



Growth pattern of temporal bone pneumatization: a computed tomography study with consecutive age groups

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Abstract

Purpose To investigate the growth pattern of temporal bone pneumatization (TBP) in consecutive age groups from birth to 18 years old using 3D air-density reconstruction of high-resolution CT (HRCT).

Methods A total of 570 patients under 18 years old who performed temporal bone HRCT and with no structural abnormalities on both sides were included. Nineteen groups were created to represent consecutive ages, with 15 males and 15 females in each group. Volume rendering of air density was performed using a segmentation threshold of -200 HU to obtain TBP volume of each side. The differences in TBP between the sides, sexes, and ages were statistically analyzed.

Results The mean volume of TBP was measured as 1.17 ± 0.44 ml in patients less than 1 year old and 6.81 ± 1.93 ml as adult size. High consistencies of TBP volume between different sides or sexes were found in most of age groups. Significant differences were shown between sides only in 9- and 11-year-old female groups ($p_9=0.031$, $p_{11}=0.016$) while between sexes only in 6- and 16-year-old groups ($p_6=0.001$, $p_{16}=0.043$), although the volume was larger in all the male groups older than 6 years. The curve drawn by the mean volume in consecutive age groups showed that TBP continued to grow linearly in both males and females until they reached 14 years old. The corresponding linear regression equations were as follows: $y_m = 1.553 + 0.370x$, ($x \leq 14$ years, $R^2=0.596$); $y_f = 1.561 + 0.304x$, ($x \leq 14$ years, $R^2=0.565$).

Conclusion The TBP volume shows a linear growth pattern from birth until reaching adult size after 14 years old.

Keywords Temporal bone · Ear, middle · Image processing, Computer-assisted · Tomography, X-ray computed · Infant · Child · Adolescent

Introduction

Temporal bone pneumatization (TBP) acts as an air reservoir and a pressure regulator of middle ear to prevent tympanic membrane retraction and mucous exudation [6]. Its size may be associated with the propensity of the epithelium to opportunistically expand and the need for a structurally sound and functionally efficient osseous configuration [14, 19]. It has been well documented that poorly pneumatized temporal bone is more likely to exhibit otitis media, while otitis media during childhood may interrupt TBP process. In addition, the degree of TBP has been reported to be associated with pneumatization of the sphenoid sinus [9], eustachian tube length [18], tinnitus [11, 17], cholesteatoma, otosclerosis,

atelectatic ear diseases, presbycusis, cystic fibrosis [2], the procedure and prognosis of otologic surgeries [1, 13], and other unknown conditions.

Since morphology and distribution of air cells vary considerably within the temporal bone, it is difficult to measure the TBP volume or surface area directly, although they are interrelated. Thus, radiological methods have been employed widely for such purposes, beginning with radiography and progressing to computed tomography (CT). While TBP surface area or volume in adults has been studied in many reports, the process of TBP over the course of aging has not been thoroughly investigated, and the related studies have always had a small sample and large age intervals [5, 7, 10, 12, 16]. Moreover, it is difficult to compare data validly from various studies owing to the diversity or uncertainty of methods [3].

The aim of this study was to investigate the growth pattern of TBP in consecutive age groups from birth to 18 years old using 3D air-density reconstruction of high-resolution

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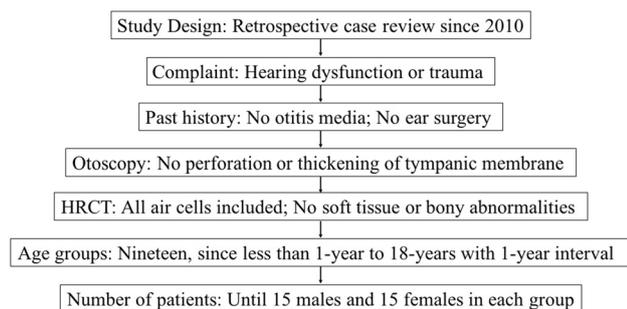


Fig. 1 Flowchart of the inclusion criteria

CT (HRCT) data, which may benefit the study of abnormalities associated with the degree or growth pattern of TBP.

