tubes, this device has less effect on airway resistance than smaller oxygen masks. Finally, patients are well served when the least obstructive oxygen administration device which provides an adequate level of therapy is chosen.

REFEREE COMMENTARY

Brian Cobb, MD *(Department of Anesthesiology, University of South Florida)* - This review of oxygen administration in the spontaneously breathing patient should assist in the selection of techniques and provide an understanding of their ramifications. It is worhtwhile to point out that when a spontaneously breathing patient is intubated, using a tube shortened to the minimum legnth combined with the largest possible diameter will decrease the work of breathing.

In addition, It might be remembered that an inadequate mask seal, e.g. when using the bag-valve-mask unit on a spontaneously breathing patient, can result in entrainment of room air with subsequent reduction in F_iO_2

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