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Spatial Orientation and Mechanical Properties of the Human Trachea: A Computed Tomography Study

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BACKGROUND: The literature generally describes the trachea as oriented toward the right and back, but there is very little detailed characterization. Therefore, the aim of this study was to precisely determine the spatial orientation and to better characterize the physical properties of the human trachea. METHODS: We analyzed lung computed tomography scans of 68 intubated and mechanically ventilated subjects suffering from acute lung injury/ARDS at airway pressures (P_{aw}) of 5, 15, and 45 cm H_2O. At each P_{aw}, the inner edge of the trachea from the subglottal space to the carina was captured. Tracheal length and diameter were measured. Tracheal orientation and compliance were estimated from processing barycenter and surface tracheal sections. RESULTS: Tracheal orientation at a P_{aw} of 5 cm H_2O showed a 4.2 ± 5.3° angle toward the right and a 20.6 ± 6.9° angle downward toward the back, which decreased significantly while increasing P_{aw} (19.4 ± 6.9° at 15 cm H_2O and 17.1 ± 6.8° at 45 cm H_2O, $P < .001$). Tracheal compliance was 0.0113 ± 0.0131 mL/cm H_2O/cm of trachea length from 5 to 15 cm H_2O and 0.004 ± 0.0041 mL/cm H_2O/cm of trachea length from 15 to 45 cm H_2O ($P < .001$). Tracheal diameter was 19.6 ± 3.4 mm on the medial-lateral axis and 21.0 ± 4.3 mm on the sternal-vertebral axis. CONCLUSIONS: The trachea is oriented downward toward the back at a 20.6 ± 6.9° angle and slightly toward the right at a 4.2 ± 5.3° angle. Understanding tracheal orientation may help in enhancing postural drainage and respiratory physiotherapy, and knowing the physical properties of the trachea may aid in endotracheal tube cuff design. *Key words: trachea anatomy; trachea orientation.* [Respir Care 0;60(0):1–•. © 0 Daedalus Enterprises]

Introduction

The trachea is commonly described only as oriented toward the right and back.[1,2] There is little information in the literature describing its spatial orientation or physical characteristics.

Tracheal mucus transport is influenced by gravitational force[3]; an orientation of the trachea/endotracheal tube (ETT) below the horizontal plane (Trendelenburg position) prevented ventilator-associated pneumonia (VAP) in

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both sheep and swine models following prolonged mechanical ventilation. The trachea/ETT orientation promoted the outward drainage of bacteria-laden mucus, avoiding bacterial translocation from the oropharynx into the lungs.[4,5] Detailed knowledge of the orientation of the human trachea is therefore imperative for VAP prevention strategy in intubated patients.[6]

In this retrospective analysis of computed tomography (CT) images, the length, diameter, orientation, and compliance of tracheas from mechanically ventilated subjects at different airway pressures (P_{aw}) were investigated.

Methods

Data from a multi-center CT scan database of a previously published study were analyzed.[7] The study was approved by the institutional review board of each hospital, and written informed consent was obtained according to the national regulations of the participating institutions in Italy, Germany, and Chile.

Sixty-eight mechanically ventilated subjects with acute lung injury/ARDS underwent whole-lung CT scanning at 3 different airway pressures (5 and 15 cm H_2O end-expiratory pause and 45 cm H_2O end-inspiratory pause).