Materials and methods

Clinical data

The ethics committee in our institution approved this study on June 1st, 2018 (No. 2018-P2-073-01). The inclusion criteria were as follows (Fig. 1). (A) Patients came to the otology department due to hearing dysfunction or trauma after 2010; (B) patients had no history of otitis media or middle ear surgery; (C) patients showed no perforation or thickening of the tympanic membrane; (D) all air cells were included in the scans; (E) no soft tissue or bony abnormalities were found on HRCT; (F) nineteen age groups were divided, ranging from infants less than 1–18 years old with 1-year interval; (G) Patients were collected until 15 males and 15 females in each group, respectively. Finally, a number of 570 patients (285 males, 285 females) were included.

CT acquisition parameters

The imaging volume data were acquired using a Phillips 64-slice spiral CT scanner. Patients were placed in a supine position from the arcuate eminence to the mastoid tip. The acquisition parameters were as follows: slice thickness, 0.67 mm; slice interval, 0.33; pitch, 0.6; matrix, 512 × 512; field of view, 18 × 18–22 × 22 cm; collimator, 16 × 0.625; 100 ~ 120 kV; 120 ~ 200 mA; bone algorithm reconstruction; window width/level, 4000 HU/700 HU.

3D volume reconstruction

Imaging data were transferred to the Phillips post-processing workstation Extended Brilliance™ Workspace. 3D air-density reconstruction was applied to calculate TBP volume automatically. A segmentation threshold of –200 HU was used to represent the pneumatized air cavities [3, 12]. The

incision function was the only tool used to exclude air density in the external auditory canal. The tympanic annulus was used as the dividing line between the external ear and middle ear (Fig. 2).

Statistical analysis

All statistical analyses were performed using SPSS for Windows 17.0, and a p value < 0.05 was considered significant. First, a test of normality and a homogeneity test of variance were performed. A paired-sample t test was then performed to evaluate the difference between the two sides of each sex in each group. An independent-sample t test was performed to evaluate the difference between the two sexes in each group. To compare the correlation between age and TBP volume, a linear regression analysis was performed.

Results

The TBP volume distribution is displayed in Table 1. There were no significant differences between the right and left sides of each sex except in 9- and 11-year-old female groups. Meanwhile, significant differences between males and females were only found in 6- and 16-year-old groups, although the volume was larger in all the male groups older than 6 years.

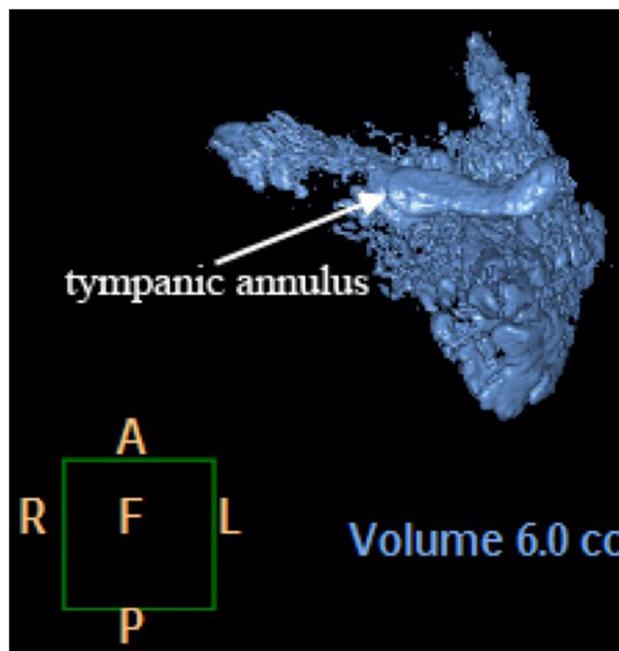


Fig. 2 Three-dimensional reconstruction shows the tympanic annulus clearly as the boundary between temporal bone pneumatization and air in the external auditory canal

