Developmental Changes of Laryngeal Dimensions in Unparalyzed, Sedated Children

Ronald S. Litman, D.O.,* Eric E. Weissend, M.D.,† Dean Shibata, M.D.,‡ Per-Lennart Westesson, M.D., Ph.D., D.D.S.§

Background: **Knowledge of the influence of age on laryngeal dimensions is essential for all practitioners whose interest is the pediatric airway. Early cadaver studies documented that the larynx is conically shaped, with the apex of the cone caudally positioned at the nondistensible cricoid cartilage. These dimensions change during childhood, as the larynx assumes a more cylindrical shape. The authors analyzed laryngeal dimensions during development to determine if this relationship continues in unparalyzed children in whom laryngeal muscles are tonically active. The authors determined the relationships between the vocal cord, sub–vocal cord, and cricoid ring dimensions and the influence of age on these relationships.**

Methods: **Infants and children undergoing magnetic resonance imaging with propofol sedation had determinations of the transverse and anterior–posterior (AP) dimensions of the larynx at the most cephalad level of the larynx (vocal cords) and the most caudad level (cricoid). Most patients had an additional measurement (sub–vocal cord) at a level between the vocal cords and the cricoid ring. Relationships were obtained by plotting age against laryngeal dimensions and the ratio of laryngeal dimensions at different levels within the larynx.**

Results: **The authors measured transverse and AP laryngeal dimensions in 99 children, aged 2 months–13 yr. The relationship between the transverse and AP dimensions at all levels of the larynx did not change during development. Transverse and AP dimensions increased linearly with age at all levels of the larynx. In all children studied, the narrowest portion of the larynx was the transverse dimension at the level of the vocal cords. Transverse dimensions increased linearly in a caudad direction through the larynx ($P < 0.001$), while AP dimensions did not change relative to laryngeal level. The shape of the cricoid ring did not change throughout childhood.**

Conclusions: **In sedated, unparalyzed children, the narrowest portions of the larynx are the glottic opening (vocal cord level) and the immediate sub–vocal cord level, and there is no change in the relationships of these dimensions relative to cricoid dimensions throughout childhood.**

THE development and growth of the larynx during childhood has been a subject of interest for over a century.[1] Knowledge of the influence of the age of the child on laryngeal dimensions is essential for all practitioners whose interest is the pediatric airway. Early studies in cadaver specimens documented the cartilaginous and bony framework of the larynx throughout childhood.[1–3] These studies determined that the larynx is conically shaped, with the apex of the "cone" caudally positioned at the nondistensible cricoid cartilage. These dimensions change during childhood as the larynx assumes a cylindrical, rather than a conical shape.[4] It is unknown if this relationship continues to exist in unparalyzed children in whom laryngeal muscles demonstrate tonic activity.[5] Therefore, we undertook this study to determine the influence of age on laryngeal dimensions. Most specifically, we were interested in the relationships between vocal cord, sub–vocal cord, and cricoid ring dimensions, and how these relationships change as children grow. We hypothesized that these relationships change during development and may influence clinical airway management.

Materials and Methods

The Research Subjects' Review Board of the University of Rochester (Rochester, New York) approved this study, and written informed consent was obtained from all parents of children in the study. Children who were old enough to understand that they were participating in a research study gave their assent. Children aged 0–14 yr who presented for an elective magnetic resonance imaging scan with deep sedation were eligible to participate. Consecutive children were enrolled within the limits of investigator-related and clinical situations. Exclusion criteria included obvious anatomical deformities of the head or neck, or any other condition the investigators felt would cause abnormal laryngeal anatomy. Children who received airway management with either a laryngeal mask airway or endotracheal tube were also excluded.

The study was performed in children who were deeply sedated with $200 \ \mu g \cdot kg^{-1} \cdot min^{-1}$ propofol. Most children did not previously have an indwelling intravenous catheter and therefore initially received a mask anesthetic with sevoflurane and nitrous oxide, both of which were discontinued after intravenous catheter placement. Spontaneous ventilation was maintained throughout the procedure. A nasal cannula provided oxygen, usually at 2 l/min. Monitors included continuous electrocardiography, pulse oximetry, capnography (*via* the nasal cannula), and intermittent automated blood pressure determinations (Medrad, Inc., Indianola, PA). A best attempt was made to position the child's head in the neutral position, usually with a folded sheet beneath the neck or shoulders. Occasionally, a nasal or oral airway device was used to assist with maintenance of upper

* Associate Professor of Anesthesiology and Pediatrics, University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania. † Staff Anesthesiologist, Lackland Air Force Medical Center, San Antonio, Texas. ‡ Assistant Professor of Radiology, University of Washington School of Medicine, Seattle, Washington. § Professor of Radiology, University of Rochester School of Medicine and Dentistry.

