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Anatomy and Physiology of Tracheostomy

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The trachea is easily accessible at the bedside. As such it provides ready access for emergency airway cannulation (eg, in the setting of acute upper airway obstruction) and for chronic airway access after laryngeal surgery. More commonly, tracheostomy tubes are placed to allow removal of a translaryngeal endotracheal tube. Tracheostomy tubes have an important effect on respiratory physiology. The most recent and methodological robust studies indicate that these tubes reduce resistive and elastic work of breathing, when compared to endotracheal tubes. This is a result of tracheostomy tubes lessening inspiratory and expiratory airways resistance and intrinsic positive end-expiratory pressure. Whether these physiologic benefits are of clinical importance in enhancing weaning success remains to be elucidated. *Key words: tracheostomy, resistance, elastance, work of breathing, mechanical ventilation, weaning, extubation.* [Respir Care 2005;50(3):476–482. © 2005 Daedalus Enterprises]

Introduction

The trachea is easily accessible at the bedside. As such it provides ready access for emergency airway cannulation (eg, in the setting of acute upper-airway obstruction) and for long-term airway access after laryngeal surgery. More commonly, tracheostomy tubes are placed to allow re-moval of a translaryngeal endotracheal tube (ETT). The procedure can be done surgically or percutaneously, and with either technique the procedure can be performed in the operating room or at the bedside in the intensive care unit (ICU).

Anatomy

The lower respiratory tract starts at the vocal cords. Inferior to the vocal cords, the rigid cricoid cartilage encases a 1.5–2.0-cm region known as the subglottic space. Access to this space is possible via the cricothyroid ligament, a membrane that runs from the thyroid cartilage inferiorly to the cricoid cartilage. Inferior to cricoid is the trachea, a cylindrical tube that extends inferiorly and slightly posteriorly. The trachea is made up of 18–22 C-shaped rings consisting of rigid cartilage anteri-

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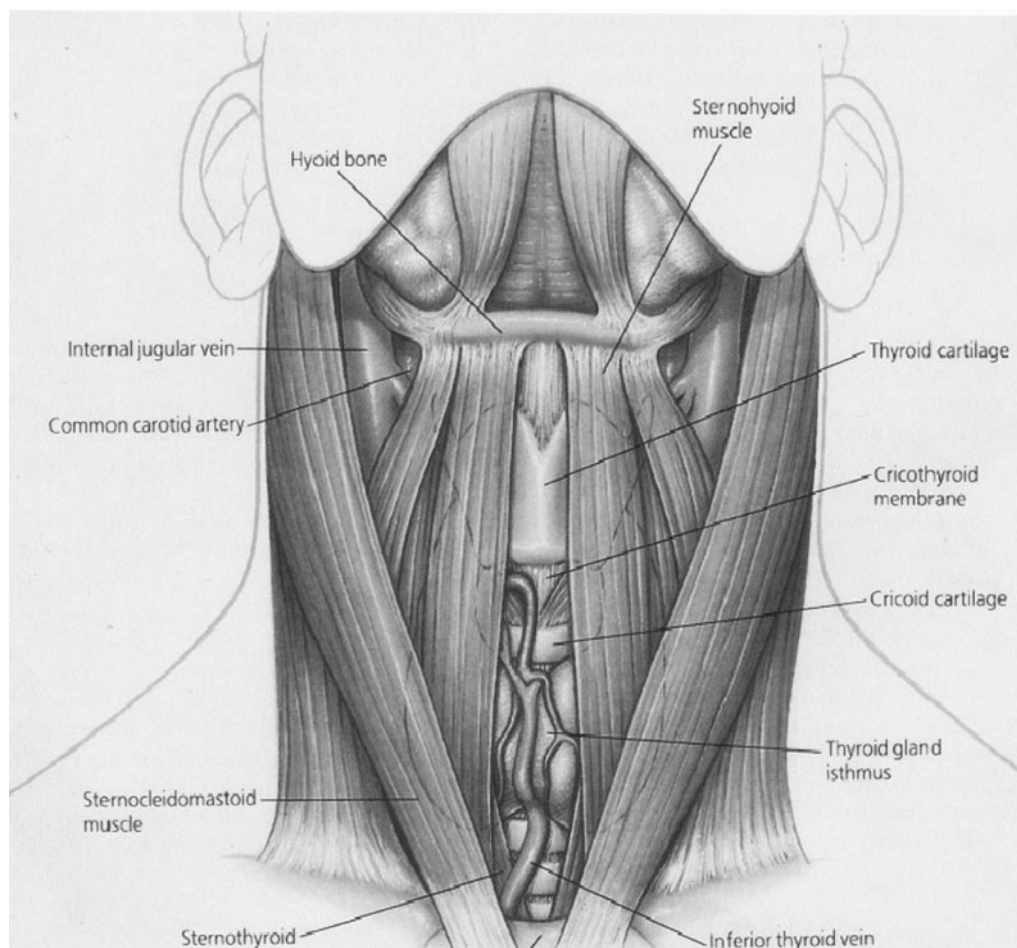
Fig. 1. Major landmarks in the neck. (From Reference 3, with permission.)

