Received: 20 November 2023 | Revised: 15 April 2024 | Accepted: 25 April 2024
DOI: 10.1002/lio2.1262

ORIGINAL RESEARCH

Laryngoscope Investigative Otolaryngology

Age-related morphological change in bony segment and cartilage segment of Eustachian tube

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Funding information
National Natural Science Foundation of China, Grant/Award Number: 82101216

Abstract

Background: Eustachian tube dysfunction (ETD) is the predominant cause of otitis media with effusion in children and adults. Balloon dilatation of the Eustachian tube (BDET) provides a new method for restoring the ventilatory function of Eustachian tube (ET). However, the differences in age-related morphological changes in the dimensions and positions of ET in children and adults are unclear.

Purpose: This study aimed to examine age-related morphological changes in bony and cartilage segments of the ET in a three-dimensional space in normal population.

Methods: A total of 71 randomly selected computed tomography (CT) images of the temporal bones of 46 people were retrospectively studied in four age groups: A (0–3 years old); B (4–8 years old), C (9–18 years old), and D (19–65 years old). Space analytic geometry was assessed to calculate the dimensions and positions of ET.

Results: The bony segment of ET lengthened from infancy to adulthood with age in groups A, B and C ($r = 0.562^{**}/0.000$). The cartilage segment of ET mostly extended with age from infancy to 8 years old in children ($r = 0.633^{**}/0.000$), but with bending close to the sagittal plane and away from the horizontal plane with age in groups A, B and C ($P < .05$), and with a constant angle to the coronal plane among the four groups ($P > .05$).

Conclusion: The bony and cartilaginous segments of ET exhibit distinct morphological changes in space with age. The bony segment of ET extends in a constant position from infancy to adulthood. In contrast, the cartilaginous segment of the ET indicates multidimensional positional changes until adulthood, in addition to the elongation from infancy to children. This may provide an accurate morphological basis for comparing the differences in ETD pathogenesis and surgical treatment between children and adults.

KEYWORDS
age, Eustachian tube, imaging, morphology

1 | INTRODUCTION

Eustachian tube (ET) connects the middle ear to the nasopharynx. ET performs three primary functions: (1) pressure equalization and ventilation of the middle ear; (2) mucociliary clearance of secretions from the middle ear, and (3) protection of the middle ear from sounds and pathogens or secretions from the nasopharynx.[1] Obstructive Eustachian tube dysfunction (OETD) is the predominant cause of otitis media with effusion in children and adults,[2,3] associated with complex anatomy and pathophysiological mechanism of the ET.

Treatment of OETD was complicated, and some had either short-lived or modest efficacy in refractory OETD after medical interventions and tympanostomy tube (TT) placement.[3,4] Recent studies have revealed that balloon dilation of the Eustachian tube (BDET) is an effective method for treating chronic OETD in adults and children by dilating the cartilage segment of the ET to restore its ventilatory function.[3–6] However, due to the angular and length changes of the cartilage and bony segments of ET in space with age, the potential risks lie in inaccurate evaluation the difference in the dimension and position of ET between children and adults in BDET. It was reported the possible injury to the adjacent middle or inner ear and the carotid artery presents with bleeding, hearing loss and patulous Eustachian tubes.[7–9]

The Eustachian tube is composed of a bony segment and a cartilage segment. The ET antero-inferiorly extended the cartilage segment to the nasopharynx.[1,10] It was reported that ET lengthens and bends with age, develops rapidly from birth to 3–4 years old, and is similar to that in adults at 7–8 years old.[11] However, considering the angular changes of cartilage and bony segments of ET in space with age, the morphological structure of ET in any single plane has not been accurately evaluated.[12,13] Therefore, this paper aimed to compare and analyze the trends of the bony segment and cartilage segment of ET in space with age in people. The work may provide a valuable morphological change of ET in space with age for ETD treatment in children and adults.

2 | MATERIALS AND METHODS

2.1 | Subjects

From January 2011 to May 2015, 71 non-pathological temporal bone CT images from 46 patients in our hospital were randomly selected for retrospective analysis. The patients were diagnosed with sensorineural deafness, tinnitus, vertigo, or unilateral congenital microtia with normal unilateral ear. The anatomical CT images of temporal bone of 46 subjects were evaluated as normal by radiologists. The population was divided into four groups based on the different changes in the growth of skull base with age[13]: (A) (0–3 years old; $n = 11$ ears; 3 males and 3 females; mean age = 1.24 ± 0.86), (B) (4–8 years old; $n = 29$ ears; 12 males and 11 females; mean age = 6.21 ± 1.34), (C) (9–18 years old; $n = 14$ ears; 4 males and 4 females; mean age = 15.36 ± 3.15), and (D) (19–65 years old; $n = 17$ ears; 4 males and 5 females; mean age = 42.53 ± 15.90). There were no significant gender differences among the four groups (Table 1). This study was approved by the Ethics Committee of our hospital.

