Received: 7 September 2019 | Revised: 9 January 2020 | Accepted: 18 January 2020
DOI: 10.1111/pan.13832

RESEARCH REPORT

Pediatric Anesthesia WILEY

Developmental changes of upper airway dimensions in children

Romain Luscan[1,2] | Nicolas Leboulanger[1,2,3] | Pierre Fayoux[4] | Gaspard Kerner[2,5] | Kahina Belhous[6] | Vincent Couloigner[1,2] | Erea-Noël Garabedian[1,2] | François Simon[1,2] | Françoise Denoyelle[1,2] | Briac Thierry[1,7]

[1]Pediatric Otorhinolaryngology Department, APHP, Hôpital Universitaire Necker-Enfants-Malades, Paris, France
[2]Université de Paris, Université Paris Descartes, Paris, France
[3]INSERM U955 Team 13 – ERL 7240, Institut Mondor Pour la Recherche Biomédicale, Créteil, France
[4]Pediatric Otorhinolaryngology - Head Neck Surgery – Jeanne de Flandre Hospital, CHU Lille, Lille, France
[5]Laboratory of Human Genetics of Infectious Diseases, INSERM UMR 1163, Necker Branch, Université de Paris, Paris, France
[6]Pediatric Radiology, APHP, Hôpital Universitaire Necker-Enfants-Malades, Paris, France
[7]Human Immunology, Pathophysiology and Immunotherapy, Division Stem cell Biotechnologies, INSERM, UMR976, Université de Paris, Paris, France

Correspondence
Romain Luscan, Pediatric Otorhinolaryngology Department, APHP, Hôpital Universitaire Necker-Enfants-Malades, 149 rue de Sèvres, 75015, Paris, France.
Email: romain.luscan@aphp.fr

Section Editor: Britta von Ungern-Sternberg

Abstract

Background: Knowledge about airway dimensions during child growth is of paramount importance for pediatric clinical practice. Decisions about airway management in children are based on relatively limited, imprecise, or incomplete data about airway size.

Aims: The aim of this work was to determine the anatomical development and size of airway structures from birth to adolescence using high-resolution computed tomography scans and to study the correlation between airway measurements and biometric data.

Methods: We conducted a retrospective study of all high-resolution computed tomography scans including the respiratory tract, performed in our tertiary pediatric center (for reasons unrelated to airway symptoms) between June 1, 2016, and October 15, 2017, on children aged from 1 day to 14 years old. On each scan, 23 measurements of the larynx, trachea, and mainstem bronchi were performed. Patients were stratified into 16 groups according to their age. We calculated median value for each measurement in each group. Statistical models were calculated to explore correlation between measurements and age or weight.

Results: A total of 192 scans were included (127 boys/65 girls). The mean age was 7 years. The correlations between airway measurements and age or weight were always significant. The relationship between measurements and age was found to be suitably represented by a cubic polynomial equation suggesting that the airway has a rapid growth phase in the first 3 years, followed by a slow growth phase and a second rapid growth phase during adolescence. The most relevant biometric parameter was age concerning 21 of the measurements.

Conclusion: This comprehensive anatomical database of upper airway dimensions provides important data in the field of pediatric airway anatomy, particularly relating to the cricoid. We demonstrated that laryngeal, tracheal, and bronchial parameters correlate better to age and have three different growth phases.

KEYWORDS
age, dimensions, endotracheal tube, pediatric airway, weight

1 | INTRODUCTION

The development and growth of the respiratory tract during childhood has been a topic of interest for over a century.[1] Indeed, knowledge of airway dimensions during child growth is of paramount importance in various pediatric fields: anesthesiology, pneumology, airway surgery, and critical care. Clinicians face two major problems: relatively limited, imprecise, or incomplete data about pediatric airway size,[2-12] and difficulty of airway size assessment in current clinical practice. Thereby, many of the decisions made in these fields rely on the physician's experience or calculations and extrapolations from age, weight, or finger size.[13-16] In the era of evidenced-based medicine, it seems important to complement this valuable experience with precise measurements of the pediatric airway based on a large number of parameters, on a large cohort and correlated to biometric data.[17]

Different techniques have been described to determine airway growth during childhood. Cadaveric studies enable precise analysis of the anatomy but muscular atony and tissue shrinkage in fixed specimens lead to distortions.[3-5,7-9,18,19] Out of the numerous radiological modalities used to assess the pediatric airway, the CT scan is the current gold standard for respiratory tract measurements due to its good discrimination of the air/tissue interface.[20-22] It allows for precise measurements of the inner portions of the larynx and trachea and is routinely used, providing a large number of available airway data.

The aim of this study was to determine the anatomical development and dimensions of laryngeal, tracheal, and bronchial structures from birth to adolescence using high-resolution computed tomography scans (HRCT scans) and to study the correlation between airway measurements and biometric data.

2 | MATERIALS AND METHODS

A retrospective monocentric study was conducted in our pediatric tertiary care center in accordance with STROBE guidelines.[23]

2.1 | Imaging characteristics and inclusion criteria

All "Willis Thoraco-Abdomino-Pelvic" (Willis TAP) HRCT scans performed in our Pediatric Trauma Center, between June 1, 2016, and October 15, 2017, on children aged from 1 day to 14 years old, were studied. The Willis TAP protocol was performed as part of the initial evaluation of children presenting with polytrauma in our pediatric trauma center. The acquisition protocol was as follows: first nonenhanced acquisition from the vertex up to C2; second acquisition from the pubic symphysis up to the orbital roof after intravenous injection of iodinated contrast medium at an arterioportal time (55-60 seconds) with bony, parenchymal, and soft-tissue reconstructions. The acquisitions were performed using GE Revolution HD scanner (GE Healthcare®), identification number: HDDGV1600015CN.

What is already known about the topic

- Decisions about airway management in children are based on relatively limited, imprecise, or incomplete data about airway size.

What new information this study adds

- We provide important new pediatric airway anatomical data, particularly regarding the cricoid. We show that a cubic polynomial seems to best represent the relationship between airway measurements and age: the pediatric airway has a rapid growth phase up until 3 years of age, followed by a slow growth phase and a second rapid growth phase during adolescence.

2.2 | Exclusion criteria

The exclusion criteria were as follows: airway trauma, airway obstruction, or any other laryngo-tracheal condition; intubated patients; incomplete CT scan or poor-quality images; vocal cord adduction or collapse of the upper airways.