orly and laterally, and a membranous posterior portion. In the average adult, the distance from cricoid to carina is approximately 11 cm in length, with a range of 10–13 cm. On average, the trachea is 2.3 cm in width and 1.8 cm from posterior membrane to the anterior cartilaginous aspect. The trachea is wider in men than in women.[1,2]

In examining the landmarks of the neck, it is evident that the trachea is protected by strap muscles (sternohyoid, sternothyroid, sternocleidomastoid) and bony structures (manubrium and sternum) (Fig. 1).[3] Furthermore, the trachea is positioned posterior to a number of blood vessels and the thyroid isthmus. Branches of the bronchial, inferior thyroid, innominate, and subclavian arteries provide the blood supply to the trachea.[1,2]

Knowledge of neck and tracheal anatomy is essential for understanding the various approaches to establishing a tracheostomy (Fig. 2).[4] As an example, surgical tracheostomy tubes are typically placed in the region of the 2nd to 4th tracheal rings and may entail removal of tracheal cartilage or the creation of a cartilaginous flap. Percutaneous tracheostomy tubes are typically placed between the 1st

and 2nd or between the 2nd and 3rd tracheal cartilages. The technique takes advantage of the Seldinger method, followed by progressive dilation of the space between tracheal rings to provide access to the trachea. Another approach is to place a tube through the cricothyroid membrane (cricothyroidotomy).[5] Though still used extensively in some centers, in other centers it has been replaced by percutaneous tracheostomy. Cricothyroidotomy can be used to gain emergency access to the airway, but its association with numerous complications has led some to advocate replacing this tube within 48–72 hours with a standard tracheostomy. The procedure is carried out by a transverse incision through the skin and the membrane and then spreading the incision vertically to allow placement of the tube. Because the cricothyroid membrane is bounded by 2 rigid structures (thyroid cartilage and cricoid cartilage) that are not easily dilated, the height of this membrane limits the size of the tube that can be placed. In addition, the curve of a standard adult tracheostomy tube and the close soft tissue distance between anterior skin and trachea (at the level of the cricothyroid membrane) causes
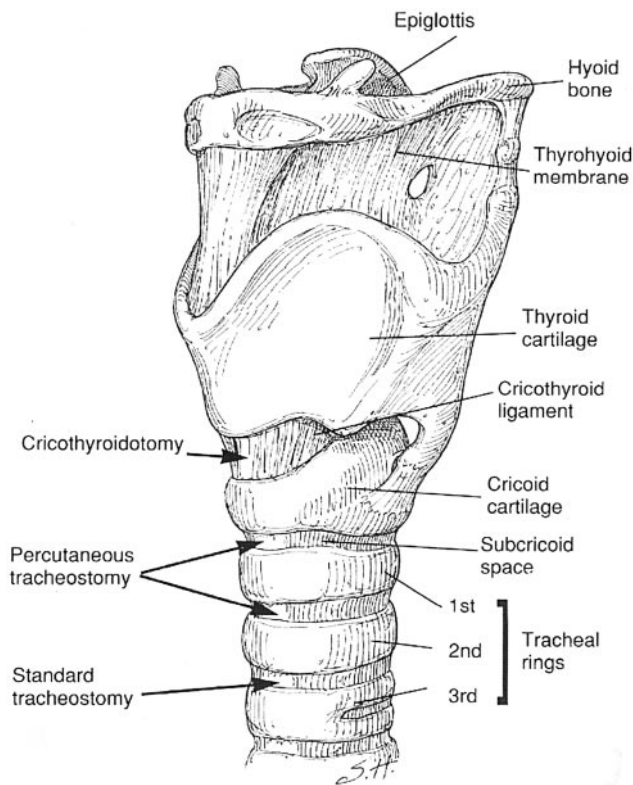
Fig. 2. Anterior oblique view of larynx and trachea. The preferred anatomic locations for placing standard tracheostomy, percutaneous tracheostomy, and cricothyroidotomy are indicated. (From Reference 4, with permission.)