2.2 | Data acquisition and post-processing

All axial images were taken in helical mode with multi-detector row CT (Sensation 16, Siemens Medical Systems, Forchheim, Germany). The scanning procedure followed the standard temporal bone imaging protocol. Scans were taken with a voltage of 120.0 kV and a current of 180.0 mA. Images were reconstructed using 0.50-mm-thick sections at 0.5 mm increments, a 512 × 512 matrix of 0.43 mm pixel size, and a display field of view (DFOV) of 22.0 cm × 22.0 cm. Images were displayed using a window center of 700 HU and a window width of 4000 HU. Digital imaging and communication in medicine (DICOM) images contained positioning data that defined the spatial coordinates in the superior–inferior, anterior–posterior, and left–right directions. CT DICOM datasets were imported into MIMICS 10.0 software (Materialize, Belgium) for image processing.

2.3 | Calculation

All landmarks around ET were defined in three-dimensional images. Point and calculation of coordinate values: define ET and all signs around ET to form a three-dimensional image. To achieve uniformity in the whole skull measurement study, the Frankfort horizontal plane (Phor) was used as the standard horizontal plane, defined as the plane passing through the superior point of the left and right auditory meatus and the left infraorbital marginal point. The sagittal plane (Psag) was defined as the plane through the top of the ethmoid comb and the line's middle point from the left foramen spinosum to the right foramen spinosum. Finally, the coronal plane (Pcor) is defined as the plane through the line from the left foramen spinosum to the right

TABLE 1 Descriptive statistics of each age group.

Group (Age, Y)	Patients, No.	Ears, No.	Age, mean (SD)	Range
0–3	6 (M3, F3)	11	1.24 ± 0.86 Y	6 D–36 M
4–8	23 (M12, F11)	29	6.21 ± 1.34 Y	4–8 Y
9–18	8 (M4, F4)	14	15.36 ± 3.15 Y	9–18 Y
19–65	9 (M4, F5)	17	42.53 ± 15.90 Y	20–65 Y

Note: M: male; F: female; Y: year; M: month; D: day.

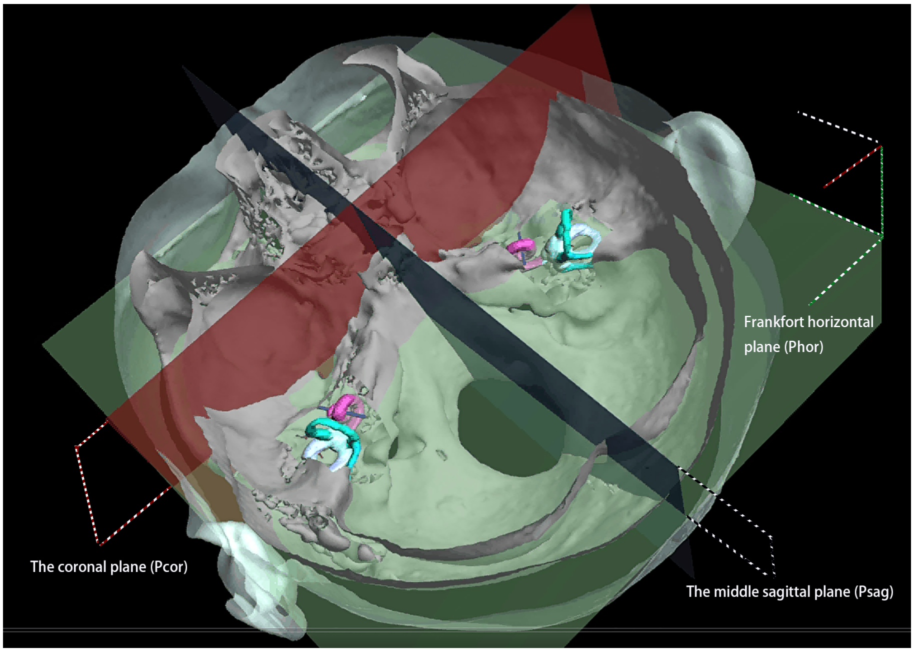

FIGURE 1 Schematics of the Frankfort horizontal plane (Phor), the sagittal plane (Psag), and the coronal plane (Pcor) in three-dimensional construction images.

foramen spinosum and is perpendicular to horizontal and sagittal planes (Figure 1).[14,15]

Using the methods described in previous research,[15,16] we defined ET anatomical sites in this study as (1) the tympanic orifice, the nearest central point in ET before the external auditory canal appears on the cross-sectional image (Figure 2A); (2) the isthmus of ET began at the layer where the bony segment of ET completely disappeared (Figure 2B); (3) the pharyngeal orifice of ET lumen, the central point nearest the pharynx where a loop-shaped ET lumen appears (Figure 2C).