Address reprint requests to Dr. Litman: Department of Anesthesiology and Critical Care Medicine, Children's Hospital of Philadelphia, 34th Street and Civic Center Boulevard, Philadelphia, Pennsylvania 19104. Address electronic mail to: litmanr@email.chop.edu. Individual article reprints may be purchased through the Journal Web site, www.anesthesiology.org.

41

airway patency if excessive head or neck movement occurred with each breath. No attempt was made to obtain images at a certain point in the respiratory cycle.

Magnetic resonance imaging was performed on a 1.5-T unit with a quadrature head coil (GE Medical Systems, Milwaukee, WI). T1 spin-echo images were obtained with 3-mm slices at 0.5-mm intervals.

Measurements

Axial scans were obtained with the oropharynx as the most cephalad limit and the trachea below the cricoid cartilage as the most caudad limit. A reference sagittal image was used to help identify the proper level of the vocal cords. The cricoid cartilage was identified as the most caudad part of the larynx that was continuous posteriorly. In each child, transverse and anterior–posterior (AP) dimensions of the larynx were measured at a minimum of two levels—the vocal cords and cricoid ring. Most children had at least one additional level measured between the vocal cords and cricoid cartilage, depending on their size. Two authors measured each child's larynx independently. When there was a discrepancy between the two, the final value was decided upon by consensus or with assistance from a third author. A radiologist author was involved with measurement of every child.

Results were obtained by plotting the dependent variable (age) against the independent variables—laryngeal dimensions, and the ratio of laryngeal dimensions at different levels (Origin, Microcal Software, Northhampton, MA). The sub-vocal cord level was defined as the magnetic resonance imaging slice immediately caudad to the vocal cords but above the cricoid ring.

Statistical Analysis

Linear regression was used to determine the relationship between dependent and independent variables. Kruskal-Wallis and Mann–Whitney tests were used to compare continuous nonparametric data (difference between laryngeal dimensions at different levels). A *P* value of 0.05 or less was used to indicate statistical significance.

Results

One hundred nine children initially enrolled in the study. Ten were excluded because of various reasons that included movement artifact (4), scanner malfunction (1), abnormal laryngeal anatomy (2), and corrupted optical disks that prevented retrieval of the scans (3). Therefore, 99 children are presented for analysis and are described in table 1. In the initial data analysis, males and females were analyzed separately. However, since their results were essentially the same, we report the aggregate results.

Table 1. Demographic Characteristics of Children Included for Analysis

Boys (n = 53)	
Age (months)	61.1 ± 41.6
Weight (kg)	21.1 ± 11.7
Height (cm)	106.0 ± 25.9
Girls (n = 46)	
Age (months)	62.1 ± 41.9
Weight (kg)	22.2 ± 16.3
Height (cm)	107.5 ± 27.5

Values are expressed as mean ± SD.

The relationship between the transverse and AP dimensions at all levels of the larynx, including the cricoid ring, did not change during development. Transverse dimensions were narrower than AP dimensions at all levels of the larynx above the cricoid ring and in most children at the cricoid ring (fig. 1). Transverse and AP dimensions increased linearly with age at all levels of the larynx (fig. 2, $P < 0.001$ for all dimensions).