the tip of the tube to impinge on the posterior membrane of the trachea.

Physiology

In studying the physiologic effects of the tracheostomy tube, one may examine pristine tubes in vitro using a lung model. Alternatively, in vivo investigations have been conducted comparing the effects of tracheostomy to spontaneous breathing through the native upper airway, breathing before and after tracheostomy decannulation, or to breathing through an ETT. Investigators have also examined the work of breathing (WOB) imposed by the tracheostomy.

Humidification

As with an ETT, many changes in airway physiology occur with insertion of a tracheostomy tube. Bypassing the nasal airway, these artificial airways disturb the normal humidification and warming of inspired air. Therefore, air must be humidified using heated humidifiers or heat-and-moisture exchangers. In the absence of adequate humidification, the trachea develops squamous metaplasia and

chronic inflammatory changes.[6] Lack of adequate humidification also leads to desiccation of the tracheal mucosa and reduced ciliary function. Indeed, by these actions and by diminishing effective cough and increasing secretions, tracheostomy tubes predispose to respiratory-tract infection. Furthermore, these tubes also hamper effective swallowing, thereby predisposing to aspiration.

Airflow Resistance

Airflow resistance of the normal upper airway is substantial, constituting up to 80% of total airway resistance during nose breathing and 50% during mouth breathing. Theoretically, tracheostomy tubes should decrease airflow resistance, but in fact this does not occur because of the smaller radius (inner diameter 7–8 mm) of the tubes. Tracheostomy tubes may reduce dead space by up to 100 mL, when compared to spontaneous breathing.[6] This occurs because the tubes are small and bypass the glottic and supraglottic spaces.

The resistance to flow of gas through a tube, represented by the Poiseuille equation, is directly proportional to length, while being inversely proportional to the radius of the tube raised to the 4th power (when flow is laminar). When flow becomes turbulent, airways resistance becomes inversely proportional to the radius of the tube raised to the 5th power. Indeed, at flows above 0.25 L/s, flow becomes turbulent when the inner diameter of a tube is < 10 mm.[7] Thus, small reductions in tube radius result in large increases in resistance. Turbulent flow occurs when flow rates are high, when secretions adhere to the inside of the tube and because of tube curvature. When compared to the ETT, the tracheostomy tube has the potential to decrease the resistive WOB. Tracheostomy tubes are shorter, more rigid, less likely to be deformed in the upper airway (by being placed below the vocal cords and the rigid structures of the subglottic region), and are easier to keep clean (they more effectively facilitate airway suctioning and removal of secretions). By decreasing resistance, expiratory flow can be enhanced, and the tendency to dynamic hyperinflation and the development of intrinsic positive end-expiratory pressure (PEEP) is reduced. Therefore, when compared to ETTs, tracheostomy tubes have the potential to also reduce the elastic WOB.