TABLE 1 Definitions of the measurements performed on each HRCT scan

Location of the measurement	Definition	Unit
Larynx	Length between the tip of epiglottis and the glottic level	mm
	Length between the glottic plan and the inferior plan of the cricoid	mm
Glottic level	AP diameter	mm
	Area	mm^2
Cricoid ring	AP diameter	mm
	T diameter	mm
	Area	mm^2
Trachea	Length between the inferior plane of the cricoid ring and the carina	mm
End of the trachea (last tracheal cartilage)	AP diameter	mm
	T diameter	mm
	Area	mm^2
RMB and LMB	Length	mm
Beginning of the RMB and the LMB	AP diameter	mm
	T diameter	mm
	Area	mm^2
End of the RMB and the LMB	AP diameter	mm
	T diameter	mm

Abbreviations: AP, Anteroposterior; LMB, Left Mainstem Bronchus; RMB, Right Mainstem Bronchus; T, Transverse.

2.3 | Measurements

The HRCT scans were analyzed using Carestream Motion View® (Carestream Health Solution). Patients' medical records were reviewed for anthropometric data (age, sex, and weight at the time of the HRCT scan).

For each CT scan, a single investigator performed 23 measurements using the same method, as described in Table 1 and Figure 1. The investigator was blinded to age and weight of the patients until measurements were performed. Images were analyzed in pulmonary window and multiplanar reconstruction mode. Different anatomical landmarks were notched: tip of the epiglottis, glottic plane, and inferior cricoid plane. Thirteen diameter and five area measurements were performed. Five lengths were measured after thickening cuts using the MinPR (8 mm) mode.

2.4 | Statistical analysis

Patients were stratified into 16 groups according to their age. Under 1 year of age, patients were divided into two groups: 0-5 months and 6-11 months; thereafter, they were divided into 1-year range groups. Mean weight and standard deviation were calculated for each group. Median value was calculated for each measurement in each group.

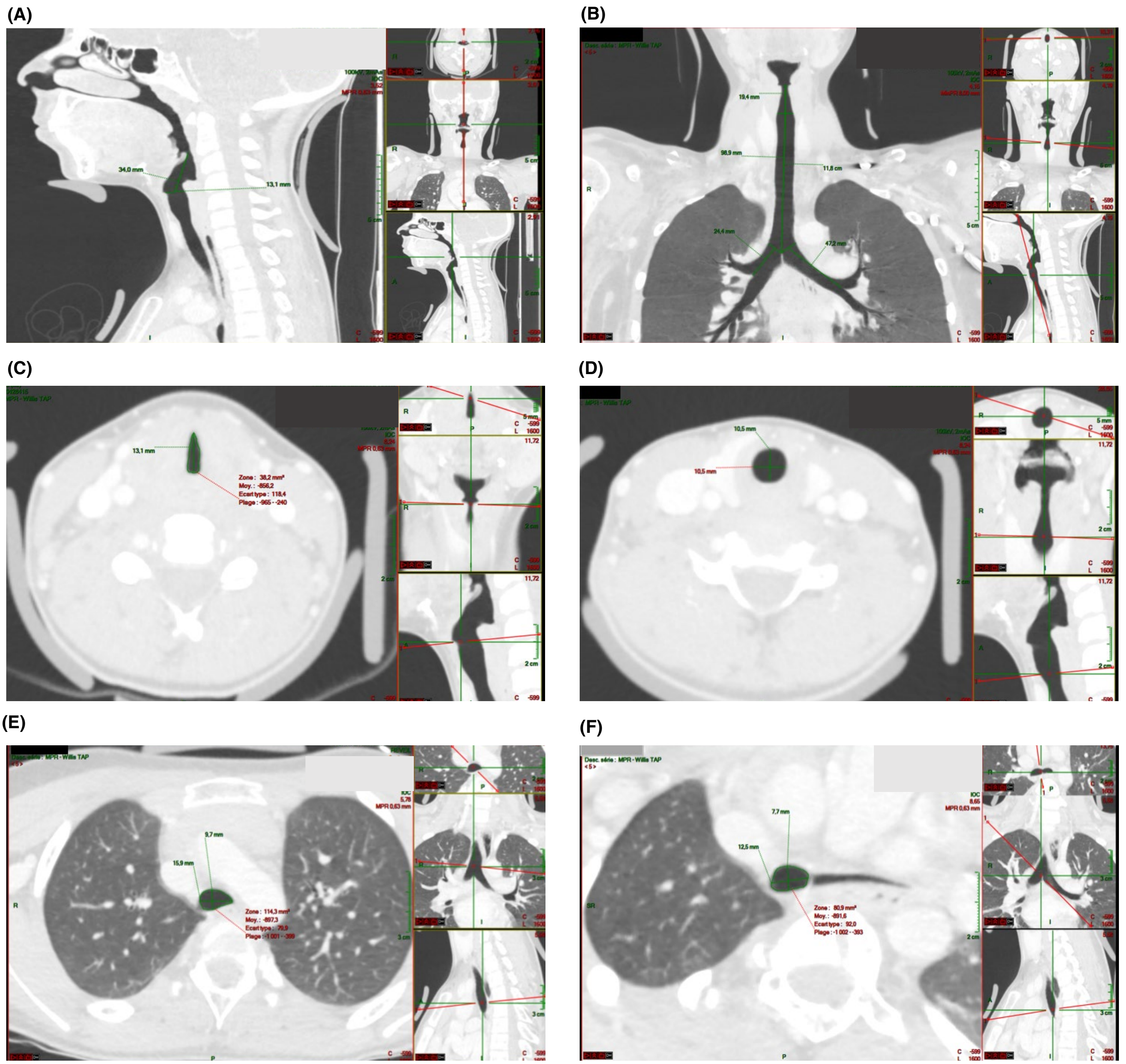

FIGURE 1 Illustrations of the methodology used for airway measurements. A, Length tip epiglottis—glottis. B, Length glottis—cricoid ring, tracheal, and bronchial length. C, Glottic level measurements. D, Cricoid level measurements. E, Tracheal measurements. F, Right mainstem bronchus proximal measurements [Colour figure can be viewed at wileyonlinelibrary.com]

To test the intra-rater reliability, the length between the glottic plane and the end of the trachea was measured and compared to the sum of, the length between the glottic plane and inferior plane of the cricoid, and the tracheal length, using a paired *t* test.

We studied the correlation between radiological airway measurements and biometric data (age and weight). Models for the dependence of airway measurements on age or weight were selected by successive testing of the cubic, quadratic, and linear models using the classical model selection estimator AIC (Akaike information criterion).[24,25] For each dependent measurement, the regression model accounting for the smallest AIC value (blue curve) and 95% confidence interval (gray shadow) was drawn on the data scatterplot. Statistical analysis was made using R (R Foundation for Statistical Computing).

In accordance with French law, no ethical agreement is necessary concerning retrospective noninterventional data studies.

3 | RESULTS

Overall, 317 CT scans were eligible, 125 were excluded (Figure S1). A total of 192 patients were included (127 boys/65 girls). Mean age was 7.3 years (range 0.1-14.8 years; SD 4.3 years, IQR 7.8 years), and mean weight was 28 kg (range 4-90 kg, SD 15.5 kg). The distribution of weight relating to age is presented in Figure S2. For each of the 16 age groups, biometric data are shown in Table 2.

