Original Article

Morphometric Study of Developing Human Fetal Trachea and Its Correlation with Fetal Growth Parameters: A Cross - Sectional Study

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Abstract

Background: The fetal trachea undergoes continuous growth and structural remodeling throughout gestation. Normative morphometric data are essential for understanding normal development, prenatal imaging, and early identification of congenital tracheobronchial anomalies. The aim is to evaluate the morphometric characteristics of the developing human fetal trachea across different gestational ages and correlate them with fetal growth parameters. **Material and Methods:** This cross-sectional observational study included 42 human fetuses of known gestational age, grouped into 13–21 weeks (n=18), 22–30 weeks (n=12), and 31–38 weeks (n=12). Fetal weight, crown-rump length, abdominal circumference, and head circumference were recorded. Tracheal measurements included total tracheal length, pre-bifurcation length, bifurcation length, proximal and distal transverse external diameters, total, right and left tracheobronchial angles, and the number of tracheal cartilages. Statistical analysis was performed using one-way ANOVA and Pearson's correlation coefficient. **Results:** Mean gestational age was 24.21 ± 7.53 weeks. Total tracheal length increased significantly from 14.99 ± 2.82 mm in the 13–21-week group to 30.56 ± 2.70 mm in the 31–38-week group. All tracheal morphometric parameters demonstrated significant age-related increases ($p < 0.0001$). Crown-rump length showed the strongest positive correlation with proximal transverse external diameter ($r = 0.962$), total tracheal length ($r = 0.956$), distal transverse external diameter ($r = 0.956$), and left tracheobronchial angle ($r = 0.955$), whereas the right tracheobronchial angle showed a strong negative correlation with fetal growth parameters. **Conclusion:** Human fetal tracheal dimensions increase progressively with gestational age and correlate strongly with fetal growth, particularly crown-rump length. These findings provide normative anatomical reference data that may facilitate prenatal evaluation and improve the recognition of congenital tracheobronchial abnormalities.

Keywords: fetal trachea; morphometry; gestational age; fetal growth; tracheobronchial angle.

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Introduction

The trachea is the principal conducting airway connecting the larynx to the main bronchi and plays a vital role in maintaining airway patency and facilitating ventilation after birth. Its development begins during the fourth week of embryogenesis with the formation of the laryngotracheal diverticulum from the ventral wall of the primitive foregut.[1]

Progressive elongation of the diverticulum, separation from the foregut by the tracheoesophageal septum, and differentiation of the surrounding mesenchyme into cartilaginous rings, smooth muscle, and connective tissue are essential steps in establishing a functional trachea.[2]

Normal fetal tracheal development is regulated by coordinated cellular proliferation, differentiation, and morphogenesis throughout gestation. Disruption of these developmental processes may result in congenital anomalies such as tracheal agenesis, congenital tracheal stenosis, tracheoesophageal fistula, and complete tracheal rings.[3] These abnormalities are uncommon but are associated with significant respiratory compromise, neonatal morbidity, and increased mortality, emphasizing the importance of understanding normal tracheal development.[4]

Throughout fetal life, the trachea undergoes continuous growth and remodeling, characterized by progressive increases in length, external diameter, branching geometry, and the number and maturation of tracheal cartilages. These morphometric changes occur in parallel with overall fetal growth and reflect the maturation of the developing respiratory system.[5]

Accurate morphometric reference values are important for developmental anatomy, interpretation of prenatal ultrasonography and fetal magnetic resonance imaging, assessment of airway development, and planning of surgical or perinatal interventions in fetuses with suspected tracheobronchial abnormalities.[6]

Advances in prenatal imaging have increased the detection of congenital airway anomalies before birth, creating a growing

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need for reliable normative anatomical data.[7] Detailed knowledge of fetal tracheal dimensions and tracheobronchial branching patterns assists radiologists, anatomists, fetal medicine specialists, and pediatric surgeons in distinguishing normal developmental variations from pathological conditions. Furthermore, morphometric information provides an anatomical basis for experimental studies, fetal airway interventions, and postnatal reconstructive procedures.[8]