Respiratory Mechanics in Bench Studies

Davis et al examined WOB in a bench lung model study comparing endotracheal and tracheostomy tubes with the same inner diameter.[8] "Question mark" shaped ETTs were used to simulate the tortuous route that these tubes often take in vivo. With either type of tube, WOB and pressure drop across the tube increased as flow rate increased (leads to turbulence) and as tube diameter decreased. At high

flow rates of 1–1.5 L/s, WOB was less through the tracheostomy tube. Presumably the longer ETT magnified the effects of turbulent flow on airways resistance. At lower flow rates (0.5 L/s) the benefit of shorter tube length for the tracheostomy was apparently counterbalanced by the increased curvature of those tubes, leading to no difference in the WOB.

In studying ETTs, Wright et al found that in vivo resistance exceeded in vitro resistance.[9] This resulted from deformation of these thermolabile ETTs and the adherence of secretions to the inner lumen of the tube (thereby increasing turbulence and narrowing the tube radius). Similarly, Yung and Snowdon demonstrated in vitro that the pressure drop across a tracheostomy tube (and therefore the resistance), at any given flow rate, was greater for a crusted tube than a clean tube.[7] These investigators also compared 3 different types of tracheostomy tubes and found greatest resistance with the tube that was longer, had a shorter radius of curvature, and a rougher inner surface.

Tracheostomy Compared to the Native Upper Airway

How does flow across the tracheostomy tube compare with that of the spontaneous airway? Older studies found that airways resistance was greater with a tracheostomy than when breathing across the normal airway.[10–12] More recently, Haberthur et al studied 10 medical ICU patients breathing spontaneously through tracheostomy tubes.[13] To determine the pressure drop across the tracheostomy tube and the imposed WOB (ie, the additional WOB attributable to the tube), the investigators passed a thin, 1.6-mm catheter through the lumen of the tube. A linear interpolation algorithm was applied to correct for the pressure drop induced by this special catheter. While breathing on a continuous positive airway pressure circuit, the pressure drop across the tracheostomy tube was as high as 20 cm H_2O when inspiratory flow rates exceeded 10 L/min. This represented a substantial increase in the expected pressure drop across the native upper airway, of 1.2 cm H_2O at a flow of 0.3 L/s and 5.2 cm H_2O at a flow of 2.0 L/s. Indeed, the imposed WOB was increased at higher flow rates, reaching a level sometimes associated with failure to wean from mechanical ventilation (Fig. 3).[13] Similarly, Davis et al found that WOB increased after extubation and then was reduced again after placement of a tracheostomy tube.[14]

In the studies discussed thus far, physiologic calculations were made as the patient breathed *through* the tracheostomy. What happens when the tracheostomy is in place but the patient must breath *around* the tube? This exact circumstance often occurs during trials to assess readiness for decannulation, when the tracheostomy tube is capped. In a single case physiologic study, Criner et al
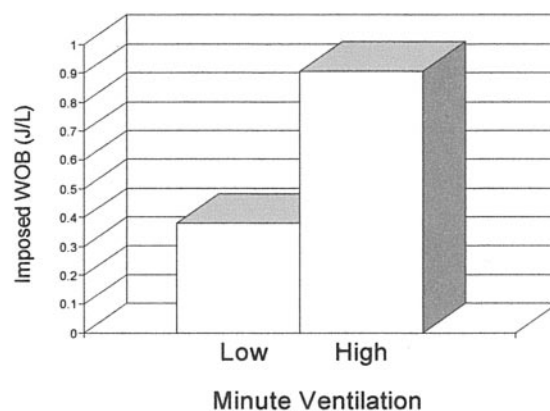

Fig. 3. Imposed work of breathing (WOB) during spontaneous breathing through a tracheostomy tube at 2 different levels of ventilation. (Adapted from Reference 13.)

examined the effect of mouth breathing while a capped, fenestrated, tracheostomy tube was in place, with the balloon deflated.[15] Airways resistance and the tension-time index were higher with the tube in place, when compared to breathing with a capped Montgomery tube or after decannulation (Fig. 4).