Median value of each airway measurement is presented in Table 3.

The mean length between the glottic plane and the end of the trachea was 89.95 mm. The mean value of the sum of, the length between the glottic plane and the inferior plane of the cricoid, and the tracheal length, was 90.05 mm. The difference between the means was 0.095 mm [IC 95%: 0.005; 0.186].

Models for the dependence of airway measurements on age or weight with the 5th and 95th percentiles curves are illustrated for each parameter in Figure 2 (anteroposterior glottic and cricoid diameters, both typical examples). Models to all the other measurements can be found in Figure S3.

Correlations between airway measurements and age were always significant ($P < .0001$) under the model selected by the AIC. The relationship between measurements and age was found to be suitably represented by a cubic polynomial equation with the highest correlation for 18 measurements. Our results showed that pediatric airways have a rapid growth phase during the first 3 years of life, followed by a slow growth phase and a second rapid growth phase during adolescence (from 11 years of age onwards) (Figure 2 and Figure S3).

Also, correlations between airway measurements and weight were always statistically significant ($P < .0001$). The relationship between measurements and weight was best represented by a cubic polynomial equation, associated with the highest correlation (14 measurements).

Concerning 21 of the 23 measures, the most relevant biometric parameter was the age (ns) according to the AIC.

TABLE 2 Demographic characteristics of children included for analysis

Age	0-0.5 y	0.5-1 y	1-2 y	2-3 y	3-4 y	4-5 y	5-6 y	6-7 y	7-8 y	8-9 y	9-10 y	10-11 y	11-12 y	12-13 y	13-14 y	14-15 y
n (Girls/Boys)	6 (2/4)	3 (3/0)	13 (8/5)	18 (8/10)	18 (4/14)	12 (3/9)	10 (0/10)	12 (5/7)	15 (4/11)	10 (6/4)	11 (4/7)	14 (6/8)	14 (3/11)	14 (4/10)	9 (2/7)	13 (5/8)
Age (years) (median ± IQR)	0.2 (0.2)	0.8 (0.2)	1.6 (0.3)	2.5 (0.4)	3.3 (0.7)	4.6 (0.3)	5.2 (0.3)	6.5 (0.4)	7.3 (0.3)	8.3 (0.4)	9.3 (0.3)	10.6 (0.3)	11.3 (0.5)	12.4 (0.6)	13.4 (0.5)	14.3 (0.3)
Weight (kg) (±SD)	6 (1)	9 (2)	12 (2)	14 (2)	16 (3)	18 (4)	18 (2)	24 (6)	26 (5)	27 (2)	32 (5)	37 (7)	38 (5)	49 (12)	49 (6)	57 (13)

TABLE 3 Median and ranges of airway measurement value for each group

Age	0-0.5 y	0.5-1 y	1-2 y	2-3 y	3-4 y	4-5 y	5-6 y	6-7 y	7-8 y	8-9 y	9-10 y	10-11 y	11-12 y	12-13 y	13-14 y	14-15 y
AP glottic diameter	5.6 (4.6-6.4)	6.2 (5.9-6.3)	7.8 (6.3-9.0)	8.2 (6.2-10.6)	8.9 (7.3-10.3)	9.1 (7.4-10.6)	9 (8.0-10.5)	10.2 (9-12.4)	10.1 (8.7-12.7)	10.6 (8.7-11.9)	9.9 (9.6-12.6)	11.5 (9.1-15.1)	11.4 (10.3-13.6)	12.2 (10.4-17.6)	13.6 (10.5-17.4)	15.7 (13.5-19.0)
Glottic area	11.4 (5.5-20.0)	10.6 (10.5-13.4)	20.4 (15.0-31.7)	21 (12.7-30.6)	28 (19.9-42.6)	27.3 (13.0-43.1)	28.3 (17.0-37.6)	34.8 (10.8-52.5)	34 (14.7-54.5)	40.2 (28.1-56.6)	40 (15.5-62.3)	43 (17.8-88.6)	48.3 (29.3-72.4)	44.3 (20.8-124.3)	65.3 (32.7-103.6)	75.9 (44.8-114.7)
AP cricoid diameter	4.9 (4.6-5.1)	4.9 (4.7-5.0)	5.9 (4.5-8.0)	6.4 (5.6-7.3)	7 (5.8-8.6)	7 (6.1-7.6)	7.2 (5.9-9.2)	7.7 (7.0-8.9)	8.4 (6.7-9.7)	9.1 (7.3-10.4)	9.87.5-10.5)	9.9 (8.1-12.4)	9.9 (7.9-10.6)	10.5 (8.8-14.2)	11.5 (9.5-14.4)	13.9 (11.5-16.1)
T cricoid diameter	4.3 (4.0-4.9)	4.6 (4.0-5.0)	5.5 (4.4-6.7)	6.5 (6.0-7.3)	7 (5.3-8.5)	7.2 (6.2-7.8)	7.2 (5.7-8.3)	8.1 (6.9-9.0)	8.1 (7.5-9.5)	8.3 (6.7-10.1)	9.5 (7.2-10.2)	9.9 (8.6-11.0)	9.7 (8.1-11.1)	10.4 (8.4-14.8)	11.7 (7.8-14.1)	12.8 (9.9-14.2)
Cricoid area	16.5 (15.9-18.5)	19.2 (16.1-20.2)	25.5 (17.5-46.7)	33.8 (27.9-42.4)	41.8 (23.3-62.0)	43.2 (32.5-47.3)	42.7 (26.7-61.0)	52.2 (42.3-71.0)	56.9 (40.9-78.2)	62 (39.1-80.1)	69.4 (46.8-88.7)	76 (62.5-107.7)	78.8 (52.7-94.5)	89.7 (65.8-168.9)	113.1 (63.6-162)	129.7 (93.0-177.3)
Tip of epiglottis—glottis distance	18.1 (16.2-21.0)	18.4 (17.3-22.2)	23 (20.5-25.5)	23.6 (20.5-29.8)	25.9 (22.5-28.2)	25.9 (24.2-31.1)	25.5 (24.1-30.1)	26.8 (25.3-31.0)	28.6 (26.2-31.3)	29.9 (28.0-33.3)	30.4 (28.5-34.8)	32.3 (28.0-37.6)	31.1 (27.5-32.9)	33.8 (29.0-40.8)	33.6 (29.2-47.2)	37.6 (34.7-45.1)
Glottis—cricoid ring distance	8 (6.0-9.4)	8.1 (8.0-8.7)	9.9 (6.4-13.5)	10.3 (6.9-12.5)	11.1 (7.7-13.9)	11.7 (7.1-14.1)	11.7 (8.5-13.9)	11.9 (9.1-15.5)	12.5 (8.3-17.7)	12.5 (10.2-16.0)	15.5 (12.5-17.3)	15.8 (11.6-18.2)	16.2 (10.5-22.0)	16.2 (13.2-23.4)	17.5 (10.4-21.4)	18.9 (17.3-22.2)
AP tracheal diameter	3.8 (3.0-4.3)	3.8 (3.8-4.4)	5.7 (2.8-7.4)	6.3 (4.6-9.1)	7 (5.5-8.9)	7 (5.1-9.3)	7.3 (5.2-8.0)	7.6 (4.9-10.5)	7.8 (6.3-9.6)	8.1 (6.7-12.5)	8.6 (5.6-14.4)	8.7 (5.9-10.5)	9.4 (7.3-11.0)	9.3 (6.5-12.6)	8.9 (6.6-9.9)	11 (8.4-15.0)
T tracheal diameter	5.7 (4.0-6.7)	5.3 (4.1-6.6)	7.3 (6.3-9.6)	9.4 (5.8-10.7)	10.2 (7.2-11.1)	10.3 (8.2-12.4)	10.3 (9.5-12.5)	11.9 (10.5-13.0)	11.8 (10.5-13.3)	12 (10.4-13.7)	12.7 (10.6-14.3)	13.5 (10.6-16.1)	13.5 (11.5-16.0)	14.8 (11.9-19.4)	14.2 (11.1-21.0)	15.9 (13.2-19.9)
Tracheal area	16.5 (12.0-22.2)	16.3 (13.0-21.0)	34.1 (17.2-52.2)	52.9 (23.4-71.7)	62 (37.0-74.7)	61.9 (41.3-82.8)	59.2 (50.8-79.5)	71.8 (55.0-107.1)	76.6 (59.2-100.6)	88 (62.2-138.5)	88.5 (58.4-115.4)	96.1 (58.8-115.0)	105.8 (50.1-129.0)	114.1 (69.0-201.4)	112.4 (73.5-136.2)	157.8 (107.2-193.4)
Tracheal length	45.1 (43.1-52.0)	47.3 (42.8-50.3)	53.4 (40.2-64.1)	63.1 (53.7-72.8)	65.8 (53.6-76.4)	70.9 (55.5-78.3)	71.1 (63.0-83.5)	74.7 (67.3-82.7)	80.3 (65.6-88.5)	84 (76.3-92.7)	81.3 (67.9-93.8)	92.2 (72.1-103.2)	86.8 (79.6-100.7)	89.3 (78.2-105.6)	101 (84.9-108.4)	99.1 (89.0-116.4)
RMB proximal AP diameter	3.5 (3.0-4.3)	4 (3.4-4.2)	4.8 (2.1-6.4)	6 (4.4-8.3)	6.7 (4.6-8.6)	6.8 (4.6-9.0)	6.9 (5.5-7.4)	6.7 (5.5-8.5)	7.5 (6.2-8.7)	7.7 (6.0-10.6)	7.6 (5.9-9.5)	8.3 (5.8-9.4)	8.3 (5.7-10.0)	8.5 (6.2-12.6)	8.9 (5.0-10.3)	10.5 (5.6-11.9)