Subjects were enrolled if they met the criteria of the American-European Consensus Conference on ARDS[8] for acute lung injury ([P_{aO_2}/F_{IO_2}] of < 300 mm Hg), with bilateral pulmonary infiltrates on the chest radiograph and no clinical evidence of left atrial hypertension (defined by a pulmonary-capillary wedge pressure of ≤ 18 mm Hg, if measured). The exclusion criteria were < 16 y of age, pregnancy, and COPD according to the subject's medical history. Immediately before each CT session, a recruitment maneuver (ie, a sustained inflation of the lungs to higher P_{aw} and volumes than those obtained during tidal ventilation) was performed in which the subject underwent ventilation for 2 min (pressure control mode at an inspiratory plateau pressure of 45 cm H_2O, P_{aw} of 5 cm H_2O, breathing frequency of 10 breaths/min, and a 1:1 inspiration-to-expiration ratio). After the recruitment maneuver, a P_{aw} of 5 or 15 cm H_2O was randomly applied. The tidal volume (8–10 mL/kg of predicted body weight), F_{IO_2}, and breathing frequency were identical to the values used in everyday clinical treatment. A whole-lung CT scan was performed at an inspiratory plateau pressure of 45 cm H_2O, during an end-inspiratory pause (ranging from 15 to 25 s), and thereafter at P_{aw} of 5 and 15 cm H_2O applied randomly during an end-expiratory pause (ranging from 15 to 25 s). The CT scanner was set as follows: collimation, 5 mm; interval, 5 mm; bed speed, 15 mm/s; voltage, 140 kV; and current, 240 mA. During each CT scan, the endotracheal tube cuff was inflated at a pressure greater than the maximal pressure used during the recruitment maneuver (ie, > 45 cm H_2O).

QUICK LOOK

Current knowledge

The human trachea is commonly described only as oriented dorsally toward the right. There is little characterization of the trachea in terms of its spatial orientation or physical characteristics and how these impact both mucus clearance and the risk of pneumonia.

What this paper contributes to our knowledge

Data from computed tomography suggest that the trachea is oriented downward toward the back at a 20° angle and slightly to the right at a 4° angle. Understanding tracheal orientation may help to enhance postural drainage, and knowing the physical trachea properties may be useful for endotracheal tube cuff design.

For analysis, the inner edge of the trachea was manually drawn in each cross-sectional image (from the subglottal space to the carina) using Maluna 3 (University of Mannheim, Mannheim, Germany). The data were analyzed with SoftEfilm (www.elekton.it, *Accessed October 30, 2014*).

The CT scans were composed of a finite number of slices along the apex-base axis (~50 at end-expiratory pressure, P_{aw} of 5 cm H_2O). Each trachea was divided into 10 sections on the medial-lateral axis (Fig. 1, A and B) and then divided into 10 sections of equal length along the apex-base axis. Since voxel dimensions are discrete, this created discrete quantities of 5-mm high CT planes (ie, if the lung CT scan is composed of 47 slices, 7 sections composed of eleven 5-mm high planes and 3 sections composed of ten 5-mm high planes). To smooth the data set without voxel interpolation, each 5-mm high CT plane was substituted with 10 identical 0.5-mm CT planes; therefore, using 500 slices instead of 50 slices allowed a smoothing of 90% of the voxel attribution imbalance.

In each section, the barycenter along the 3 axes (coronal, frontal, and sagittal planes) was computed as: (1) barycenter on the medial-lateral axis (mm) = sum of positions on the medial-lateral axis/(n voxels), (2) barycenter on the apex-base axis (mm) = sum of positions on the apex-base axis/(n voxels), and (3) barycenter on the sternal-vertebral axis (mm) = sum of positions on the sternal-vertebral axis/(n voxels). Tracheal displacement along each axis was defined as: (4) tracheal displacement (mm) = barycenter (mm) of section 1 − barycenter (mm) of section n.