Other studies have compared respiratory mechanics of breathing through the tracheostomy and mouth breathing (without the tracheostomy in the airway). To determine the effect of then removing the tracheostomy tube, Chadda et al examined 9 neuromuscular patients who underwent decannulation.[16] With removal of the tube (eg, mouth breathing), resistance and elastance were unchanged, but dead space increased from 156 mL to 230 mL, tidal volume (V_T) and minute ventilation increased (P_{aCO_2} was unchanged), and WOB increased by 30%. Moscovici da Cruz et al studied 7 patients who underwent surgical tracheostomy for malignancy, 3 of whom had tumors of the larynx and tonsils not felt to be causing upper-airway obstruction.[17] When compared to spontaneous breathing, tracheostomy was associated with a trend toward lower resistive WOB and reductions in elastic WOB, intrinsic PEEP, and pressure-time product.

Tracheostomy Compared to Translaryngeal Endotracheal Intubation

Tracheostomy, compared to translaryngeal endotracheal intubation, has been purported to have many physiologic benefits, including improved patient comfort, more efficient airway care (improved airway suctioning), better oral care, and provision of a more secure airway, allowing for safe patient transfer out of the acute-care ICU.[18,19] One of the most important benefits is the potential to improve patient liberation from mechanical ventilation. Failure to wean often results from an imbalance between reduced
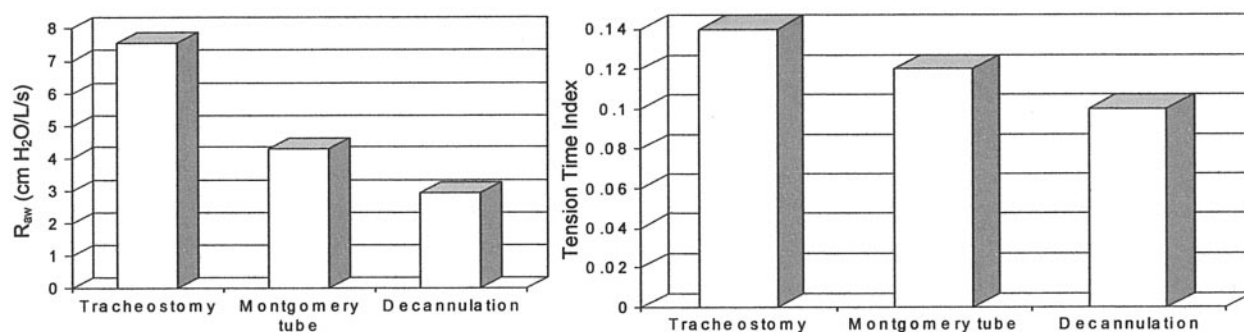
Fig. 4. Airways resistance (R_{aw}) and tension-time index while breathing through a tracheostomy tube, a Montgomery tube, and after decannulation. (Adapted from Reference 15.)
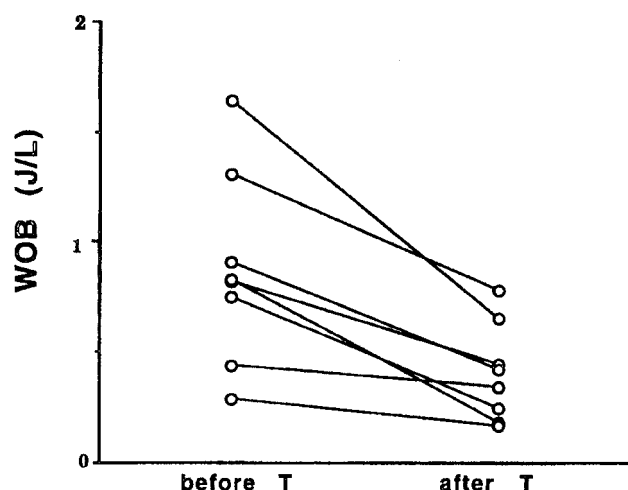