The length of bony segment of ET (bonyET-L) and cartilage segment of ET (cartiET-L) are all from a straight line: the distance from the tympanic orifice to the central point of the isthmus and the distance from the central point of the isthmus to the pharyngeal orifice. The total length of ET (ET-TL) is the sum of bonyET-L and cartiET-L. Otym-Phor, Otym-Psag, and Otym-Pcor represent the distance from the central point of the tympanic orifice of ET (Otym) to the plane of Phor, Psag, and Pcor, respectively. Opha-Phor, Opha-Psag, and Opha-Pcor represent the distance from the central point of the pharyngeal orifice of the ET (Opha) to the plane of Phor, Psag, and Pcor, respectively. Isth-Phor, Isth-Psag, and Isth-Pcor represent the distance from the ET's central point of the isthmus to the plane of Phor, Psag, and Pcor, respectively. The symbol ∠bonyET/cartiET represents the angle between the bony and cartilaginous parts of ET. The angles of symbols ∠bonyET/Phor, ∠bonyET/Psag, and ∠bonyET/Pcor indicate the angle between the bony segment of ET (bonyET) and Phor, Psag, and Pcor. The angels of symbols ∠cartiET/Phor, ∠cartiET/Psag, and ∠cartiET/Pcor represent the angles between the cartilage segment of ET (cartiET) and Phor, Psag, and Pcor, respectively (Figure 3).[15]

The coordinate values of the above landmarks were imported into ET calculation program developed by (Matrix laboratory, Natick, MA, USA) based on MATLAB software. The data for ET can be automatically calculated by MATLAB software according to analytic geometry through point-to-point distance, point to line distance, point-to-plane distance, the line-to-line angel of intersection, or line to plane angle of intersection (Figure 3). All the abbreviations defined in the study were listed in the Supplementary materials (Supplemental Table 1).

2.4 | Statistics

The data were confirmed to have a normal distribution. All data are shown as mean ± standard deviation (SD). Differences among more than two age groups were analyzed with one-way analysis of variance (ANOVA) and Fisher's protected least significant difference (PLSD) tests. A value of $P < .05$ was accepted as statistically significant. The Pearson correlation analysis was used to analyze the correlativity of ET data (taken as being extraordinarily marked where $P < .01$, marked where $P < .05$). All statistical data were analyzed with the SPSS 16.0 (SPSS, Inc., Chicago, IL).

3 | RESULTS

As displayed in Table 2, a significant difference was found in bonyET-L, cartiET-L, ET-TL, and the angles (between cartiET and bonyET, cartiET and Psag, cartiET, and Phor) in whole age groups ($P < .05$). It was indicated that bonyET-L was 6.41 ± 1.09 (mm), 7.78 ± 2.17 (mm), 11.29 ± 5.55 (mm), and 9.24 ± 2.55 (mm) in groups A, B, C, and D, respectively (Table 2). A significant difference was found in bonyET-L among groups A, B, and C ($P < .05$), but no significant