In all children studied, the narrowest portion of the larynx was the transverse dimension at the level of the
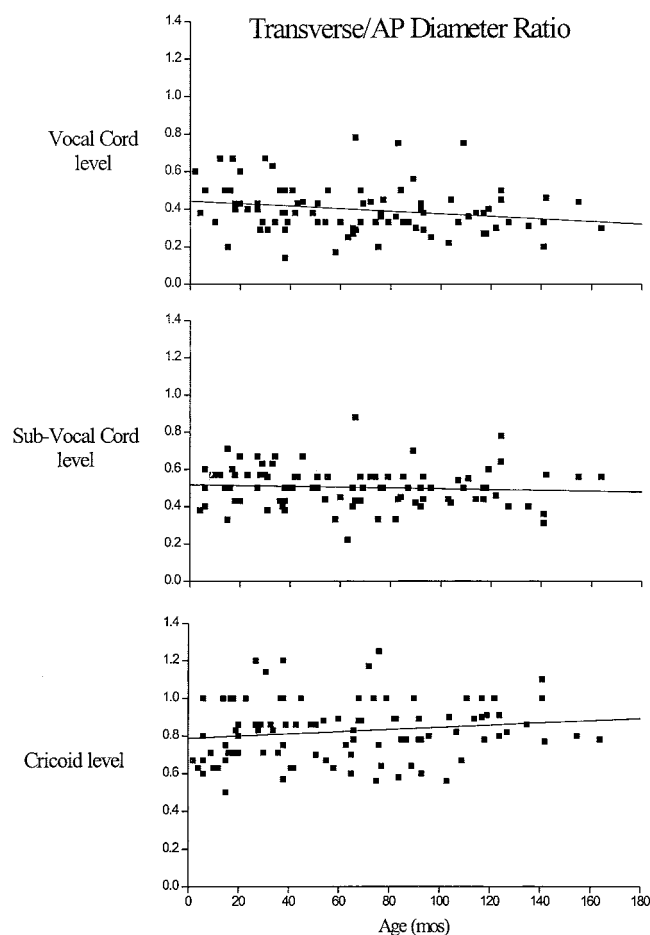

Fig. 1. Transverse to anterior–posterior (AP) dimension ratios at different levels within the larynx. These ratios do not change during development. Vocal cord level: $r = -0.2$, $P = 0.04$; sub–vocal cord level: $r = -0.1$, $P = 0.4$; cricoid level: $r = 0.2$, $P = 0.1$.
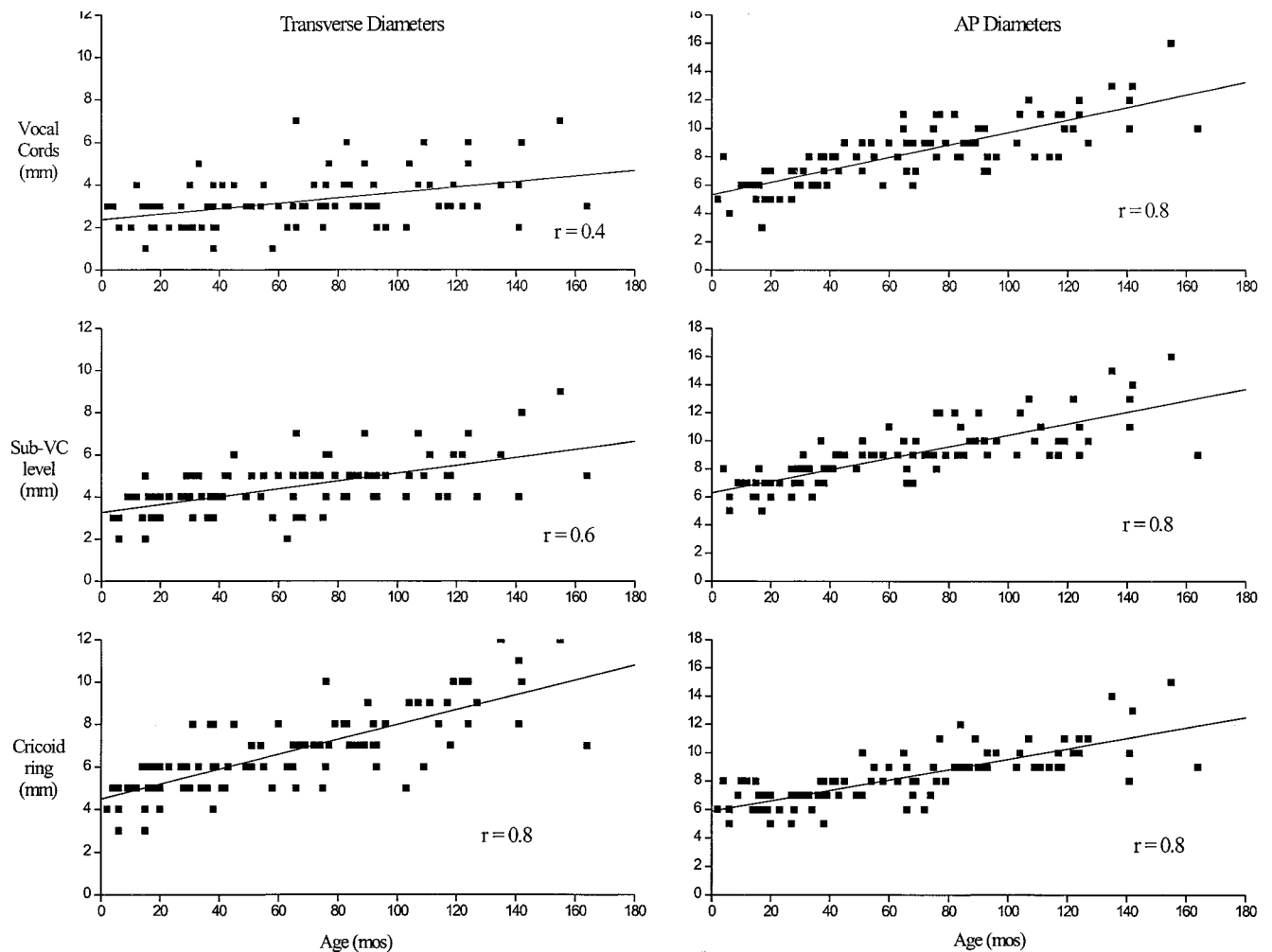
Fig. 2. Absolute transverse and absolute laryngeal diameters during development. All increase linearly with increasing age (*P* < 0.001). AP = anterior–posterior; VC = vocal cord.