(Continues)

TABLE 3 (Continued)

Age	0-0.5 y	0.5-1 y	1-2 y	2-3 y	3-4 y	4-5 y	5-6 y	6-7 y	7-8 y	8-9 y	9-10 y	10-11 y	11-12 y	12-13 y	13-14 y	14-15 y
RMB proximal T diameter	4.4 (4.0-5.8)	4.8 (3.2-4.9)	6.2 (4.8-7.9)	6.9 (5.4-10.2)	7.4 (5.0-8.8)	8.1 (6.2-10.1)	8.0 (6.5-10.0)	9.1 (7.2-11.0)	8.8 (6.1-11.1)	9.9 (8.5-12.1)	9.6 (7.1-13.0)	10.5 (8.1-12.0)	10.6 (7.3-12.6)	11.8 (8.7-14.9)	11.6 (10.1-16.5)	11.9 (8.8-16.3)
RMB proximal area	12.5 (11.0-14.8)	13.6 (8.1-14.8)	21.7 (9.6-36.8)	33.1 (18.6-56.6)	38.7 (22.8-53.8)	43.4 (25.4-55.9)	39.1 (30.5-50.0)	47 (27.7-69.8)	51.3 (30.8-76.1)	56.4 (44.0-93.4)	53.5 (40.3-104.5)	68 (46.4-80.6)	71.5 (46.5-87.7)	80.7 (45.0-149.7)	73.8 (44.2-125.2)	92 (57.2-195.8)
LMB proximal AP diameter	2.3 (1.7-3.3)	2.9 (2.3-3.0)	4.3 (2.3-4.9)	5 (3.1-6.6)	5.1 (2.7-6.2)	5.2 (2.9-6.1)	5.3 (3.7-6.7)	5.6 (3.5-8.0)	6.1 (4.9-7.5)	5.7 (3.2-9.3)	6.5 (4.5-7.6)	6.7 (5-7.7.0)	7.3 (4.9-8.0)	6.4 (5.1-10.5)	6.6 (3.9-9.6)	8.4 (5.3-11.0)
LMB proximal T diameter	3.5 (2.7-4.3)	3.4 (2.0.8-4)	5.1 (4.3-7.2)	6.2 (5.0-9.4)	6.2 (3.8-8.6)	7.4 (5.6-8.9)	7.1 (5.4-9.6)	8.2 (6.4-10.1)	8.1 (6.8-10.1)	9.1 (6.8-11.3)	8.8 (7.0-10.6)	9.2 (8.3-12.1)	9.4 (7.5-12.5)	9.7 (7.8-14.0)	10.3 (6.6-13.6)	10.7 (6.5-13.0)
LMB proximal area	6.3 (3.3-10.7)	6.2 (5.7-6.7)	16.1 (7.0-27.2)	24.8 (13.0-40.1)	23.9 (9.3-38.5)	28.6 (15.6-40.6)	27.9 (20.6-34.9)	36.2 (18.5-53.9)	36.6 (29.4-56.2)	41.5 (20.7-78.4)	46.2 (28.7-60.9)	48.5 (40.0-63.3)	53.3 (35.1-69.5)	48.8 (33.4-118.6)	47.9 (32.6-84.0)	71.5 (45.7-112.8)
RMB distal AP diameter	2.6 (2.0-3.0)	2.3 (2.2-2.6)	3.6 (1.9-4.8)	4.1 (2.7-6.0)	4.1 (3.1-5.6)	4.5 (2.9-6.1)	4.3 (3.4-5.4)	4.7 (3.9-6.3)	4.8 (3.1-6.9)	5.5 (3.8-7.0)	5.2 (2.5-7.0)	5.4 (3.9-6.5)	5.5 (3.6-7.3)	5.1 (4.0-9.0)	6.1 (2.9-7.8)	6.8 (5.1-9.2)
RMB distal T diameter	7 (5.9-12.5)	6.7 (5.1-7.1)	9.1 (6.5-10.9)	10.1 (7.9-11.9)	10 (3.5-11.4)	10.6 (8.8-15.4)	11.5 (9.7-17.0)	13.5 (10.7-17.9)	12.7 (10.2-16.5)	14.1 (13.0-18.8)	15.3 (12.1-18.0)	14.8 (11.5-19.5)	14.6 (11.3-17.5)	15.3 (11.9-19.1)	15.3 (11.5-18.9)	18.1 (14.1-21.1)
LMB distal AP diameter	1.7 (1.5-4.0)	2.1 (2.0-6.4)	3.1 (0.8-3.8)	3.5 (2.2-4.2)	3.2 (2.5-4.1)	3.4 (2.8-4.5)	3.4 (2.6-5.1)	3.6 (2.9-5.2)	4.3 (2.7-6.5)	4.1 (3.1-8.3)	4.6 (3.3-6.3)	5.2 (3.7-6.3)	4.7 (3.9-6.5)	5.3 (3.6-8.5)	4.9 (4.3-7.5)	6.8 (5.0-8.2)
LMB distal T diameter	4.7 (2.8-7.9)	4.7 (2.1-5.2)	6.8 (3.2-9.7)	8.2 (4.8-10.3)	7.6 (5.8-10.2)	8.2 (6.8-10.6)	8.5 (7.7-10.2)	10.5 (9.1-14.6)	9.6 (7.3-12.3)	10 (8.9-12.9)	10.8 (8.5-13.6)	11.3 (9.7-15.1)	10.6 (7.2-13.5)	11.2 (8.3-16.1)	11.5 (8.4-16.2)	13.4 (10.2-15.5)
RMB length	10.9 (7.8-14.5)	10.6 (9.5-12.3)	13.5 (10.1-16.8)	14.6 (9.1-27.8)	13.9 (10.0-18.2)	16.3 (13.8-19.1)	17.2 (12.7-21.1)	17.3 (10.8-21.5)	18.2 (13.2-24.2)	19.1 (13.4-23.3)	19.6 (15.8-25.2)	20.8 (17.6-25.3)	20.4 (13.0-23.7)	20.8 (15.3-28.2)	19.9 (16.8-35.5)	22.6 (16.1-29.2)
LMB length	22.9 (20.2-26.9)	25.1 (21.7-27.2)	28.4 (23.7-33.8)	29.9 (25.9-34.9)	31.6 (27.0-39.9)	33.1 (29.7-39.4)	34.2 (29.3-38.2)	36 (31.4-44.4)	37.3 (31.2-42.4)	36.7 (31.4-41.7)	39.6 (38.0-43.1)	43.8 (36.5-56.2)	39.6 (35.2-46.3)	42.1 (36.9-51.4)	44.2 (39.0-55.7)	45.1 (40.6-52.8)