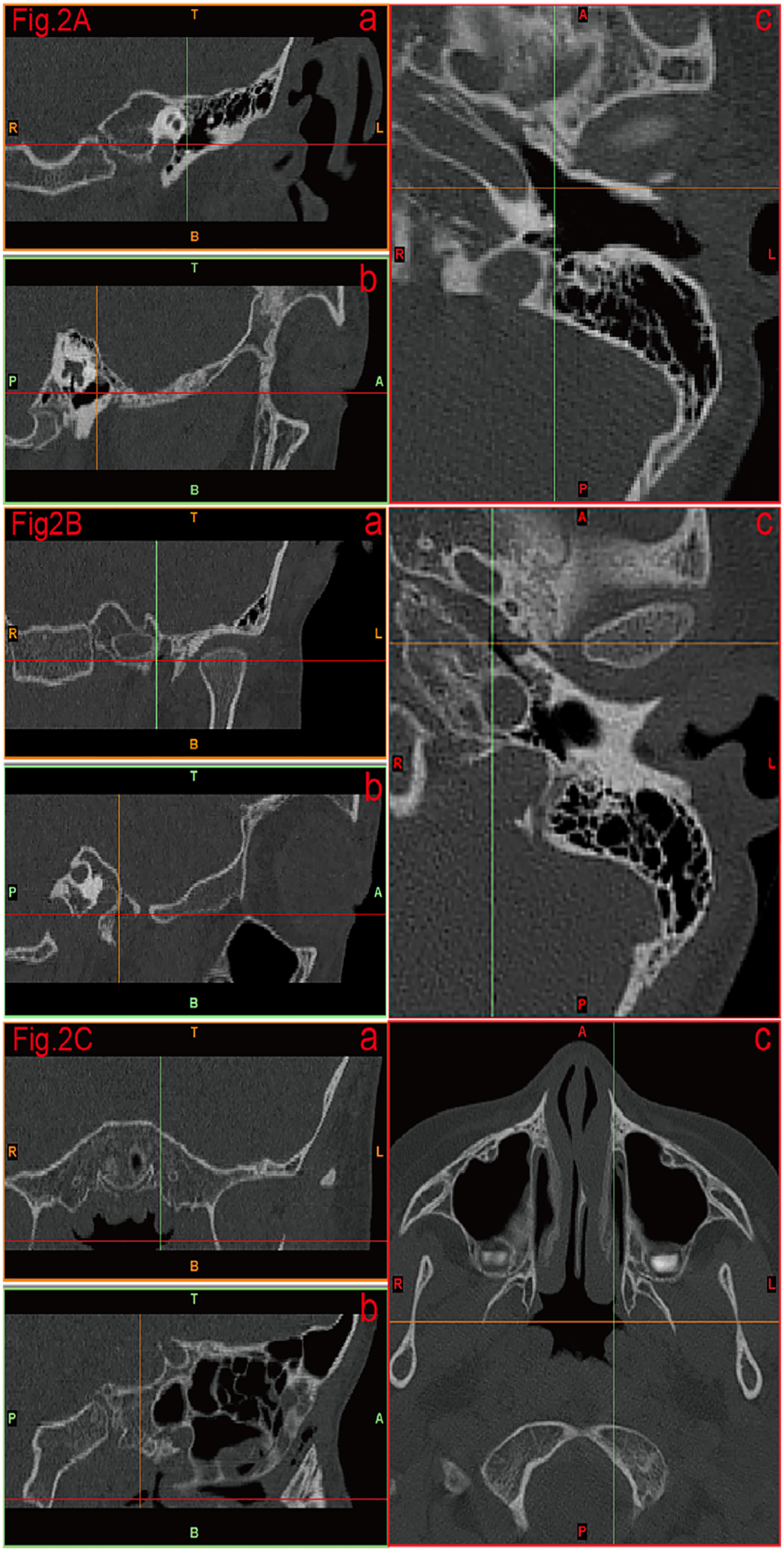

FIGURE 2 The screenshot of the position of tympanic orifice, the isthmus and pharyngeal orifice of Eustachian tube (ET) lumen in space. (A) The tympanic orifice, the nearest central point in ET before the external ear canal appears on the cross-sectional image. (A, B, and C) The location of the tympanic orifice of left ET lumen in the Pcor, Psag, and Phor. ET is located between internal carotid artery and semicanal of tensor tympani muscle on the cross-sectional image. (B) The isthmus of ET began at the lay where the bony segment of ET completely disappeared. (A, B, and C) The location of the middle points of the isthmus of left ET lumen in the Pcor, Psag, and Phor. (C) The pharyngeal orifice of left ET lumen. (A, B, and C) The central point where a loop-shaped ET lumen appears in the Pcor, Psag, and Phor. The coronal plane (Pcor), the sagittal plane (Psag), and the Frankfort horizontal plane (Phor). ET NP orifice, ET pharyngeal orifice. *ICA, internal carotid artery. # semicanal of tensor tympani muscle. T: top; B: bottom; R: right; L: left. A: anterior; P: posterior.

difference existed in bonyET-L between groups C and D ($P > .05$) and groups B and D ($P > .05$) (Table 2). A significantly correlation was found between the bonyET-L and age in children from birth to adults (0–18 years old) ($r = 0.562^{**}/0.000$) (Table 3, Figure 4A). It was suggested that bonyET-L extended gradually from birth to adulthood with age.