Although several investigators have described fetal tracheal development, available literature remains limited, particularly in the Indian population. Many previous studies have focused on isolated morphometric parameters or included relatively small sample sizes, while comprehensive evaluation of tracheal length, proximal and distal external diameters, bifurcation morphology, tracheobronchial angles, and cartilage number in relation to fetal biometric variables remains scarce.[9] Consequently, region-specific normative data describing tracheal growth throughout gestation are still insufficient.[10-12]

Therefore, the present study was undertaken to evaluate the gross morphometric characteristics of the developing human fetal trachea across different gestational age groups and to determine their correlation with fetal growth parameters, including fetal weight, crown-rump length, abdominal circumference, and head circumference. The findings are expected to provide baseline anatomical reference values that may contribute to developmental anatomy, prenatal diagnosis, and improved understanding of congenital tracheobronchial disorders.

Materials and Methods

Study Design and Setting: This observational cross-sectional study was conducted in the Department of Anatomy, Motilal Nehru Medical College, Prayagraj, Uttar Pradesh, India, in collaboration with the Departments of Obstetrics and Gynaecology and Pathology, between March 2024 and March 2026. The study protocol was approved by the Institutional Ethics Committee prior to commencement.

Study Sample: A total of 42 human fetuses of known gestational age were included using consecutive sampling. Fetuses with gross congenital malformations, damaged specimens, or evidence of maceration were excluded from the study. Gestational age was confirmed using crown-rump length (CRL) and available obstetric records, wherever applicable. Based on gestational age, the fetuses were categorized into three groups:

a. Group I - 13–21 weeks (n = 18)

b. Group II - 22–30 weeks (n = 12)

c. Group III - 31–38 weeks (n = 12)

Inclusion Criteria

- Human fetuses of known gestational age (13–38 weeks).
- Intact fetuses suitable for tracheal dissection and morphometric analysis.
- Gestational age confirmed by obstetric records and/or crown-rump length.

Exclusion Criteria

- Fetuses with gross congenital anomalies.
- Macerated or damaged specimens.
- Fetuses with uncertain gestational age or incomplete tracheal anatomy.

Morphometric Measurements: Before dissection, general fetal morphometric parameters, including fetal weight, crown-rump length (CRL), abdominal circumference (AC), and head circumference (HC), were recorded using standard anatomical techniques. The thoracic cavity was carefully dissected to expose the trachea along with its bifurcation while preserving its anatomical relationships.

The following tracheal morphometric parameters were measured using a digital Vernier caliper and standard protractor where appropriate. All measurements were recorded in millimetres (mm), except the tracheobronchial angles (degrees) and the number of tracheal cartilages.

a. Fetal Weight (FW) - The body weight of the fetus measured using a calibrated electronic weighing machine with an accuracy of 0.01 g and recorded in grams (g).

b. Crown-Rump Length (CRL) - The linear distance from the vertex of the skull (crown) to the most prominent point of the buttocks (rump). It was measured using a non-stretchable thread, which was subsequently aligned against a metric scale, and the measurement was recorded in millimetres (mm).

c. Chest Circumference (CC) - The circumference of the thorax measured at the level of the nipples using a flexible measuring tape, ensuring that the tape remained snug without compressing the soft tissues. The measurement was recorded in millimetres (mm).

d. Abdominal Circumference (AC) - The circumference of the abdomen measured at the level of the umbilicus using a flexible measuring tape or non-stretchable thread and recorded in millimetres (mm).

e. Total Tracheal Length (TL) - The distance measured along the longitudinal axis of the trachea from the superior border of the first tracheal cartilage to the carina.

f. Pre - bifurcation Length (PBL) - The distance from the superior border of the first tracheal cartilage to the superior margin of the carina, excluding the carinal ridge.

g. Bifurcation Length (BL) - The vertical extent of the tracheal bifurcation measured from the point where the tracheal lumen begins to divide to the inferior-most projection of the carinal ridge between the origins of the right and left main bronchi.

h. Proximal Transverse External Diameter (PTED) - The maximum external mediolateral diameter of the trachea measured at its proximal end near the inferior border of the cricoid cartilage.

i. Distal Transverse External Diameter (DTED)The maximum external mediolateral diameter of the trachea measured immediately proximal to the carina.