vocal cords. Transverse dimensions increased linearly in a caudad direction through the larynx (*P* < 0.001, fig. 3, top), while AP dimensions did not change relative to laryngeal level (fig. 3, bottom). Thus, during spontaneous breathing in unparalyzed, sedated children, the larynx is conical shaped in the transverse dimension (with the apex of the cone at the level of the vocal cords) and is cylindrical shaped in the AP dimension. These relationships are demonstrated in a representative scan (fig. 4).

Discussion

The major finding of this study is that in sedated, unparalyzed children, the shape of the larynx is conical in the transverse dimension (with the apex of the cone at the level of the vocal cords) and cylindrical in the AP dimension, and does not change throughout development. This is in contrast to that of the atonic larynx, in which cadaver specimens have demonstrated that the larynx is conical with the apex at the caudally positioned cricoid ring during early childhood.[1–3] During develop-

ment, the transverse dimension of the atonic larynx assumes a more cylindrical shape, although the age at which this occurs is not precisely known.[4]

In publications that used measurements from cadaver specimens, the portions of the larynx cephalad to the cricoid ring could be distended since these areas do not contain full circumferential cartilage. The patients included in the present study were deeply sedated and not paralyzed. Active contraction of the laryngeal muscles influenced the dimension of the larynx above the cricoid ring, especially at the level of the vocal cords, which continue to move during spontaneous respiration.[5] Indeed, lightening of consciousness in anesthetized adults is associated with increasing tracheal cuff pressures,[6] and lack of paralysis in anesthetized children is associated with an audible leak at an increased airway pressure.[7] This is further borne out by the increased variability of the transverse dimensions at the level of the vocal cords compared with other levels of the larynx (fig. 2, top left). Thus, although our measurements describe the glottic opening to be the narrowest portion of the larynx
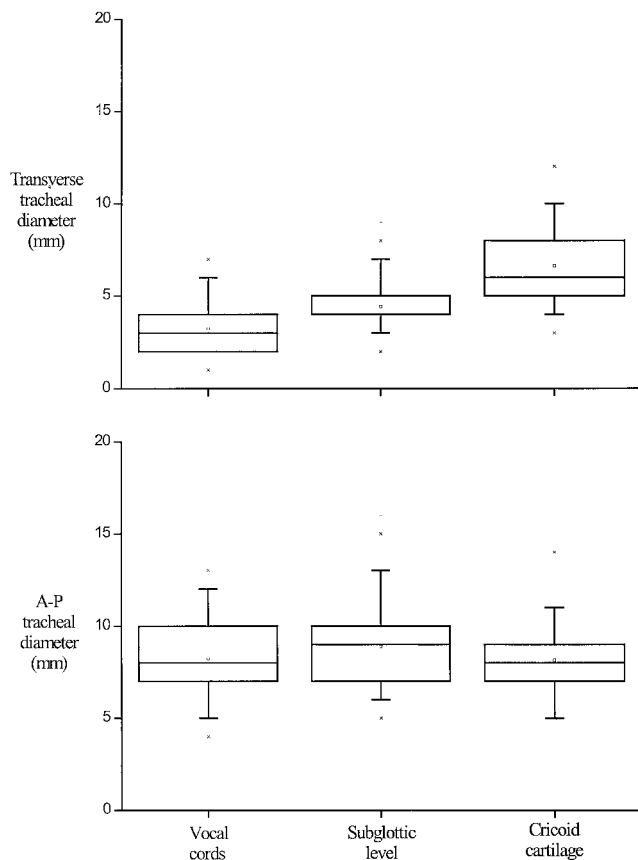
Fig. 3. Box plots demonstrating the relationship between tracheal transverse (*top*) and anterior–posterior (A-P; *bottom*) diameters at the levels of the vocal cords, subglottic area, and cricoid ring. Transverse diameters increased linearly in a caudad direction ($P < 0.001$). The middle line of the box is the 50th percentile, the ends of the boxes are the 25th and 75th percentiles, and the whiskers represent the 5th and 95th percentiles. The square box represents the mean, the 1st and 99th percentiles are denoted by Xs, and the dashed lines are the minimum and maximum values.