Note: Distances are expressed in mm. Areas are expressed in mm^2.

Abbreviations: AP, Anteroposterior; LMB, Left Mainstem Bronchus; RMB, Right Mainstem Bronchus; T, Transverse.

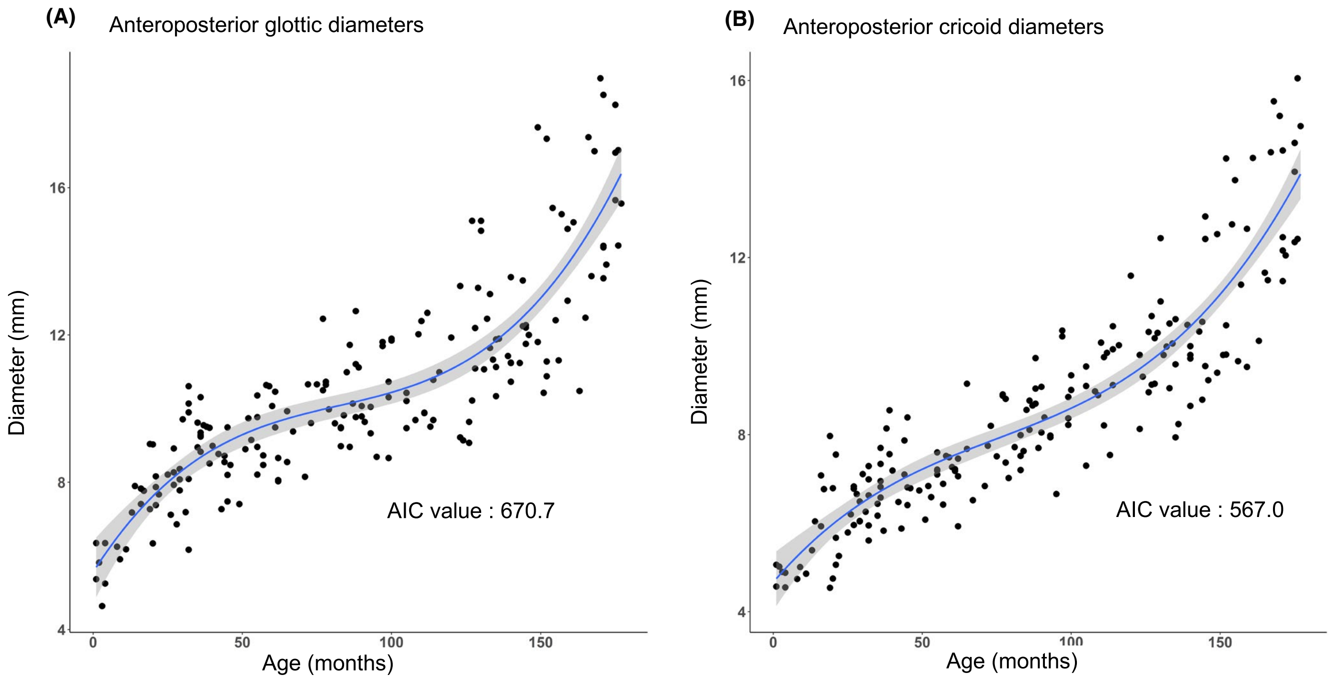

FIGURE 2 Relation between the age and airway measurements. Models for the dependence of anteroposterior glottic diameters (A) or anteroposterior cricoid diameter (B) on age with the 5th and 95th percentiles curves [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

The present work studied airway measurements involving a large radiological cohort of patients. The characteristics of this study enabled us to perform precise measurements using high-quality images of children without any airway condition and to carry out on each HRCT scans all the predefined measurements. Our results compared with data available for each measurement in the literature are presented in Tables 4 and 5. While most studies focus on a small number of parameters and on restricted ages, we performed 23 airway measurements on children aged from 1 day to 14 years old. Moreover, we studied the evolution of these measurements according to age and weight thus analyzing the correlation between airway measurements and biometric data.