j. Total Tracheobronchial Angle (TTBA) - The angle formed between the longitudinal axes of the right and left main bronchi at the tracheal bifurcation (carina).

k. Right Tracheobronchial Angle (RTBA) - The angle formed between the longitudinal axis of the trachea and the longitudinal axis of the right main bronchus.

l. Left Tracheobronchial Angle (LTBA) - The angle formed between the longitudinal axis of the trachea and the longitudinal axis of the left main bronchus.

m. Number of Tracheal Cartilages (NTC) - The total number of C-shaped hyaline cartilaginous rings extending from the first tracheal cartilage below the cricoid cartilage to the last cartilage immediately proximal to the carina.

Figure 1: Measurement of Total Length (TL) of Trachea

Figure 2: Measurement of Bifurcation Length

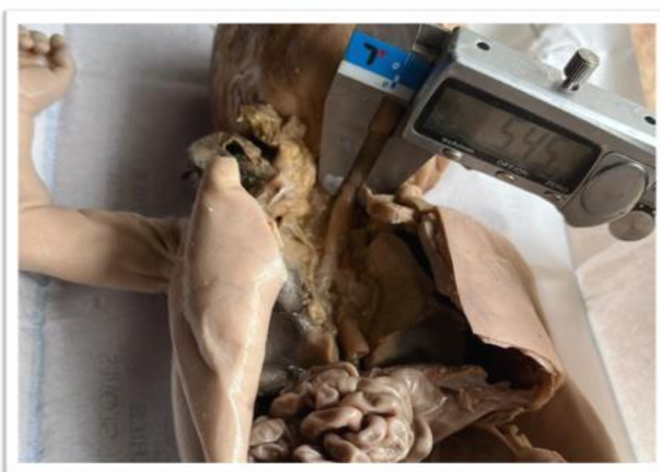

Figure 3: Measurement of Proximal Transverse External Diameter

Statistical Analysis: Data were entered into Microsoft Excel and analysed using IBM SPSS Statistics version 30 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD). Differences among gestational age groups were evaluated using one-way analysis of variance (ANOVA). Pearson's correlation coefficient was used to assess the relationship between fetal biometric variables and tracheal morphometric parameters, as well as correlations among tracheal measurements. A p-value < 0.05 was considered statistically significant.

Figure 4: Measurement of Total Tracheobronchial Angle

Figure 5: Number of Tracheal cartilages at 13 week gestation

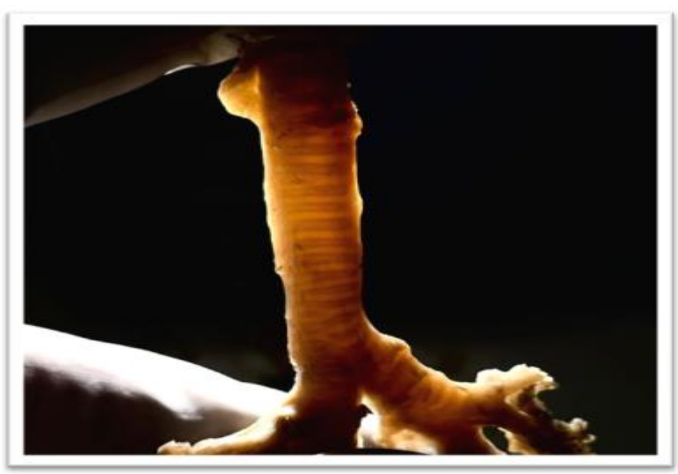

Figure 6: Number of Tracheal cartilages at 32 week gestation

Results

Table 1: Overall general fetal morphometric characteristics (n = 42)

Variable	Mean ± SD	Minimum	Maximum
Gestational age (weeks)	24.21 ± 7.53	13	36
Fetal weight (g)	541.19 ± 425.68	73	1750
Crown-rump length (mm)	196.29 ± 76.70	66	330
Abdominal circumferenc (mm)	152.51 ± 54.02	72	272
Head circumference (mm)	193.19 ± 68.57	90	355

Table 2: Overall fetal tracheal morphometric characteristics (n = 42)