in spontaneously breathing, unparalyzed children, the rigid cricoid ring is functionally the narrowest portion of the larynx.

A limitation of these findings is that we did not attempt to image the larynx in any particular phase of respiration. Since vocal cord dimensions likely change in spontaneously breathing, sedated children, the dimensions that we measured should be considered to be an average measurement during movement of the vocal cords during spontaneous respiration. Therefore, it is possible that in some children, the vocal cords were "captured" in a more adducted state than usual, as in expiration. If this occurred in a significant number of our subjects, the shape of the larynx in the transverse direction would be more cylindrical than conical. An alternative explanation for our findings is the possible influence of propofol on vocal cord position. In dogs, propofol depresses vocal cord abductor (posterior cricoarytenoid muscle) and vocal cord tensor (cricothyroid muscle) activity[8] and may

have influenced vocal cord positions in the children we studied.

In 1951, Eckenhoff[4] published a seminal article on characteristics of the infant larynx and their influence on endotracheal anesthesia. This article was one of the first to emphasize that the cricoid cartilage is functionally the narrowest point of the upper respiratory tract of the child. Eckenhoff described the cricoid plate as "inclined posteriorly at its superior aspect, so that the larynx is funnel shaped with the narrowest point of the funnel at the laryngeal exit." This narrowest point is described as possibly smaller than more cephalad portions of the trachea. Eckenhoff stated that as the child grows, the cricoid plate becomes vertical, and the larynx becomes more cylindrical shaped. He derived this information from Bayeux,[1] who used moulages and anatomic sections of 15 children, aged 4 months to 14 yr. Bayeux documented that the circumference of the cricoid ring was narrower than that of the trachea or the glottis. Our results do not allow us to make direct comparisons with the findings of Eckenhoff and Bayeux since we measured dimensions in the tonically active larynx.

The clinical importance of our findings is speculative. On one hand, our results indicate that choosing an endotracheal tube based on the size of the cricoid ring may not prevent mucosal damage to the larynx cephalad to the cricoid ring in unparalyzed children. On the other hand, these more cephalad portions of the larynx consist of yielding structures that distend with placement of a relatively larger endotracheal tube. The cricoid ring is unyielding and prone to development of edema and scarring in response to excessive mucosal pressures.
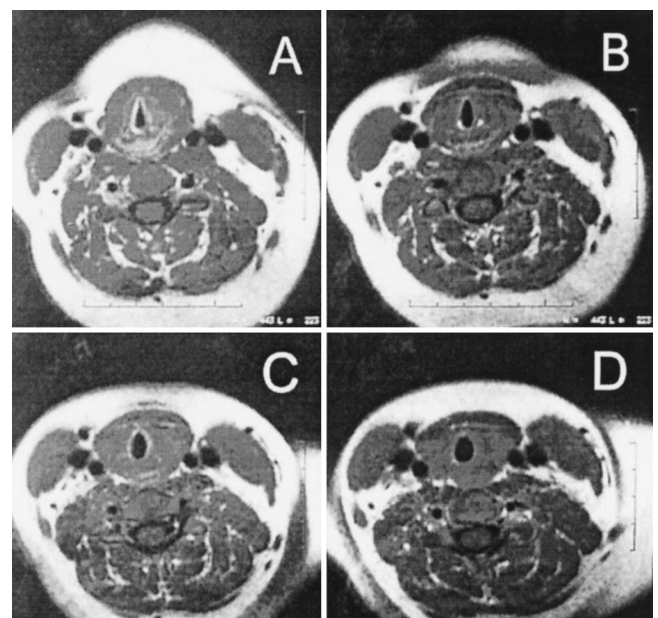