There was a predominance of boys in our study (2/1) which corresponds to the usual sex ratio of polytrauma in pediatric population.[26]

Most of the previous studies have focused on the narrowest area of the pediatric airway. Autopsy data are consistent with the "funnel shape" description of the pediatric larynx and suggest that the cricoid is the area of smallest diameter.[7,8,18] But recent in vivo studies challenge this concept. Indeed, Littman et al[10] evaluated pediatric airway dimensions using MRI demonstrating that the larynx is conical in a coronal plane with the smallest diameter in the immediate subglottic area and has a cylindrical shape in a transverse plane. Dalal et al[27] confirmed these results using videoendoscopic measurements. More recently, Wani et al[20] concluded, using CT scans, that the smallest diameter of the larynx is the transverse diameter of the immediate subglottic area (elliptical shape). The cricoid was not shown to be the area of greatest resistance in the larynx, but the acquisitions were not standardized on tidal breathing, casting doubt on the conclusion.

It is difficult to take a stand between these two theories. Indeed, we could consider that the in vivo studies are closer to the clinical reality but the variability of the measurements is also greater (position of the vocal folds, depth of the anesthesia, and precision of the location of the measurements). Contrarily, cadaveric measurements appear to be more precise and more reproducible but the muscular atony, the mucosal atrophy, and tissue shrinkage in fixed specimens induce a measurement bias. This debate did not seem relevant to us for several reasons. First, measurements of the immediate subglottic area lack reliable landmarks and therefore reproducibility. In addition, the subglottis is elastic and therefore more compliant to the impact of an endotracheal tube than the cricoid cartilage. Therefore, the recommended endotracheal tube has to be determined using the cricoid diameter.

The HRCT scan, due to its excellent spatial resolution and discrimination of the air/tissue interface, enables precise measurements and is therefore the gold standard for airway measurements.[20-22] The intra-rater reliability was satisfactory, with a very small difference between the means (0.095 mm) of the measurements compared, confirming the reliability of the measurement method. However, some limitations are important to note. Indeed, it is difficult to perform accurate measurements of the transverse diameter and the area at the glottic level because of the variability of vocal cord position during breathing phases. Furthermore, anteroposterior tracheal diameter measurements vary greatly due to the malacia of the child's trachea.

TABLE 4 Laryngeal and tracheal measurements in our study and in the literature

Age	0-0.5 y	0.5-1 y	1-2 y	2-3 y	3-4 y	4-5 y	5-6 y	6-7 y	7-8 y	8-9 y	9-10 y	10-11 y	11-12 y	12-13 y	13-14 y	14-15 y
AP glottic diameter	5.6	6.2	7.8	8.2	8.9	9.1	9	10.2	10.1	10.6	9.9	11.5	11.4	12.2	13.6	15.7
AP glottic diameter Eckel (8)	7.2	7.2	7.2	9.6	9.6	9.6										
Glottic area	11.4	10.6	20.4	21	28	27.3	28.3	34.8	34	40.2	40	43	48.3	44.3	65.3	75.9
Glottic area Dalal (27)		20.4	20.4	27.8	27.8	24.3	24.3	33.2	33.2	39	39	40.2	40.2	40.2		
AP cricoid diameter	4.9	4.9	5.9	6.4	7	7	7.2	7.7	8.4	9.1	9.8	9.9	9.9	10.5	11.5	13.9
AP cricoid diameter Wani (11)	6.7	6.7	7.1	6.9	8.9	8.7	9.6	9.3	9.6	10.9						
AP cricoid diameter Wani (20)	6.7	6.7														
T cricoid diameter	4.3	4.6	5.5	6.5	7	7.2	7.2	8.1	8.1	8.3	9.5	9.9	9.7	10.4	11.7	12.8
T cricoid diameter Wani (11)	6.4	6.4	6.9	7.6	8.9	8.5	9.5	9.9	10.1	10.3						
T cricoid diameter Wani (20)	6.1	6.1														
Cricoid area	16.5	19.2	25.5	33.8	41.8	43.2	42.7	52.2	56.9	62	69.4	76	78.8	89.7	113.1	129.7
Cricoid area Dalal (27)		34	34	49.5	49.5	48.2	48.2	49.4	49.4	54.9	54.9	55	55	55		
AP tracheal diameter	3.8	3.8	5.7	6.3	7	7	7.3	7.6	7.8	8.1	8.6	8.7	9.4	9.3	8.9	11
AP tracheal diameter Griscom (6)	5.3	5.3	5.3	7.4	7.4	8	8	9.2	9.2	10.5	10.5	11.6	11.6	13	13	13.9
AP tracheal diameter Szelloe (12)	6.0	6.0	7.0	7.9	7.9	7.5	7.5	8.8	8.8	9.9	9.9	11.1	11.1	11.7	11.7	13
T tracheal diameter	5.7	5.3	7.3	9.4	10.2	10.3	10.3	11.9	11.8	12	12.7	13.5	13.5	14.8	14.2	15.9
T tracheal diameter Griscom (6)	6.4	6.4	6.4	8.1	8.1	9	9	9.3	9.3	10.7	10.7	11.8	11.8	13.3	13.3	14.6
T tracheal diameter Szelloe (12)	6.5	6.5	7.3	8.5	8.5	8.5	8.5	9.4	9.4	10.6	10.6	11	11	12.9	12.9	13.8
Tracheal area	16.5	16.3	34.1	52.9	62	61.9	59.2	71.8	76.6	88	88.5	96.1	105.8	114.1	112.4	157.8
Tracheal area Griscom (6)	28	28	28	48	48	58	58	69	69	89	89	110	110	139	139	162
T tracheal area Szelloe (12)	31.5	31.5	38.8	56	56	51.7	51.7	63	63	84.2	84.2	104.3	104.3	123.5	123.5	145.9
Tracheal length	45.1	47.3	53.4	63.1	65.8	70.9	71.1	74.7	80.3	84	81.3	92.2	86.8	89.3	101	99.1
Tracheal length Griscom (6)	54	54	54	64	64	72	72	82	82	88	88	100	100	108	108	112

Note: Distances are expressed in mm. Areas are expressed in mm^2.

Abbreviations: AP, Anteroposterior; T, Transverse.