Fig. 5. Work of breathing (WOB) in joules per liter (J/L) before (with endotracheal tube) and after tracheostomy (T) tube placement in 8 patients. (From Reference 25, with permission.)
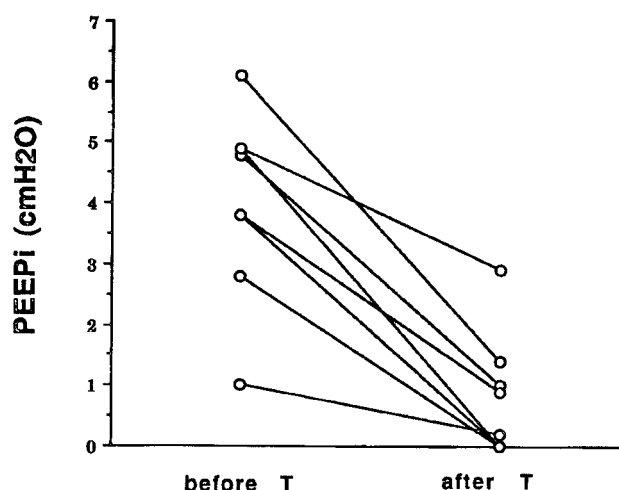

Fig. 6. Intrinsic positive end-expiratory pressure (PEEPi) before (with endotracheal tube) and after tracheostomy (T) tube placement in 8 patients. (From Reference 25, with permission.)

respiratory muscle capacity and increased WOB.[20,21] Even in patients without pre-existing lung disease, the WOB imposed by artificial airways can lead to iatrogenic weaning failure.[22] In those with substantial underlying disease, slight reductions in imposed WOB resulting from placement of a tracheostomy may be important. Therefore, comparison of WOB through the ETT and the tracheostomy tube is of critical importance.

In a study before and after tracheostomy in 20 mechanically ventilated patients with chronic obstructive pulmonary disease, Lin et al found that, when compared to ETTs, tracheostomy tubes were associated with a lower peak airway pressure (33 cm H_2O vs 29 cm H_2O), but there was no difference in WOB, pressure-time product, or airways resistance.[23] Mohr et al studied 45 surgical ICU patients before and after tracheostomy during mechanical ventilation with combined synchronized intermittent mandatory ventilation and pressure support.[24] No differences were found in respiratory rate, V_T, minute ventilation, peak airway pressure, dead space, or blood gases. Furthermore, no

differences were noted in these variables when patients weaned within 72 hours of tracheostomy were compared to those remaining on ventilation > 5 days postoperatively.

In contrast to these studies, 2 superbly performed investigations indicate that tracheostomy does offer physiologic improvements, when compared to translaryngeal ETTs. Diehl et al examined 8 medical ICU patients (3 with diaphragmatic weakness, 2 with chronic obstructive pulmonary disease, 1 with asthma, 3 with coma) who had been ventilated for a mean of 31 days.[25] Patients were studied 24 hours prior to and 6 hours after surgical tracheostomy, at 3 different ventilator settings: baseline pressure support; 5 cm H_2O above baseline pressure support; and 5 cm H_2O below baseline pressure support. The diameter of the inner cannula of the tracheostomy tube was identical to the inner diameter of the removed ETT (8 mm in 7 patients, 7 mm in 1 patient). Tracheostomy was associated with trends in reductions in V_T, respiratory rate, and minute ventilation. At all pressure-support levels, tra-

Table 1.   Respiratory Variables Before and After Tracheostomy in 20 Surgical Intensive-Care Patients

Variable	Before Tracheostomy	After Tracheostomy	p
V_T (mL)	329 ± 104	312 ± 119	0.47
$\dot{V}_E$ (L/min)	9.2 ± 3.0	8.1 ± 3.1	0.26
f (breaths/min)	28 ± 5	26 ± 6	0.51
PEEPi (cm H_2O)	2.9 ± 1.7	1.6 ± 1.0	0.02
PTP (cm $H_2O \cdot$ s/min)	236 ± 122	155 ± 101	0.09
WOB (J/L)	0.97 ± 0.32	0.81 ± 0.46	0.09
WOB (J/min)	8.9 ± 2.9	6.6 ± 1.4	0.04
Exp R_{aw} (cm H_2O/s)	9.4 ± 4.1	6.3 ± 4.5	0.07

V_T = tidal volume
V_E = minute volume
f = respiratory rate
PEEPi = intrinsic positive end-expiratory pressure
PTP = pressure-time product
WOB = work of breathing
Exp R_{aw} = expiratory airway resistance (From Reference 14, with permission.)