Fig. 4. Representative sample of axial magnetic resonance imaging slices through the vocal cords (*A*), subglottic levels (*B* and *C*), and cricoid ring (*D*). Transverse diameters increase in a caudad direction.

Autopsy studies have described the laryngeal pathology that occurs with prolonged intubation and mechanical ventilation in children. The entire larynx is often involved, and the most severe damage often occurs at the level of the vocal cords.[9-14] Our findings are consistent with these pathologic observations. Although it is not specifically mentioned in these studies, one can speculate that the children included in these autopsy studies did not consistently receive neuromuscular blockade, and therefore, the glottic regions above the cricoid were the most narrow and bore the brunt of endotracheal tube irritation and mucosal damage.

In summary, we found that in sedated, unparalyzed children, the narrowest portions of the larynx are the glottic opening (vocal cord level) and the immediate sub–vocal cord level, and there is no change in the relationships of these dimensions, relative to cricoid ring dimensions, throughout childhood. In addition, we found that the shape of the cricoid ring does not change during development. Our findings offer a plausible mechanism for the more cephalad laryngeal (glottic) damage that occurs in chronically intubated children.

References

1. Bayeux: Tubage de Larynx dans le Croup. Presse Med 1897; 20:I
2. Butz RO Jr: Length and cross-section growth patterns in the human trachea. Pediatrics 1968; 42:336–41
3. Wailoo MP, Emery JL: Normal growth and development of the trachea. Thorax 1982; 37:584–7
4. Eckenhoff JE: Some anatomic considerations of the infant larynx influencing endotracheal anesthesia. ANESTHESIOLOGY 1951; 12:401–10
5. Van Lunteren E, Strohl KP: The muscles of the upper airways. Clin Chest Med 1986; 7:171–88
6. Knowlson GT, Bassett HF: The pressures exerted on the trachea by endotracheal inflatable cuffs. Br J Anaesth 1970; 42:834–7
7. Finholt DA, Henry DB, Raphaely RC: Factors affecting leak around tracheal tubes in children. Can Anaesth Soc J 1985; 32:326–9
8. Iwasaki H, Ohmori H, Yamauchi M, Namiki A: Differential effects of propofol, thiamylal and ketamine on the crico-thyroid and posterior cricoarytenoid muscles of the canine larynx. Can J Anaesth 1996; 43:39–43
9. Liu H, Chen JC, Holinger LD, Gonzalez-Crussi F: Histopathologic fundamentals of acquired laryngeal stenosis. Pediatr Pathol Lab Med 1995; 15:655–77
10. Chen JC, Holinger LD: Acquired laryngeal lesions: Pathologic study using serial macrosections. Arch Otolaryngol Head Neck Surg 1995; 121:537–43
11. Minnigerode B, Richter HG: Pathophysiology of subglottic tracheal stenosis in childhood. Prog Pediatr Surg 1987; 21:1–7
12. Hawkins DB: Hyaline membrane disease of the neonate prolonged intubation in management: effects on the larynx. Laryngoscope 1978; 88:201–24
13. Gould SJ, Graham J: Long term pathological sequelae of neonatal endotracheal intubation. J Laryngol Otol 1989; 103:622–5
14. Joshi VV, Mandavia SG, Stern L, Wiglesworth FW: Acute lesions induced by endotracheal intubation: Occurrence in the upper respiratory tract of newborn infants with respiratory distress syndrome. Am J Dis Child 1972; 124:646–9