Variable	Mean ± SD	Minimum	Maximum
Total tracheal length (mm)	21.75 ± 7.15	9.80	36.09
Pre-bifurcation length (mm)	18.18 ± 6.07	8.32	30.24
Bifurcation length (mm)	3.58 ± 1.22	1.48	7.30
Proximal transverse external diameter (mm)	4.77 ± 1.48	2.43	7.75
Distal transverse external diameter (mm)	4.21 ± 1.46	1.80	7.89
Total tracheobronchial angle(°)	77.43 ± 2.08	74	82
Right tracheobronchial angle(°)	25.43 ± 2.97	20	30
Left tracheobronchial angle (°)	52.00 ± 4.71	44	60
Number of tracheal cartilages (n)	15.10 ± 1.63	12	18

Table 3: General fetal morphometric parameters across gestational age groups

Variable	13–21 weeks (n=18)	22–30 weeks (n=12)	31–38 weeks (n=12)	p value
Fetal weight (g)	217.17 ± 196.64	515.75 ± 194.83	1052.67 ± 346.08	<0.0001
Crown-rump length (mm)	121.11 ± 34.81	215.83 ± 21.13	289.50 ± 21.56	<0.0001
Abdominal circumference (mm)	102.189 ± 20.91	168.333 ± 33.12	212.167 ± 28.39	<0.0001
Head circumference (mm)	134.00 ± 40.28	201.25 ± 25.23	273.92 ± 38.33	<0.0001

Table 4: Fetal tracheal morphometric parameters across gestational age groups

Variable	13–21 weeks (n=18)	22–30 weeks (n=12)	31–38 weeks (n=12)	p value
Total tracheal length (mm)	14.99 ± 2.82	23.08 ± 3.13	30.56 ± 2.70	<0.0001
Pre-bifurcation length (mm)	12.41 ± 2.35	19.31 ± 2.72	25.70 ± 2.01	<0.0001
Bifurcation length (mm)	2.59 ± 0.55	3.77 ± 0.68	4.87 ± 1.08	<0.0001
Proximal transverse external diameter (mm)	3.33 ± 0.60	5.20 ± 0.65	6.49 ± 0.67	<0.0001
Distal transverse external diameter (mm)	2.86 ± 0.59	4.44 ± 0.60	6.00 ± 0.74	<0.0001
Total tracheobronchial angle (°)	75.78 ± 1.35	77.67 ± 1.43	79.67 ± 1.15	<0.0001
Right tracheobronchial angle (°)	28.33 ± 1.41	24.33 ± 1.15	22.17 ± 1.33	<0.0001
Left tracheobronchial angle (°)	47.44 ± 2.35	53.33 ± 1.55	57.50 ± 1.73	<0.0001
Number of tracheal cartilages (n)	13.61 ± 0.85	15.42 ± 0.66	17.00 ± 0.85	<0.0001

Table 5: Correlation of general fetal morphometry with fetal tracheal morphometry (r values)

Tracheal parameter	CRL	AC	HC	Weight
Total tracheal length (mm)	0.956	0.900	0.878	0.836
Pre-bifurcation length (mm)	0.951	0.895	0.879	0.829
Bifurcation length (mm)	0.875	0.819	0.774	0.733
Proximal transverse external diameter (mm)	0.962	0.917	0.894	0.869
Distal transverse external diameter (mm)	0.956	0.918	0.920	0.887
Total tracheobronchial angle (°)	0.805	0.770	0.796	0.735
Left tracheobronchial angle (°)	0.955	0.916	0.895	0.852
Right tracheobronchial angle (°)	-0.950	-0.913	-0.862	-0.837
Number of tracheal cartilages (n)	0.947	0.898	0.854	0.855

Table 6: Selected inter-correlations among fetal tracheal morphometric parameters

Parameter 1	Parameter 2	r	p value
Total tracheal length	Pre-bifurcation length	0.996	<0.001
Total tracheal length	Bifurcation length	0.999	<0.001
Total tracheal length	Proximal transverse external diameter	0.959	<0.001
Total tracheal length	Distal transverse external diameter	0.946	<0.001
Total tracheal length	Number of tracheal cartilages	0.917	<0.001
Right tracheobronchial angle	Left tracheobronchial angle	-0.953	<0.001
Right tracheobronchial angle	Proximal transverse external diameter	-0.940	<0.001
Right tracheobronchial angle	Distal transverse external diameter	-0.927	<0.001
Right tracheobronchial angle	Number of tracheal cartilages	-0.922	<0.001