On the coronal plane, it was possible to draw a right-angle triangle with, as cathetus, the distance between the barycentric coordinates of 2 sections on the lung medial-lateral axis and the distance between the barycentric coordinates of 2 sections on the lung apex-base axis (see

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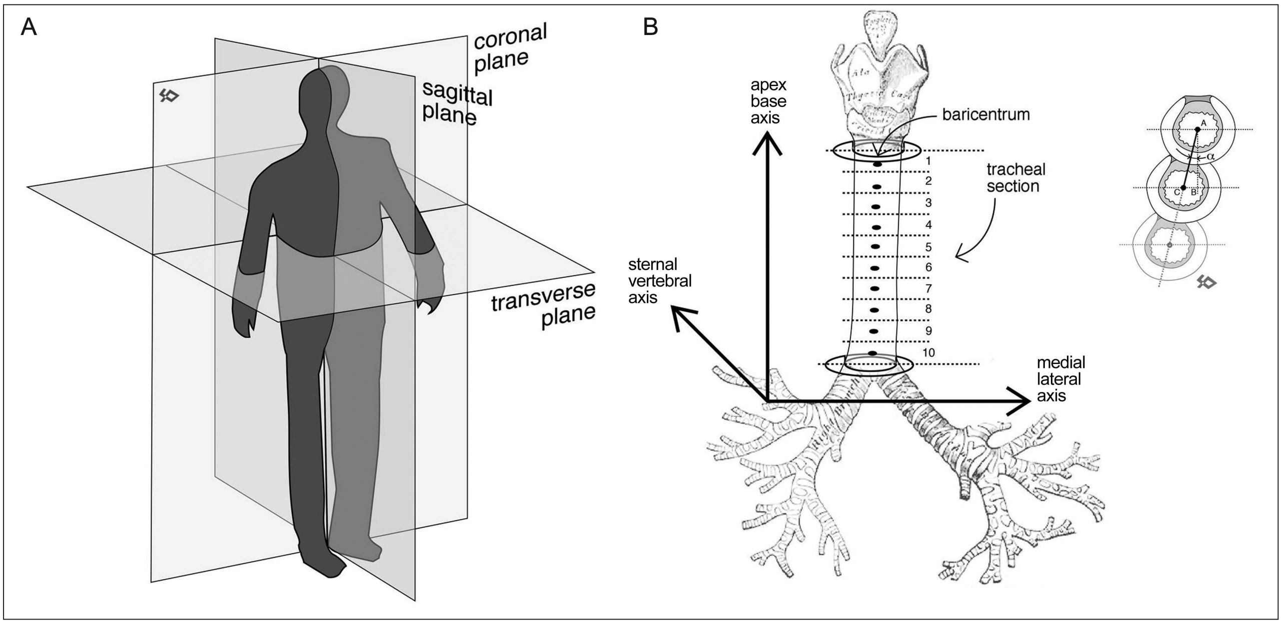

Fig. 1. A: The 3 different planes: sagittal, coronal, and transverse. B: The trachea divided into 10 sections, computed barycenter of each section along the 3 axes, and calculated tracheal displacement and tracheal angles on the coronal and sagittal planes.

Fig. 1). It follows that the tracheal angle on the coronal plane is: (5) angle on the coronal plane = arctan (tracheal displacement on the medial-lateral axis [mm] between sections 1 and 10/tracheal displacement on the lung apex-base axis [mm] between sections 1 and 10).

In the same way it was possible to compute the tracheal angle on the sagittal plane (Fig. 2): (6) angle on the sagittal plane = arctan (tracheal displacement on the sternal-vertebral axis [mm] between sections 1 and 10/tracheal displacement on the apex-base axis [mm] between sections 1 and 10).

Tracheal diameters and compliance were computed on sections 7 and 8, which represent ~1 cm of trachea length located 1 cm above the carina. These slices were selected because they are always below the ETT cuff, and in this position, the trachea maintains its shape, whereas immediately above the carina, the trachea elongates along the coronal plane. Tracheal compliance (normalized per cm of length) was calculated as the ratio between the increase in tracheal gas volume (mL) in sections 7 and 8 and the increase in P_{aw} (5–15 and 15–45 cm H_2O, respectively).

Statistical Analysis

Data are expressed as mean ± SD. Tracheal displacements, angles, diameters, and compliances at different P_{aw} were compared with the Friedman repeated-measures test; the Tukey correction was used for multiple comparisons. Statistical analysis was performed with the program R (http://www.R-project.org, *Accessed October 30, 2014*).