TABLE 5 Bronchial measurements in our study and in the literature

Age	0-0.5 y	0.5-1 y	1-2 y	2-3 y	3-4 y	4-5 y	5-6 y	6-7 y	7-8 y	8-9 y	9-10 y	10-11 y	11-12 y	12-13 y	13-14 y	14-15y
RMB proximal AP diameter	3.5	4	4.8	6	6.7	6.8	6.9	6.7	7.5	7.7	7.6	8.3	8.31	8.5	8.9	10.5
RMB proximal AP diameter Szelloe (12)	4.2	4.2	5.4	7.1	7.1	6.6	6.6	7.7	7.7	8.5	8.5	9.4	9.4	10.2	10.2	11.5
RMB proximal T diameter	4.4	4.8	6.2	6.9	7.4	8.1	8.0	9.1	8.8	9.9	9.6	10.5	10.6	11.8	11.6	11.9
RMB proximal T diameter Szelloe (12)	5.2	5.2	6.6	7.5	7.5	8.3	8.3	8.9	8.9	9.9	9.9	11.5	11.5	12	12	12.6
RMB proximal area	12.5	13.6	21.7	33.1	38.7	43.4	39.1	47	51.3	56.4	54	68	71.5	80.7	72.8	92
RMB proximal area Szelloe (12)	17.4	17.4	31.4	39.4	39.4	42.2	42.2	60.2	60.2	67.6	67.6	82.9	82.9	104.2	104.2	118.8
LMB proximal AP diameter	2.3	2.9	4.3	5	5.1	5.2	5.3	5.6	6.1	5.7	6.5	6.7	7.3	6.4	6.6	8.4
LMB proximal AP diameter Szelloe (12)	3.5	3.5	4.2	5.6	5.6	5.4	5.4	6.7	6.7	7.3	7.3	7.8	7.8	8.9	8.9	10
LMB proximal T diameter	3.5	3.4	5.1	6.2	6.2	7.4	7.1	8.2	8.1	9.1	8.8	9.2	9.4	9.7	10.3	10.7
LMB diameter Wani (11)	4.8	4.8	5.2	5.9	6.8	6.8	7.2	8.2	8	8.3						
LMB proximal T diameter Szelloe (12)	4.3	4.3	5.6	6.6	6.6	7.3	7.3	7.8	7.8	8.8	8.8	10	10	10.5	10.5	11.4
LMB proximal area	6.3	6.2	16.1	24.8	23.9	28.6	27.9	36.2	36.6	41.5	46.2	48.5	53.3	48.8	47.9	71.5
LMB proximal area Szelloe (12)	12.1	12.1	19.6	30.4	30.4	30.7	30.7	41.7	41.7	50.5	50.5	63.8	63.8	80.6	80.6	91.4
RMB distal AP diameter	2.6	2.3	3.6	4.1	4.1	4.5	4.3	4.7	4.8	5.5	5.2	5.4	5.5	5.1	6.1	6.8
RMB distal AP diameter Szelloe (12)	3.9	3.9	4.9	6.1	6.1	6.1	6.1	6.8	6.8	7	7	8.2	8.2	8.5	8.5	9.8
RMB distal T diameter	7	6.7	9.1	10.1	10	10.6	11.5	13.5	12.7	14.1	15.3	14.8	14.6	15.3	15.3	18.1
RMB distal T diameter Szelloe (12)	5.3	5.3	6.6	7.3	7.3	8.5	8.5	9.5	9.5	10.3	10.3	11.2	11.2	12.6	12.6	14.1
LMB distal AP diameter	1.7	2.1	3.1	3.5	3.2	3.4	3.4	3.6	4.3	4.1	4.6	5.2	4.7	5.3	4.9	6.8
LMB distal AP diameter Szelloe (12)	3.4	3.4	4.2	5.5	5.5	5.3	5.3	6	6	6.6	6.6	7.5	7.5	8.1	8.1	9.2
LMB distal T diameter	4.7	4.7	6.8	8.2	7.6	8.2	8.5	10.5	9.6	10	10.8	11.3	10.6	11.2	11.5	13.4
LMB distal T diameter Szelloe (12)	3.8	3.8	4.6	6.2	6.2	6.3	6.3	7.1	7.1	7.6	7.6	8.3	8.3	10.1	10.1	10.5

Note: Distances are expressed in mm. Areas are expressed in mm^2.

Abbreviations: AP, Anteroposterior; LMB, Left Mainstem Bronchus; RMB, Right Mainstem Bronchus; T, Transverse.

Concerning laryngeal measurements, we conclude that the cricoid has a round shape regardless of the child's age. Its diameter is smaller than the anteroposterior diameter of the glottic area, but the glottic area is smaller than the cricoid area. We can note a significant variability in the glottic measurements. These can reflect the positional variability of the vocal folds during tidal breathing. Although we excluded the scanners with vocal cords adduction, the glottic area value depends on the position of the vocal cords. Moreover, the passive mobility of the vocal cords, that cannot be assessed radiologically, allows for an enlargement of the transverse glottic diameter.[9]

As expected, the tracheal measurements show that the trachea is not round in shape. Its transverse diameter is greater than the anteroposterior diameter. This observation is in agreement with previous studies.[6,9] Due to the lack of reliable landmarks of the tracheal diameters and area measurements location, it is difficult to compare the results with other studies; however, our results are consistent with Griscom et al and Szelloe's et al[6,12] (Tables 4 and 5). In our study, to have a reliable landmark, we decided to perform the tracheal measurements at the level of the last tracheal cartilage, before the distal widening of the carina. The variability of anteroposterior diameter measurements may reflect interindividual variability of the children's tracheal rigidity. But as CT scan acquisitions were performed at different periods of the breathing cycle and were not correlated to ventilation, it was not possible to confirm this suspicion.

The main bronchi also present a larger transverse diameter compared to the anteroposterior diameter. The right bronchus is shorter than the left bronchus, and its surface area is greater. These observations are consistent with known anatomy and previous studies.[8]

In the study of Griscom,[6] significant measurement variability was found for the younger patients. It was explained by the lack of spatial resolution of scanners in the 80s. This variability of measurement was not found in our results.

Considering the bronchial measurements, we found that the right bronchus diameter is greater than the left which is in accordance with the literature.[12] Our results are consistent with Szelloe's and Wani's studies[11,12] (Tables 4 and 5).

In our study, we present the evolution of the airway dimensions according to age and weight. Correlations between measurements and age or weight were always significant. While previous growth studies present results in linear regression form, our results suggest that the relationship between measurements and age is suitably represented by a cubic polynomial equation. The measures we presented with a linear or quadratic model could probably also correspond to a cubic model but we have too few patients to conclude. The pediatric airways have a rapid growth phase up to 3 years of age followed by a slow growth phase and a second rapid growth phase during adolescence (as from 11 years of age). Our results are consistent with Sempé's body growth curve.[28]

Concerning correlation between child airway dimensions and age or weight, the most relevant biometric parameter was found to be age in 21 of the 23 measurements (not significant). This result is in accordance with Szelloe et al.[12] It would be interesting to conduct further studies to answer this question.