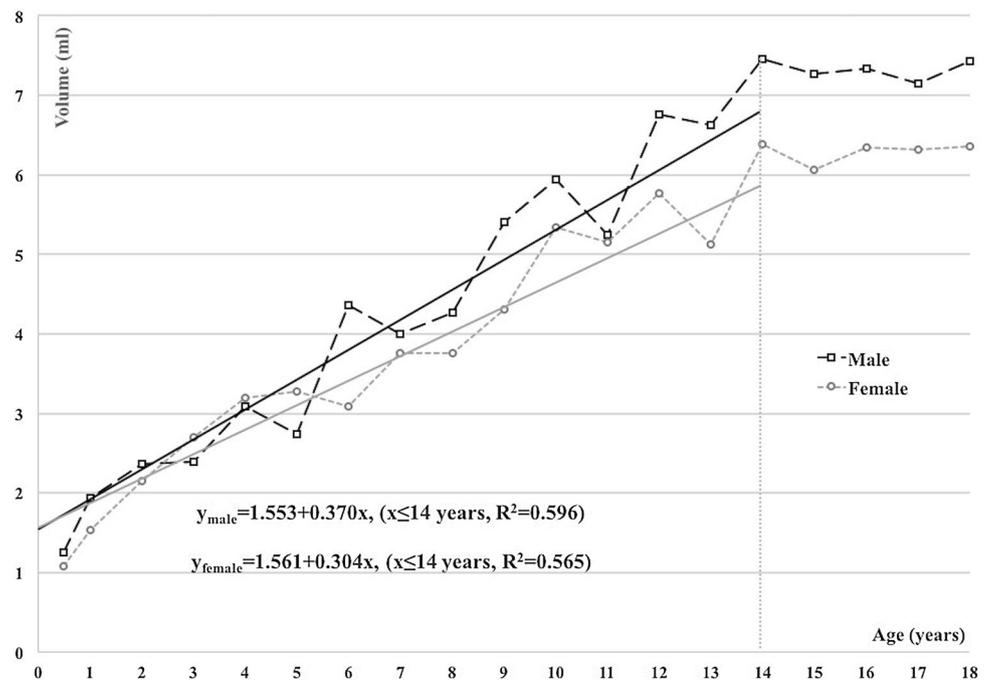
Table 1 Temporal bone pneumatization volume from birth to 18 years of age