Results

Subjects were: 49% females, 55 ± 17 y old, body mass index of 25 ± 5 kg/m^2, Simplified Acute Physiology Score II of 37 ± 11, P_{aO_2}/F_{IO_2} of 200 ± 77 mm Hg, P_{aCO_2} of 42 ± 4 mm Hg, and expiratory minute volume of 9.8 ± 3 L/min.[7]

Tracheal lengths studied were 84 ± 19 mm. The total tracheal gas volume was 19.1 ± 7.6 mL at a P_{aw} of 5 cm H_2O. It significantly increased to 22.4 ± 9.1 and 26.3 ± 9.9 mL at 15 and 45 cm H_2O ($P < .001$), respectively.

Tracheal orientation at a P_{aw} of 5 cm H_2O showed a 4.2 ± 5.3° angle toward the right on the coronal plane corresponding to a tracheal displacement of 6.2 ± 7.6 mm (see Fig. 2A), and a 20.6 ± 6.9° angle corresponding to a displacement of 32.2 ± 11.0 mm downward toward the back on the sagittal plane (see Fig. 2B). Tracheal displacements at P_{aw} of 15 and 45 cm H_2O are reported in Table 1. The angle on the coronal plane did not significantly change with increasing P_{aw} ($P = .56$), whereas the angle on the sagittal plane significantly decreased with increasing P_{aw} ($P < .001$).

Tracheal diameters (sections 7 and 8) showed, on the coronal plane, a slight but significant increase with increasing P_{aw}, whereas on the sagittal plane, the increase was more significant (Table 2). Tracheal compliance (sections 7 and 8) was 0.0113 ± 0.0131 mL/cm H_2O/cm of trachea length at a P_{aw} of 5–15 cm H_2O and 0.004 ±

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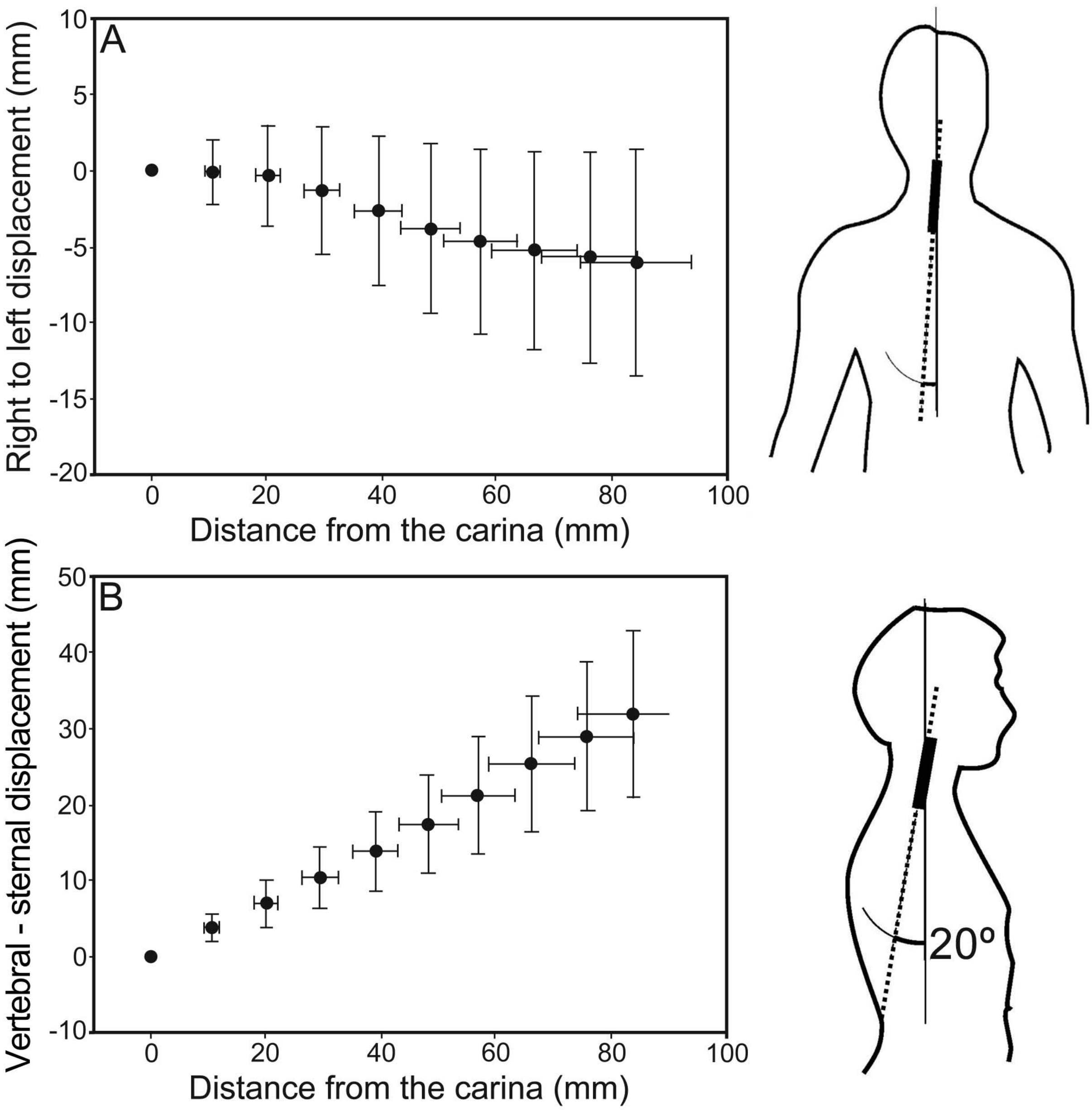