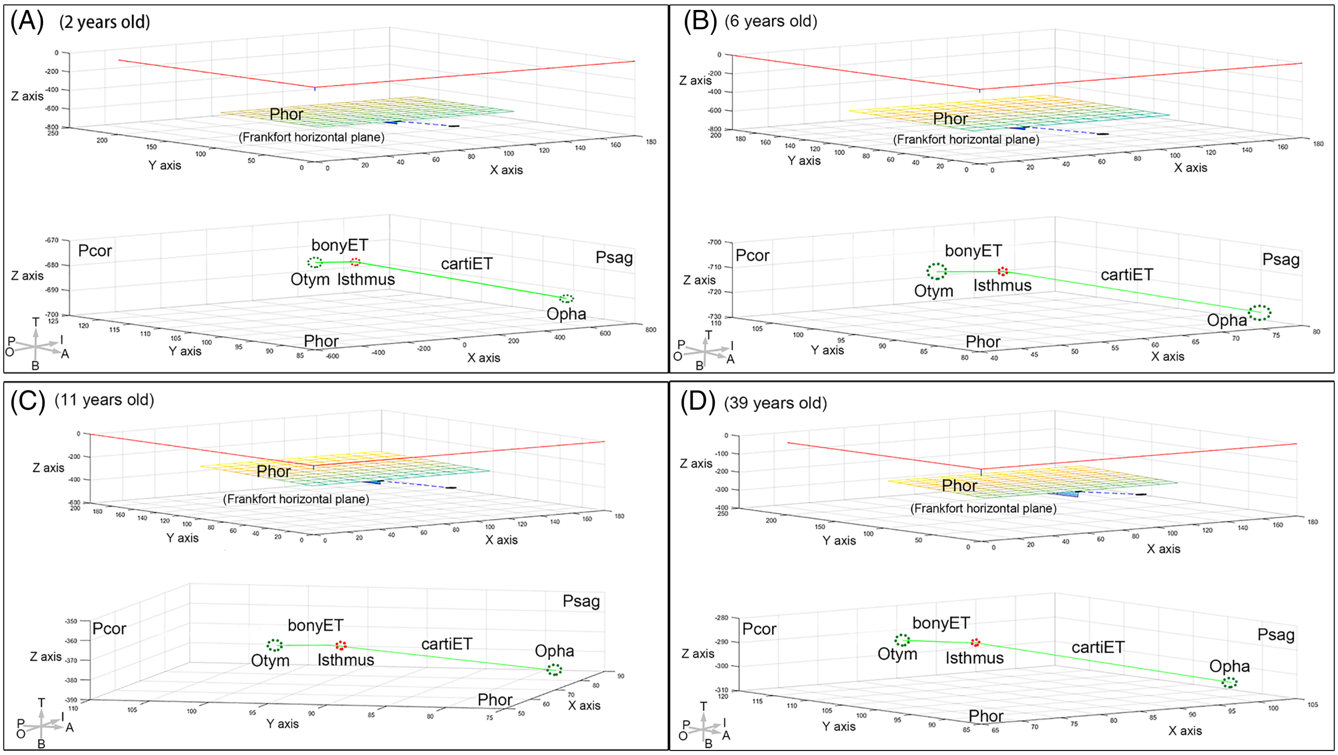

FIGURE 3 Schematic drawing of the dimension and position of the right Eustachian tubes (ET's) bony and cartilaginous segments in people with four aged groups in three-dimensional space. In each set of image, the upper graph shows the standard horizontal plane (yellow-green gradient plane) and the morphology of the ET (blue dashed line segment); the lower graph shows the position and dimension of the ET's bony and cartilaginous segments in the standard three-dimensional space after enlargement. (A) The data from a 2-year-old child, representing group A (0–3 years old); (B) The data from a 6-year-old child, representing group B (4–8 years old); (C) The data from a 11-year-old child, representing group C (9–18 years old); (D) The data from a 39-year-old adult, representing group D (19–65 years old). The bonyET extends at a constant position from infancy to adulthood with age in groups A, B, and C ($P < .05$). In contrast, the cartiET mostly extends with age from infancy to 8 years old in children, but with bending close to the Psag and away from the Phor from infancy to adulthood in groups A, B, and C ($P < .05$), and with a constant angle to the Pcor among four groups ($P > .05$). bonyET: bony segment of the ET; cartiET: cartilaginous segment of the ET; Otym: the tympanic orifice of the ET; Opha: the pharyngeal orifice of the ET; Isthmus: the isthmus of ET lumen; ET: Eustachian tube; Phor: the Frankfort horizontal plane; Psag: the middle sagittal plane; Pcor: the coronal plane. T: top; B: bottom; O: outside; I: inside; A: anterior; P: posterior.

It was indicated that the cartiET-L was 25.10 ± 2.46 (mm), 29.61 ± 3.08 (mm), 30.36 ± 4.23 (mm), and 30.51 ± 2.63 (mm) in groups A, B, C, and D, respectively. Although a significant difference was found in cartiET-L between groups A and B, groups A and C, and groups A and D ($P < .05$), no significant difference was observed in cartiET-L among groups B, C, and D ($P > .05$) (Table 2). A significantly correlation was found between the cartiET-L and age in children from birth to 8 years old ($r = 0.633^{**}/0.000$) (Table 3, Figure 4B). It was suggested that the cartiET-L predominately lengthened from birth to 8 years old in children with age.

By comparing the position of ET in space, it was found that the position of bony segment of ET was constant ($P > .05$, Table 2). Interestingly, a significant difference existed in the angles between the cartiET and the Phor, the cartiET and the Psag among four groups ($P < .05$, Table 2). It was indicated that the angles between the cartiET and the Phor was 19.34 ± 4.98, 24.97 ± 6.33, 32.16 ± 7.63, and 30.26 ± 6.03 degrees in groups A, B, C, and D, respectively; the angles between the cartiET and the Psag was 44.46 ± 2.68, 41.14 ± 3.69, 34.44 ± 6.58, and 39.22 ± 5.58 degrees in groups A, B, C, and D, respectively (Table 2).