Table 2.   Inner Diameter, Length, and Dead Space of Endotracheal and Tracheostomy Tubes

Tube Type	ID (mm)	Length (cm)	Dead Space (mL)
Endotracheal			
No. 6.0	6.0	31.5	11.0
No. 7.0	7.0	34.5	15.0
No. 8.0	8.0	35.5	18.0
No. 8.5	8.5	36.5	24.0
Tracheostomy*			
Size 4	5.0	10.0	3.0
Size 6	7.0	12.0	5.0
Size 8	8.5	12.0	6.0
Size 10	9.0	12.0	8.0

*Tracheostomy tube size is not equal to inner diameter.
ID = inner diameter (From Reference 14, with permission.)

cheostomy was associated with a decrease in the airway-occlusion pressure, a measure of respiratory drive. Moreover, reductions in both resistive WOB (Fig. 5) and elastic WOB, as indicated by a reduction in intrinsic PEEP (Fig. 6), occurred with placement of the tracheostomy. The latter physiologic benefits may explain the improvement in patient-ventilator synchrony seen in 3 patients who had frequent trigger asynchrony while breathing through an ETT.

Davis et al studied 20 surgical ICU patients (14 men, 6 women, mean age 58 years) with acute lung injury, ventilated for a mean of 16 days, who met extubation criteria but had failed extubation twice before the decision was made to proceed with tracheostomy.[14] Eighty percent of these patients had a #8 (8 mm inner diameter) ETT, while the remainder had a #7 (7 mm inner diameter) tube. Physiologic measurements were made 6–8 hours before and 10–12 hours after placement of a surgical tracheostomy. Tracheostomy was associated with trends in reduction in pressure-time product and expiratory airways resistance (Table 1). Importantly, as in the study by Diehl et al,[25] WOB (J/min) and intrinsic PEEP decreased after placement of the tracheostomy. Assuming equivalent inner diameter, reductions in resistive WOB most likely result from the reduction in tube length in going from ETT to tracheostomy tube (Table 2). Although dead space is also lower with tracheostomy, the magnitude is quite limited.

Tracheostomies differ from ETTs because the former may have a removable inner cannula. This inner cannula allows for easy removal and cleaning and occludes the fenestration to allow for effective mechanical ventilation. Cowan et al used a lung model to compare the physiologic effects of nonfenestrated tubes with and without the inner cannula.[26] Tubes of various sizes were studied during different ventilator settings (respiratory rate 12, 24, and 36 breaths/min, V_T 300 and 500 mL). Not unexpectedly, WOB decreased when the inner cannula was removed.

Summary

Tracheostomy tubes have an important effect on respiratory physiology. The most recent and methodological robust studies indicate that these tubes reduce resistive and elastic WOB when compared to ETTs. This is a result of tracheostomy tubes lessening inspiratory and expiratory airways resistance and intrinsic PEEP. Whether these physiologic benefits are of clinical importance in enhancing weaning success remains to be elucidated.

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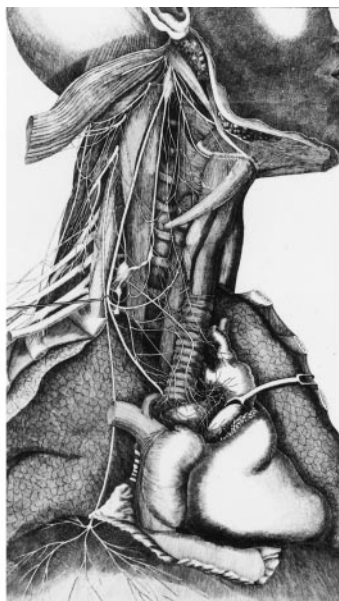
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