Fig. 2. A: Tracheal orientation on the coronal plane. The X axis represents the distance from the carina of each tracheal section (mm), and the Y axis represents the displacement on the medial-lateral axis (mm). Horizontal and vertical bars represent SD. The silhouette with the superimposed trachea shows the average angle of tracheal orientation (4.2 ± 5.3° angle downward toward the right). B: Tracheal orientation on the sagittal plane. The X axis represents the distance from the carina of each tracheal section (mm), and the Y axis represents the displacement on the sternal-vertebral axis (mm). Horizontal and vertical bars represent SD. The silhouette with the superimposed trachea shows the average angle of tracheal orientation (20.6 ± 6.9° angle downward toward the back).

0.0041 mL/cm H_2O/cm of trachea length at a P_{aw} of 15–45 cm H_2O.

Discussion

The results obtained on tracheal orientation agree with literature data that describe the trachea as a tube orientated toward the back and right. The calculations showed a 4.2 ± 5.3° angle toward the right and a 20.8 ± 6.7° angle toward the back at a P_{aw} of 5 cm H_2O. At higher P_{aw}, both angles decreased. The relevant angle toward the back implies a gravitational movement of secretions toward the lungs in a supine position and toward the mouth in a prone position. These results are compatible with the finding of ETT obstructions as a complication of a prone position[9] and the observed reduction in VAP incidence in a prone

Table 1. Summary of Tracheal Orientation With Increasing P_{aw} of 5, 15, and 45 cm H_2O

	Angle on sagittal plane	Tracheal displacement on sagittal plane (mm)	Angle on coronal plane	Tracheal displacement on coronal plane (mm)
P_{aw}				
5 cm H_2O	20.6 ± 6.9°	31.8 ± 11	4.2 ± 5.3°	6.2 ± 7.6
15 cm H_2O	19.4 ± 6.9°*	30.7 ± 11.1*	3.9 ± 5.1°	5.9 ± 7.7
45 cm H_2O	17.1 ± 6.9°*†	38.2 ± 11.2*†	3.8 ± 4.9°	6.2 ± 7.7
P (between P_{aw})	< .001	< .001	0.56	0.45

Angles and tracheal displacements between airway pressures (P_{aw}) were compared with the Friedman test for repeated measures, and the Tukey correction was applied for multiple comparisons.
* $P < .05$ vs P_{aw} of 5 cm H_2O.
† $P < .05$ vs P_{aw} of 15 cm H_2O.