From infancy to 18 years old people, the angle between the cartiET and Phor increased ($r = 0.642^{**}/0.000$), and the angle between the cartiET and Psag decreased ($r = -0.654^{**}/0.000$). They were found to be significantly related to age (Table 3, Figure 4). No significant difference was found in the angles between the cartiET and the Pcor among the four groups ($P > .05$) (Tables 2 and 3). It has been suggested that the cartiET gradually bends close to the sagittal plane and away from the horizontal plane from infancy to adulthood, with a constant deviation to the coronal plane.

4 | DISCUSSION

In this study, the age-related morphological trends differed in the bony and cartilage segments of the ET in children and adults. The bony segment of the ET extends from infancy to adulthood, with a constant position with age. The cartilage segment of ET predominantly keeps Antero-inferiorly extension from infancy to 8-year-old children but with consistent bending toward the

TABLE 2 Morphometric analysis of the Eustachian tube (ET) among age groups (distance in millimeter and angle in degree).

	Group A (0–3 Y)	Group B (4–8 Y)	Group C (9–18 Y)	Group D (19–65 Y)	*P*	*Pab*	*Pac*	*Pad*	*Pbc*	*Pbd*	*Pcd*
bonyET-L	6.41 ± 1.09	7.78 ± 2.17	11.29 ± 5.55	9.24 ± 2.55	<0.01	<0.05	<0.01	<0.05	<0.05	NS	–
cartiET-L	25.10 ± 2.46	29.61 ± 3.08	30.36 ± 4.23	30.51 ± 2.63	<0.01	<0.01	<0.01	<0.01	NS	–	–
ET-TL	31.51 ± 3.13	37.40 ± 2.80	41.65 ± 4.35	39.75 ± 3.78	<0.01	<0.01	<0.01	<0.01	<0.01	NS	–
∠bonyET/cartiET	157.32 ± 9.43	148.77 ± 9.30	148.25 ± 15.07	152.36 ± 11.19	<0.05	<0.05	<0.05	<0.05	<0.05	NS	–
∠bonyET/Psag	48.77 ± 5.05	52.09 ± 7.02	50.25 ± 5.44	49.34 ± 6.48	NS	<0.05	NS	–	–	–	–
∠bonyET/Pcor	40.44 ± 5.30	36.22 ± 6.90	38.29 ± 6.29	39.81 ± 6.36	NS	<0.05	NS	–	–	–	–
∠bonyET/Phor	6.09 ± 2.83	8.24 ± 5.16	7.05 ± 5.68	6.11 ± 3.43	NS	–	–	–	–	–	–
∠cartiET/Psag	44.46 ± 2.68	41.14 ± 3.69	34.44 ± 6.58	39.22 ± 5.58	<0.01	<0.05	<0.01	<0.01	<0.01	NS	<0.05
∠cartiET/Pcor	38.84 ± 4.21	37.96 ± 5.68	38.38 ± 3.39	36.60 ± 3.82	NS	–	–	–	–	–	–
∠cartiET/Phor	19.34 ± 4.98	24.97 ± 6.33	32.16 ± 7.63	30.26 ± 6.03	<0.01	<0.05	<0.01	<0.01	<0.01	<0.05	NS

Note: Morphometric analysis of the ET among age groups (distance in millimeter and angle in degree). bonyET-L, cartiET-L the length of bony part, cartilaginous part of ET, respectively; ET-TL the total length of the ET; ∠bonyET/cartiET the intersection angle of bony part and cartilaginous part of the ET; ∠bonyET/Phor, ∠bonyET/Sag, ∠bonyET/Pcor the intersection angle of bony part of the ET against Frankfort horizon plane, sagittal plane, and coronal plane, respectively; ∠cartiET/Phor, ∠cartiET/Psag, ∠cartiET/Pcor the intersection angle of cartilaginous part of the ET against Frankfort horizon plane, sagittal plane, and coronal plane, respectively; ET: Eustachian tube. Values are presented as mean ± SD. Groups A–D indicate 0–3, 4–8, 9–18, and 19–65 years old group, respectively; Pab, Pac, Pad, Pbc, Pbd, Pcd indicate *P*-value for differences between groups A and B, between groups A and C, between groups A and D, between groups B and C, between groups B and D, and between groups C and D, respectively; Psag: the middle sagittal plane. Pcor: the coronal plane. Phor: the Frankfort horizontal plane. NS, not significant.

sagittal plane and far from the horizontal plane from infancy to adulthood.

Previous studies about ET morphology were based on tissue sections, imaging, and endoscopic measurements.[11,16–18] In early studies, ET length was presented with the distance of a straight line from ET pharynx orifice to the tympanic orifice, and ET angles were indicated with the angle between the straight line representing ET length and the Reid standard horizontal plane on the coronal plane in CT images.[11,16–19] Angular changes in the cartilage and bony segments of ET were ignored. Moreover, a two-dimensional measurement may provide incorrect or incomplete data due to the possible different head positions under CT imaging.