Discussion

The present morphometric study of 42 fetuses demonstrated a clear and orderly increase in all major tracheal measurements with advancing gestational age. Mean total tracheal length rose from 14.99 ± 2.82 mm in the 13–21 week group to 30.56 ± 2.70 mm in the 31–38 week group, while proximal transverse external diameter increased from 3.33 ± 0.58 mm to 6.49 ± 0.50 mm and distal transverse external diameter from 2.86 ± 0.65 mm to 6.00 ± 0.57 mm.

These findings indicate progressive elongation and calibre enlargement of the fetal trachea during intrauterine life. The developmental relevance of normative tracheal dimensions for prenatal assessment and perinatal airway planning has also been emphasized in earlier anatomical and fetal procedural studies. Montgomery PQ et al (2011),[9] David AL et al (2013),[10] and Cobb LM et al,[11] (1975) highlighted the usefulness of reference tracheal measurements in fetal evaluation and airway-related planning.

The progressive rise in total tracheal length, pre-bifurcation length, bifurcation length, and tracheal diameters in the present study is comparable with previous morphometric investigations. Matos CC et al,[12] (2020) reported that total tracheal length, pre-bifurcation length, and external diameters increased with gestational age, while Tuncer I,[14] (2018) observed significant gestational increases in tracheal and bronchial lengths and diameters.

Similar developmental patterns were documented by Szpinda M et al (2013),[15] Szpinda M et al (2012),[16] Szpinda M et al (2012),[17] Fayoux P et al (2008),[18] and Adamiec E et al (2002).[19] Collectively, these studies support the concept that the fetal trachea enlarges in a coordinated manner throughout gestation.

Angular remodeling was another important feature of the present series. The right tracheobronchial angle decreased progressively from 28.33 ± 1.41° to 22.17 ± 1.33°, whereas the left tracheobronchial angle increased from 47.44 ± 2.35° to 57.50 ± 1.73°. The total tracheobronchial angle also showed a modest increase from 75.78 ± 1.35° to 79.67 ± 1.15°. Almeida RR et al (2020),[13] similarly found that the right bronchial angle remained consistently smaller than the left and that total tracheobronchial angle changed with gestational age. Tuncer I (2018),[14] also documented age-related changes in tracheobronchial angles. In the present study, however, angular parameters were not merely age-related; they were also significantly associated with linear growth, particularly the inverse relation of the right tracheobronchial angle with tracheal size.

The number of tracheal cartilages increased from 13.61 ± 0.85 in the earliest gestational group to 17.00 ± 0.85 in the latest group. This suggests progressive segmentation and maturation of the tracheal cartilaginous framework during fetal life. Matos CC et al (2020),[12] and Almeida RR et al (2020),[13] reported mean cartilage counts around 16 with limited influence of sex, while Adamiec E et al (2002),[19] described a relatively stable ring count in their material. The present findings are close to those reports, although the current study demonstrated a clearer gestational rise in cartilage count.

An important strength of the present study is the demonstration of strong association between fetal somatic growth and tracheal development. Crown-rump length showed the strongest correlation with total tracheal length (r = 0.956), pre-bifurcation length (r = 0.951), proximal transverse external diameter (r = 0.962), distal transverse external diameter (r = 0.956), left tracheobronchial angle (r = 0.955), and number of tracheal cartilages (r = 0.947).

Abdominal circumference, head circumference, and fetal weight also showed strong positive correlations with nearly all tracheal parameters, whereas the right tracheobronchial angle showed strong negative correlation with all general fetal measurements. Fayoux P et al (2008),[18] observed that laryngotracheal structures grow proportionally with fetal growth, Adamiec E et al (2002),[19] found that tracheal length increased proportionally with crown-rump length, and Matos CC et al (2020),[12] also demonstrated coordinated growth of major tracheal dimensions with gestational age. Cobb LM et al (1975),[11] likewise supported the concept that fetal tracheal enlargement parallels overall fetal development rather than occurring in isolation.