Table 2. Summary of Tracheal Diameters Measured at Sections 7 and 8 With Increasing P_{aw} of 5, 15, and 45 cm H_2O

	Trachea diameter of sagittal plane (mm)	Trachea diameter of coronal plane (mm)
P_{aw}		
5 cm H_2O	19.6 ± 3.5	21.0 ± 4.3
15 cm H_2O	20.2 ± 3.5*	22.3 ± 4.3*
45 cm H_2O	20.4 ± 3.3*†	23.6 ± 4.4*†
P (between P_{aw})	< .001	< .001

Tracheal diameters were compared with one-way analysis of variance for repeated measures; the Tukey correction was applied for multiple comparisons.
* $P < .05$ vs P_{aw} of 5 cm H_2O.
† $P < .05$ vs P_{aw} of 15 cm H_2O.
P_{aw} = airway pressure

position.[10,11] Animal models of VAP have consistently found an association between the development of VAP and an orientation of the trachea/ETT below the horizontal plane.[3-5,12]

The translation of experimental results obtained in animal models in the clinical setting implies the understanding of the anatomical differences between humans and swine/sheep. In quadrupeds, the oral cavity is directly aligned with the pharynx and the tracheal opening, whereas in humans, the mouth forms a 90° angle with the pharynx. Thus, to utilize gravitational drainage of secretions and prevent aspiration, patients could be positioned prone or on their side to orient the trachea/ETT below the horizontal plane. When a patient is in a lateral or recovery position, being rotated on the left side would be more effective in preventing aspiration; to achieve the same effectiveness on the right side, it would require adding some degrees of Trendelenburg positioning. There is no conclusive evidence that the reduction of aspiration obtained with a prone position results in a significantly decreased rate of VAP in mechanically ventilated patients with respiratory failure,[13] whereas a randomized trial comparing semirecumbent and lateral-Trendelenburg positions with intubated and mechanically ventilated subjects is currently ongoing (http://compartint.net/gravityvaptrial/joomla/, *Accessed October 30, 2014*).

Characterization of the physical properties of the trachea may be relevant for the design of new ETT cuffs.[14-16] The trachea is a semirigid tube that connects the larynx to the main bronchi to allow the passage of air. It is composed of 15–20 C-shaped cartilaginous rings, opened dorsally, where a membranous wall (pars membranacea) completes the ring. The internal diameter is ~25 mm, and the length is ~12 cm.

As shown in this study regarding tracheal compliance, the pars membranacea is much more flexible than the cartilaginous rings. With increasing P_{aw}, the trachea was observed to deform and dilate, especially on the posterior side. Therefore, once the ETT cuff is inflated inside the trachea, the pressure exerted might differ on the posterior and anterior sides. Moreover, the low compliance observed in the applied P_{aw} range allows us to model the trachea as a semirigid body, which is unlikely to significantly affect the efficiency of protective ventilation with low tidal volumes. The main limitation of the data regarding tracheal compliance is that the section of the trachea with the ETT cuff was already deformed when the ETT cuff was inflated at a pressure slightly > 45 cm H_2O during the recruitment maneuver.

Conclusions

The trachea is oriented with a 4.2 ± 5.3° angle toward the right and a 20.6 ± 6.9° angle toward the back. This information can be useful in the prevention of pulmonary aspiration and VAP and also in all pathological conditions that require strategies to promote the clearance of oropharyngeal and tracheal secretions.

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