In this study, we referred to standard planes and identified all landmarks on the three-dimensional image of CT. Then, the length of bony segment, the cartilage segment of ET, and the orientational changes in three dimensions were calculated. Our results suggest that the ET length is slightly longer than that reported in a study on normal temporal bone specimens and similar to that measured on CT images.[11,18,19] The difference may be mostly due to separate definitions of the bony and cartilage segments of ET in three-dimensional space. An enlarged number of specimens in different age groups is needed to reduce sampling errors in further studies. On the other hand, our work had certain limitations. Although the morphological trends in bony segment and cartilage segment of the ET was shown in the study, the specific angles and orientation likely vary between populations due to the racial differences.

It has been reported that ET lengthened and bent with age and was similar to that in adults at 7–8 years old.[11] In our study, the age-related morphological trends differed in the bony and cartilage segments of ET in people. Although our results also suggested the cartilage segment of ET predominately extended from infancy to 8 years old children with age (Figure 4B), but with bending close to the sagittal plane and away from the horizontal plane from infancy to adults (0–18 years old), and with a constant deviation to the coronal plane (Figure 4C, D). It was suggested a fast and dynamic process in the dimension and position of the cartilage segment of ET in childhood could tend to cause ETD in children (0–8 years old).

Balloon dilation of the Eustachian tube (BDET) was increasingly applied in adults and children as an effective option for chronic otitis media.[4,20] Previous studies have focused on the different lengths of the cartilaginous segment of the ET in children and adults.[5–9] In addition to the short length of the ET, the position of ET's cartilage segment was flat and close to the horizontal plane in childhood. The cartilage segment of the ET gradually bent close to the sagittal plane and away from the horizontal plane from birth to adulthood. Our results provide accurate morphological data for ET to compare the differences in BDET between children and adults.

In the study, it was demonstrated that there were differences in age-related morphological trends of bony and cartilage segments of ET. Studies have revealed that the anatomical development of ET depends on the development of the craniofacial region.[2,10,13]

TABLE 3 The correlation coefficients (*r*) and significant difference (*P*) among the dimension and position of bony segment and cartilage segment of Eustachian tube (ET) with age.

	Pearson correlation (*r*)/sig. (*p*)			
Indexes	Age (0–3 Y); *N* = 11	Age (0–8 Y); *N* = 40	Age (0–18 Y); *N* = 54	Age (0–65 Y); *N* = 71
ET-TL	0.488/0.128	0.716**/0.000	0.735**/0.000	0.297*/0.012
bonyET-L	0.021/0.952	0.274/0.087	0.562**/0.000	0.232/0.051
cartiET-L	0.611*/0.046	0.633**/0.000	0.377**/0.005	0.160/0.181
∠bonyET/cartiET	−0.274/0.415	−0.429**/0.006	−0.295*/0.030	−0.063/0.601
∠cartiET/Psag	0.106/0.756	−0.385*/0.014	−0.654**/0.000	−0.313**/0.008
∠cartiET/Pcor	−0.694*/0.018	−0.203/0.209	−0.096/0.490	−0.160/0.182
∠cartiET/Phor	0.784**/0.004	−0.512**/0.001	0.642**/0.000	0.418**/0.000

Note: The Pearson correlation analysis was used to analyze the morphological indexes (*P < .05, **P < .01). BonyET-L, cartiET-L the length of bony part, cartilaginous part of ET, respectively; ET-TL the total length of the ET; ∠bonyET/cartiET the intersection angle of bony part and cartilaginous part of the ET; ∠cartiET/Psag, ∠cartiET/Pcor, ∠cartiET/Phor the intersection angle of cartilaginous part of the ET against sagittal plane, coronal plane, and Frankfort horizon plane, respectively; ET: Eustachian tube. Psag: the middle sagittal plane. Pcor: the Coronal plane. Phor: the Frankfort horizontal plane.