Inter-correlation among tracheal parameters was also notable. Total tracheal length showed very strong positive correlation with pre-bifurcation length (r = 0.996), bifurcation length (r = 0.999), proximal transverse external diameter (r = 0.959), distal transverse external diameter (r = 0.946), and number of tracheal cartilages (r = 0.917). The right tracheobronchial angle showed strong negative correlation with the major size parameters, while the left and total tracheobronchial angles showed positive correlation.

These findings suggest that elongation of the trachea, enlargement of its calibre, segmentation of its cartilaginous rings, and remodeling of the carinal region proceed in a coordinated manner during fetal life. Szpinda M et al (2012),[17] observed proportional growth of prebifurcation and bifurcation lengths, with a stable bifurcation-to-prebifurcation ratio, supporting the concept that different components of the trachea enlarge in a coordinated fashion. Szpinda M et al (2012),[16] reported that tracheal length and external transverse diameter developed proportionally to each other.

Table 7: Comparison of the present study with selected morphometric studies on the fetal trachea

Study	Material	Principal morphometric observation	Comparison with present study
Present study	42 fetuses 13 - 36 weeks	Progressive increase in all major tracheal dimensions; right angle decreased while left and total angles increased with gestational age.	Provides Indian reference data with gestational grouping and correlation analysis.
Matos CC et al (2020)	51 fetuses 20 - 38 weeks	Total tracheal length, pre-bifurcation length, and transverse diameters increased with gestational age; no significant sex difference.	Agreement for progressive increase in major linear dimensions.
Almeida RR et al (2020)	41 fetuses 20 - 38 weeks	Right tracheobronchial angle remained smaller than the left; total angle varied with gestational age.	Agreement regarding smaller right angle; present study additionally showed significant correlations with linear dimensions.

Tuncer I (2018)	50 fetuses 14 - 40 weeks	Tracheal and bronchial lengths, diameters, and tracheobronchial angles increased significantly with gestation.	Broadly consistent with progressive fetal airway enlargement observed in the present study.
Szpinda M et al (2012; 2013)	73 fetuses 14 - 40 weeks	Tracheal growth followed linear or logarithmic patterns depending on the variable; proportional growth was emphasized.	Supports the coordinated and proportionate enlargement demonstrated by the present inter-correlation analysis.
Fayoux P et al (2008)	Prenatal and early postnatal material	Laryngotracheal structures showed linear growth proportional to fetal growth.	Consistent with strong correlations between tracheal dimensions and fetal biometric variables.
Adamiec E et al (2002)	Normal fetuses 8 - 40 weeks	Continuous increase in tracheal length and diameters across gestation.	In agreement with the current progressive gestational increase in tracheal size.

In contrast, Almeida RR et al (2020),[13] did not find significant correlation between tracheobronchial angles and linear tracheal measurements or cartilage number. The present study differs from that observation by demonstrating significant relationships between angular and linear measurements, especially the inverse relation of the right tracheobronchial angle with tracheal size.

Taken together, the present findings establish a morphometry-only reference framework for fetal tracheal development in this series. The study demonstrates that tracheal dimensions enlarge continuously with gestational age and closely reflect overall fetal growth. Such normative data may be useful in developmental anatomy, fetal imaging, and future studies dealing with congenital tracheobronchial abnormalities.

Conclusion

The present study shows that the developing human fetal trachea undergoes progressive and statistically significant morphometric enlargement with advancing gestational age. Total length, pre-bifurcation length, bifurcation length, proximal and distal transverse external diameters, total and left tracheobronchial angles, and number of tracheal cartilages increased progressively, while the right tracheobronchial angle decreased. All tracheal morphometric parameters demonstrated significant correlation with general fetal biometric variables, with crown-rump length showing the strongest overall association. Inter-correlation among tracheal parameters further supports coordinated growth of tracheal length, calibre, angular configuration, and cartilaginous framework. These findings provide useful baseline morphometric data for normal fetal tracheal development.

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Conflicts of interest

There are no conflicts of interest.

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