Age group (years)	Male (n=285)				Female (n=285)				p	Mean (ml)
	Left (ml)	Right (ml)	p	Mean (ml)	Left (ml)	Right (ml)	p	Mean (ml)		
< 1 (0.55)	1.30±0.60	1.21±0.53	0.220	1.25±0.55	1.12±0.30	1.05±0.34	0.130	1.08±0.31	0.310	1.17±0.44
1	1.90±0.75	1.97±0.71	0.333	1.94±0.72	1.48±0.46	1.58±0.45	0.175	1.53±0.44	0.074	1.73±0.62
2	2.43±0.92	2.31±0.90	0.442	2.37±0.86	2.13±0.61	2.17±0.75	0.688	2.15±0.65	0.438	2.26±0.76
3	2.44±0.82	2.33±0.75	0.387	2.39±0.75	2.75±1.10	2.66±1.04	0.303	2.70±1.05	0.349	2.54±0.91
4	3.16±0.82	3.03±0.83	0.343	3.09±0.79	3.18±0.94	3.22±1.03	0.798	3.20±0.96	0.737	3.15±0.86
5	2.75±1.23	2.74±1.26	0.932	2.74±1.22	3.33±1.11	3.23±1.00	0.575	3.28±1.00	0.197	3.01±1.13
6	4.34±1.04	4.38±1.14	0.828	4.36±1.02	3.18±0.73	3.01±0.93	0.198	3.09±0.80	0.001	3.73±1.11
7	4.08±1.68	3.91±1.67	0.480	4.00±1.61	3.73±1.44	3.82±1.86	0.598	3.76±1.63	0.709	3.88±1.59
8	4.23±1.33	4.29±1.57	0.837	4.26±1.35	3.75±1.01	3.77±0.97	0.871	3.76±0.96	0.255	4.01±1.18
9	5.43±1.84	5.37±1.90	0.831	5.40±1.80	4.54±1.16	4.06±1.06	0.031	4.30±1.04	0.053	4.85±1.55
10	6.01±1.80	5.86±2.08	0.603	5.94±1.86	4.94±1.71	5.07±1.63	0.527	5.00±1.63	0.155	5.47±1.78
11	5.21±1.62	5.29±1.75	0.776	5.25±1.61	5.41±2.04	4.89±2.07	0.016	5.15±2.02	0.887	5.20±1.78
12	6.87±2.89	6.64±2.89	0.490	6.76±2.83	5.79±1.54	5.75±1.67	0.871	5.77±1.51	0.246	6.26±2.28
13	6.46±2.60	6.80±2.62	0.279	6.63±2.54	5.43±1.92	5.54±1.63	0.682	5.49±1.69	0.157	6.06±2.20
14	7.39±2.20	7.50±1.77	0.803	7.45±1.80	6.78±2.49	5.98±2.26	0.081	6.38±2.23	0.160	6.91±2.06
15	7.35±2.15	7.19±2.13	0.619	7.27±2.06	6.16±2.02	5.96±2.49	0.478	6.06±2.20	0.130	6.68±2.18
16	7.59±1.71	7.61±1.52	0.930	7.60±1.50	6.45±1.78	6.22±1.90	0.407	6.34±1.76	0.043	6.97±1.73
17	7.16±2.51	7.12±1.94	0.937	7.14±1.99	6.47±2.19	6.17±1.97	0.235	6.32±2.03	0.274	6.73±2.02
18	7.13±1.88	7.21±2.17	0.815	7.17±1.91	6.13±1.47	6.58±1.17	0.230	6.36±1.14	0.204	6.76±1.73

The changes of TBP mean volume from birth to 18 years old was shown (Fig. 3). The curve drawn by the mean volume showed that TBP continued to grow linearly in both male and female groups until they reached 14 years old. The linear regression equations of male and female were as follows: $y_m = 1.553 + 0.370x$, ($x \leq 14$ years,

$R^2 = 0.596$); $y_f = 1.561 + 0.304x$, ($x \leq 14$ years, $R^2 = 0.565$). Then, the TBP remained stable to 18 years old in both groups.

The mean volume of TBP from 14 to 18 years old as adult size was 6.29 ± 1.91 ml for females, 7.33 ± 1.82 ml for males, and 6.81 ± 1.93 ml for both.

Fig. 3 Mean volume of temporal bone pneumatization from birth to 18 years old

Discussion

The size of TBP in adults varies considerably. The inconsistencies may be owing to factors such as race, sample size, the reproducibility of the methods, the intrinsic error of a given technique, inclusion criteria, and the extent of the measurements, which make it difficult to do valid comparisons of TBP size among different studies.

The size of TBP is difficult to measure, because the temporal bone is pyramidal-shaped and contains numerous irregularly distributed air cavities. Several methods have been used to indirectly and quantitatively evaluate TBP, such as water-weight, pressurized transducer, and acoustic methods. However, radiological methods have been most widely utilized, beginning with lateral radiography and progressing to CT, which requires a little time and effort on the part of the subject and is more suitable for large surveys of the population.

The 3D reconstruction and volume analysis technique presented has been shown to be simple and highly reproducible [3, 8, 12, 16]. The selection of the segmentation threshold or grayscale value is of great importance for accurate measurement. Setting the threshold too high includes soft tissues and produces noise, resulting in the overestimation of the TBP volume. In contrast, too low of a threshold excludes some of the air cells, resulting in underestimation. Sung Wan Byun et al. compared the TBP volume at segmentation thresholds from -700 to 0 HU at intervals of 50 HU and suggested a threshold of -200 HU as a standard for measuring TBP volume [3], which was applied in this study and very few previous studies [12].