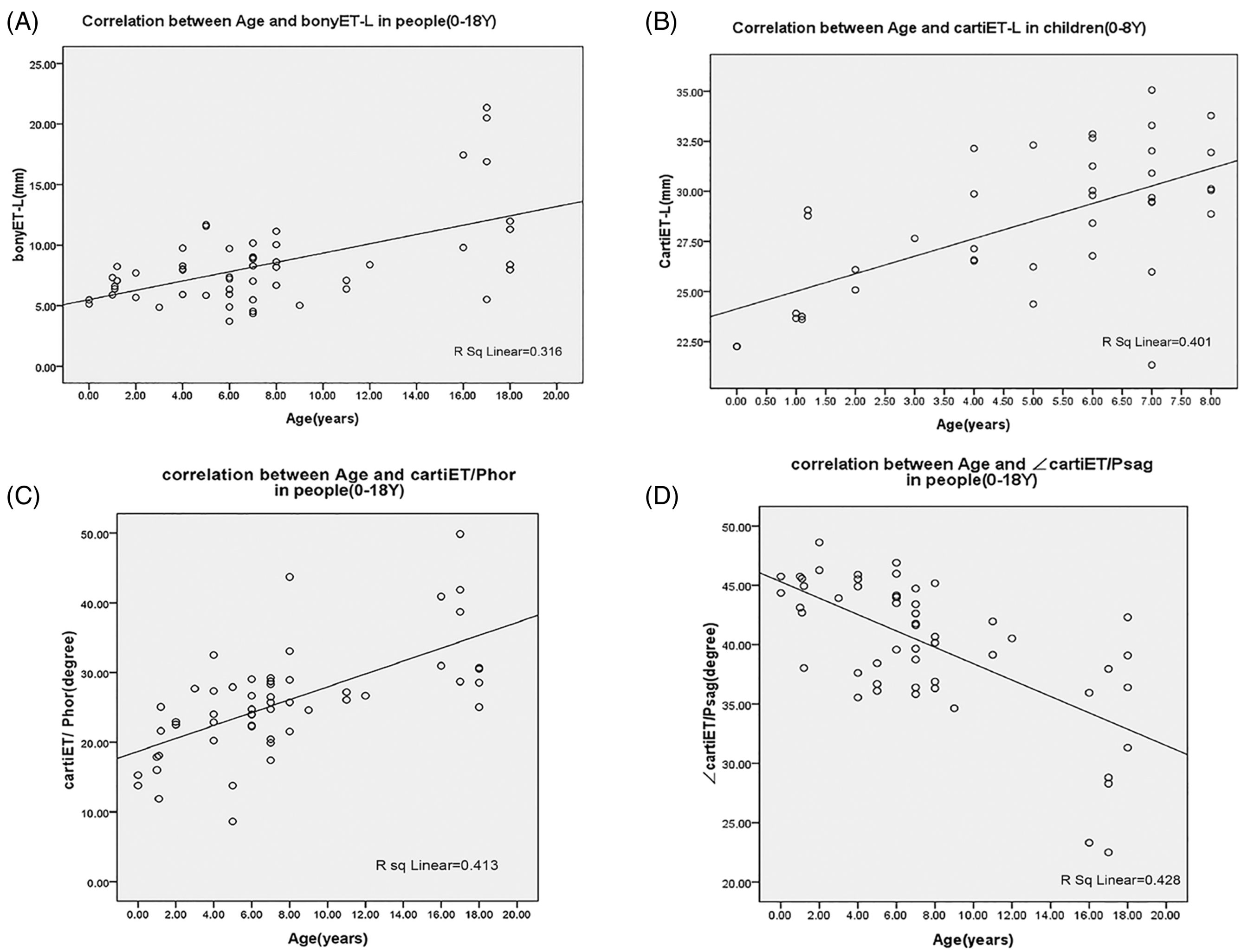

FIGURE 4 The age-related morphological trends are different in the dimension and position of the bony and cartilage segments of Eustachian tube (ET) in normal population with age. (A) The correlation between the bonyET-L and age in people from birth to adulthood (0–18 years old) was presented with the scatter diagram. (B) The correlation between the cartiET-L and age in children from birth to 8 years old was presented with the scatter diagram. (C) The correlation between the ∠cartiET/Phor and age in people from birth to adulthood was presented with the scatter diagram. (D) The correlation between the ∠cartiET/Psag and age in people from birth to adulthood was presented with the scatter diagram. bonyET-L, cartiET-L: the length of bony and cartilaginous segment of ET, respectively; ∠cartiET/Phor, ∠cartiET/Psag: the intersection angle of cartilaginous segment of the ET against Frankfort horizon plane and sagittal plane, respectively.

The bony segment of ET is located in the petrosquamous fissure of the temporal bone near the occipital and sphenoid bones. As a result, the position of the bony segment of ET is relatively constant. The maxilla is antero-inferiorly extended with age from childhood to adulthood, resulting in the morphological growth of the cartilaginous segment of ET in space.[12] Moreover, it influences the insertion of para tubal muscles (tensor and levator Veli palatine) and the vitality of the cartilaginous segment of ET, affecting the function of ET.[21]

5 | CONCLUSIONS

The study suggests different trends in the dimensions and positions of bony and cartilage segments of ET with age in children and adults. The bony segment of ET was lengthened at a constant position from infancy to adulthood. However, the cartilage segment of ET mostly extends from infancy to 8 years old in children, and gradually bends close to the sagittal plane and away from the horizontal plane from infancy to adults. This may provide an accurate morphological basis to compare the differences in ETD pathogenesis and surgical treatment between children and adults.

ACKNOWLEDGMENTS

This study was supported by grant from the National Natural Science Foundation of China (No. 82101216).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Hong J, Dai P, Sun G, Lin L, Lyu H, Chen K. Age-related morphological change in bony segment and cartilage segment of Eustachian tube. *Laryngoscope Investigative Otolaryngology*. 2024;9(3):e1262. doi:10.1002/lio2.1262