The main limitation of our study is the retrospective design. Children's height was not available from patient charts. Regarding the study design, we can suppose that we only included patients without any growth disorder, and also we could assume that in our cohort, height was directly related to age. However, it would be interesting to carry out a prospective study to evaluate the airway dimensions of patients with stunted growth. The second limitation is the inclusion method (trauma victims) which induces age and gender constraints. In adults, gender has an impact on airway dimensions and we could assume that this is also the case in adolescents. However, we were not able to study the impact of gender on airway dimensions due to the too small number of adolescent girls in our cohort to conduct reliable statistics. Concerning childhood, several studies have already shown that gender is not correlated to airway size.[6,10,27] Moreover, we have too few patients under the age of 18 months. This age group should be subjected to further focused study. Ethnic origin of the patients was not analyzed, in accordance with French law. It would be interesting to compare our results with similar studies performed in other centers around the world, using the same methodology.

5 | CONCLUSION

We performed 23 systematic airway measurements in a large CT scan database of children without any respiratory condition, aged from 1 day to 14 years old. This comprehensive anatomical study provides important data in the field of pediatric airway anatomy, particularly related to the cricoid.

We studied the evolution of these measurements according to age and weight and analyzed the correlation between airway measurements and biometric data, finding excellent correlation with age. The relationship between measurements and age was found to be suitably represented by a cubic polynomial. The pediatric airway has a rapid growth phase up until 3 years old, followed by a slow growth phase and a second fast growth phase during adolescence (after 11 years old).

CONFLICT OF INTEREST

The authors declare no competing interests.

ORCID

Romain Luscan https://orcid.org/0000-0003-1219-727X
Briac Thierry https://orcid.org/0000-0002-1898-1906

REFERENCES

1. Holzki J, Brown KA, Carroll RG, Coté CJ. The anatomy of the pediatric airway: has our knowledge changed in 120 years? A review of historic and recent investigations of the anatomy of the pediatric larynx. *Pediatr Anesth*. 2018;28(1):13-22.
2. Eckenhoff JE. Some anatomic considerations of the infant larynx influencing endotracheal anesthesia. *Anesthesiology*. 1951;12(4):401-410.
3. Butz RO. Length and cross-section growth patterns in the human trachea. *Pediatrics*. 1968;42(2):336-341.

4. Tucker GF, Tucker JA, Vidic B. Anatomy and development of the cricoid: serial-section whole organ study of perinatal larynges. *Ann Otol Rhinol Laryngol*. 1977;86(6 Pt 1):766-769.
5. Wailoo MP, Emery JL. Normal growth and development of the trachea. *Thorax*. 1982;37(8):584-587.
6. Griscom NT, Wohl ME. Dimensions of the growing trachea related to age and gender. *AJR Am J Roentgenol*. 1986;146(2):233-237.
7. Sellars I, Keen EN. Laryngeal growth in infancy. *J Laryngol Otol*. 1990;104(8):622-625.
8. Eckel HE, Koebke J, Sittel C, Sprinzl GM, Pototschnig C, Stennert E. Morphology of the human larynx during the first five years of life studied on whole organ serial sections. *Ann Otol Rhinol Laryngol*. 1999;108(3):232-238.
9. Fayoux P, Marciniak B, Devisme L, Storme L. Prenatal and early postnatal morphogenesis and growth of human laryngotracheal structures. *J Anat*. 2008;213(2):86-92.
10. Litman RS, Weissend EE, Shibata D, Westesson P-L. Developmental changes of laryngeal dimensions in unparalyzed, sedated children. *Anesthesiology*. 2003;98(1):41-45.
11. Wani TM, Rafiq M, Terkawi R, Moore-Clingenpeel M, AlSohaibani M, Tobias JD. Cricoid and left bronchial diameter in the pediatric population. *Pediatr Anesth*. 2016;26(6):608-612.
12. Szelloe P, Weiss M, Schraner T, Dave MH. Lower airway dimensions in pediatric patients-A computed tomography study. *Pediatr Anesth*. 2017;27(10):1043-1049.
13. Khine HH, Corddry DH, Kettrick RG, et al. Comparison of cuffed and uncuffed endotracheal tubes in young children during general anesthesia. *Anesthesiology*. 1997;86(3):627-631.
14. Cole F. Pediatric formulas for the anesthesiologist. *AMA J Dis Child*. 1957;94(6):672-673.
15. Duracher C, Schmautz E, Martinon C, Faivre J, Carli P, Orliaguet G. Evaluation of cuffed tracheal tube size predicted using the Khine formula in children. *Pediatr Anesth*. 2008;18(2):113-118.
16. Tweedie DJ, Cooke J, Stephenson KA, et al. Paediatric tracheostomy tubes: recent developments and our current practice. *J Laryngol Otol*. 2018;132(11):961-968.
17. Dave MH, Kemper M, Schmidt AR, Both CP, Weiss M. Pediatric airway dimensions-A summary and presentation of existing data. *Pediatr Anesth*. 2019;00:1-8.
18. Fayoux P, Devisme L, Merrot O, Marciniak B. Determination of endotracheal tube size in a perinatal population: an anatomical and experimental study. *Anesthesiology*. 2006;104(5):954-960.
19. Too-Chung MA, Green JR. The rate of growth of the cricoid cartilage. *J Laryngol Otol*. 1974;88(1):65-70.
20. Wani TM, Rafiq M, Akhter N, AlGhamdi FS, Tobias JD. Upper airway in infants-a computed tomography-based analysis. *Pediatr Anesth*. 2017;27(5):501-505.
21. Reinhardt JM, D'Souza ND, Hoffman EA. Accurate measurement of intrathoracic airways. *IEEE Trans Med Imaging*. 1997;16(6):820-827.
22. Schlesinger AE, Hernandez RJ. Radiographic imaging of airway obstruction in pediatrics. *Otolaryngol Clin North Am*. 1990;23(4):609-637.
23. von Elm E, Altman DG, Egger M, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Lancet Lond Engl*. 2007;370(9596):1453-1457.
24. Akaike H. Information theory and an extension of the maximum likelihood principle. In Parzen E, Tanabe K, Kitagawa G, eds. *Selected Papers of Hirotugu Akaike, Springer Series in Statistics*. New York, NY: Springer New York; 1998:199-213.
25. Zucchini W. An introduction to model selection. *J Math Psychol*. 2000;44(1):41-61.
26. Danseco ER, Miller TR, Spicer RS. Incidence and costs of 1987–1994 childhood injuries: demographic breakdowns. *Pediatrics*. 2000;105(2):e27.
27. Dalal PG, Murray D, Messner AH, Feng A, McAllister J, Molter D. Pediatric laryngeal dimensions: an age-based analysis. *Anesth Analg*. 2009;108(5):1475-1479.
28. Jolicoeur P, Pontier J, Pernin MO, Sempé M. A lifetime asymptotic growth curve for human height. *Biometrics*. 1988;44(4):995-1003.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Luscan R, Leboulanger N, Fayoux P, et al. Developmental changes of upper airway dimensions in children. *Pediatr Anesth*. 2020;30:435–445. https://doi.org/10.1111/pan.13832