The inclusion criteria of subjects may influence the results, such as the age range. TBP has been reported to decline slowly after the third decade and rapidly after the seventh decade [12]. If so, the relatively older patients were included, the smaller the TBP volume as adult size may be. In this study, it was 6.81 ± 1.93 ml, which was calculated as the average volume of the age groups from 14 to 18 years.

Besides, the extent in the measurement of TBP was not the same in the previous studies. Most of the studies with identified extent and CT 3D reconstruction included the middle ear cavity (including tympanic cavity and eustachian tube) [3, 5, 10, 16] as the middle ear and temporal air cells may act as a whole for the pathophysiologic changes of the ear. It was beneficial to include the middle ear to compare the results with the previous studies. Meanwhile, it avoided heavy imaging processing workload to exclude the middle ear from temporal air cells using the adopted workstation.

Consecutive age groups from less than 1–18 years old were divided to investigate TBP development process in

a detailed manner in this study. To the best of our knowledge, the TBP volume in patients less than 1 year old has not been reported previously, which was 1.17 ± 0.44 ml in this study. High consistencies of TBP volume between different sides or sexes were found in most of age groups [4, 5, 10, 12]. Only the 9- and 11-year-old females showed significant differences between sides, while differences between the sexes were found in the 6 and 16 years old. These differences could be attributed to the relatively small sample in each age group. TBP has been reported to increase with growth of the temporal bone [16], which may partly explain why the TBP volume was larger in males older than 6 years, as male adolescents usually develop faster and have a larger skull and temporal bone than females.

There has been no consensus on the developmental pattern of TBP. Schillinger R et al. reported that the development of TBP could be divided into three stages: the infantile, from birth to 2 years old; the transitional, from 2 to 5 years old; and, thereafter, the adult, after 6 years old. In the infantile stage, air cells began to appear and were readily visible by 2 years old. In the transitional stage, the squamomastoid underwent gradual enlargement, with the migration of air cells toward the periphery. Once the adult stage was reached, pneumatization ceased [14]. However, other studies showed that TBP would continue to grow until puberty or older. Singh et al. claimed that the development of TBP was completed by 10 years old in females and 15 years old in males [15]. Lee et al. [12] and Chatterjee et al. [4] suggested that TBP showed rapid growth up to the early second decade of life and then slower growth until the third decade. Cinamon [5] summarized some previous data sources and stated that TBP followed a linear growth pattern until 6 years old, followed by slower growth until achieving adult size at puberty. Isono et al. [10] showed that the volume reached about 80% of the adult size by 9–10 years old and 100% by 14–15 years old, which was consistent with ours. Besides, our results showed a similar linear growth pattern in both males and females.

All patients in this study underwent temporal bone HRCT because of otologic complaints, which may have influenced the results, although strict criteria were set to exclude most conditions associated with TBP. HRCT was chosen, because most of the subjects were infants and children who rarely underwent other radiological examinations including the whole temporal bone. In addition, the area-to-volume ratio of TBP seems to be better than volume alone to reflect the function level of gas exchange [6, 7]. However, the TBP area was not measured, because it heavily depended on the scanning resolution, which was limited to a voxel size of approximately 0.6 mm in this study. Small air cells and air septae below the resolution cannot be detected, which resulted in

decreasing of the TBP area, while the TBP volume is largely independent of the resolution [6, 7].

The relationship between TBP development from birth to adult size and some factors such as height, body weight, size of head, volume of nasal cavities or sinuses, size of adenoid, shape of nasopharynx, and shape of eustachian tube should be studied furtherly. These results may be more contributive for the knowledge of TBP development.

Summary

This study aimed to provide a reference for TBP volume and growth pattern from birth to 18 years using a simple and reproducible imaging method. The TBP volume was shown with a linear growth pattern from birth until reaching adult size after 14 years. The results may be beneficial for further studies about TBP and the associated abnormalities.

Author contributions PZ: project development, data collection, and manuscript writing. Heyu Ding: data collection and manuscript editing. HL: data collection. JL: data analysis. XL: manuscript editing. ZY: manuscript editing. Z W: project development and data management.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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