Classification and volumetric analysis of temporal bone pneumatization using cone beam computed tomography

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Objective. This study performed volumetric analysis and classified different repeated patterns of temporal bone pneumatization in adults using cone beam computed tomography (CBCT) scans.

Study Design. A total of 155 temporal bones were retrospectively evaluated from 78 patients with no radiographic evidence of pathology. Two reference structures were used to classify temporal bone pneumatization into 3 groups. Volumetric analysis of the pneumatization was performed using a window thresholding procedure on multiplanar CBCT images. Correlation between direct communication of peritubal cells with the eustachian tube and the degree of pneumatization was also assessed.

Results. Using 2 reference structures, pneumatization pattern in the temporal bone can be classified into 3 groups. Statistically significant differences were present in their mean volumes between 3 groups. Statistically significant correlation was found between degree of pneumatization and presence of peritubal cells associated with ET.

Conclusions. This study showed that CBCT can be effectively used for imaging temporal bone air cavities and for volumetric assessment. (Oral Surg Oral Med Oral Pathol Oral Radiol 2014;117:376-384)

The advances in cone beam computed tomography (CBCT) over the past decade, with its applications in general dentistry and oral and maxillofacial (OMF) radiology in particular, has led to a variety of maxillofacial applications, including evaluation of portions of the skull base. During routine OMF radiology practice, portions of the skull base that include the temporal bone are visualized. The temporal bone often presents a varied pneumatization pattern that has a specific clinical significance especially important for planning any surgical procedures in this area.

Each temporal bone consists of 4 components: the squamous, petromastoid, and tympanic parts and the styloid processes. Pneumatization is the process whereby epithelium infiltrates the developing bone and forms epithelium-lined air cell cavities. The squamous, petromastoid, and tympanic parts are the most frequently pneumatized parts, but pneumatization may extend to the articular eminence of the zygomatic process. The pneumatization process usually begins prenatally, during the 22nd to 24th gestational weeks. At around 28 weeks of gestation, the petrous apex begins to be pneumatized. The pattern of pneumatization of the temporal bone is usually completed by the age of 10 years in females and 15 years in males.

Numerous studies have reported on the variety of pneumatization patterns of the temporal bone and their classifications using conventional computed tomography (CT). Although CT has several advantages over CBCT, especially for depicting soft tissues, comparable evaluation of the osseous components of the skull base and sinonasal anatomy is possible at a lower radiation dose and at a lower cost with CBCT.

A proposed function of aeration includes resonance, acting as a reservoir of air for the middle ear to compensate for altered function of the eustachian tube (ET), thereby preventing negative pressure, and avoiding changes in middle ear mucosa which may progress to otitis media. A study conducted by Sözen et al. stated that diffuse pneumatization of the petrous part of the temporal bone is one of the etiologic factors in the development of subjective pulsatile tinnitus.

Apart from this, pneumatization pattern can affect any surgical procedures involving the skull base region.

Statement of Clinical Relevance

Because cone beam computed tomography is being used widely and is approaching standard-of-care status across the field of dentistry, it is important to identify early changes in the temporal bone and to make appropriate referrals to specialists to avoid long-term functional disability.
because these air cells can become sources of cerebrospinal fluid (CSF) leak postoperatively. In routine OMF radiology practice, a bulk of the temporal bone is routinely visualized on temporomandibular joint and orthodontic studies; thus, it is important for dentists in general and oral radiologists in particular to know normal anatomical variations and pneumatization patterns to identify any pathologic changes and make appropriate referrals to specialists in this region, such as otolaryngologists and neuroradiologists.

The aim of this study was to perform volumetric analysis and classify different repeated patterns of temporal bone pneumatization in adults using CBCT data sets.

**MATERIALS AND METHODS**

**Data collection**

Data for the study were gathered after an approval from the Institutional Review Board of the University of Connecticut Health Center. All the scans were acquired on a NewTom CBCT unit (QR srl) at 110 kilovolt peak and 1 mA.

The inclusion and exclusion criteria for this retrospective analysis of CBCT scans were as follows (Table I):

1. Patients must be older than 18 years and not older than 70 years.
2. All the scans must have a field of view (FOV) more than 8 inches in diameter, with slice thickness varied from 0.2 mm to 0.4 mm.
3. The analysis is performed at the minimum slice thickness of 0.5 mm, as standard to the DICOM (Digital Imaging and Communications in Medicine) viewer.

The inclusion criteria for the selected scans consist of complete visualization of the external auditory canal, middle ear, perilabyrinthine area, and articular eminence. Cases with presence of soft tissue, fluid levels, bone sclerosis and destruction, and any radiographic evidence of surgery were excluded (see Table I).

A total of 125 CBCT scans (250 temporal bones) were identified which met our selection criteria for evaluation (i.e., FOV more than 8 inches in diameter and scans which adequately showed the area of interest). We excluded 95 temporal bones because of evidence of incomplete visualization of portions of temporal bone and radiographic evidence of pathology.

A total of 155 temporal bones were analyzed from 78 patients who were asymptomatic for any oronasal pathology; one temporal bone was excluded because of incomplete visualization of the area of interest.

**Analysis of the scans**

There are 3 primary regions where pneumatization in the temporal bone can be seen: the mastoid area, perilabyrinthine area, and petrous apex. There are numerous studies that looked at mastoid pneumatization, owing to the area’s large air cells, using multislice CT (MSCT) and conventional radiography. In this study, we limited the assessment of the pneumatization pattern to the middle ear, perilabyrinthine area, and petrous apex region because the majority of large-FOV scans of this region show only a part of the mastoid air cells. The mastoid air cells are not included in toto in the large-volume CBCT scanning protocols, because they are usually not the specific area of interest. Both sides of the skull base were assessed for quantitative and qualitative analysis using the CB works 3.0 (Hitachi Medical System America Inc) DICOM viewer. To see the greatest area of pneumatization, a correction of the Z-axis was done in such a way that the malleoincudal complex appeared as an ice-cream-cone-shaped structure on axial images.

**Establishing reference structures for simple classification of temporal bone pneumatization**

This study followed the method of selection of the reference structures from a study conducted by Han et al. Temporal bone pneumatization is classified into the 3 groups using the labyrinthine and petrous segments of the internal carotid canal as reference structures.

Labyrinthine is used as a reference structure to classify the pneumatization of the temporal bone around the inner ear structures using the following grouping:

- **Group 1**: No evidence of pneumatization in the region of the inner ear (Figure 1, A).
- **Group 2**: Pneumatization present either medial or lateral to the superior semicircular canal on axial section (see Figure 1, B).
- **Group 3**: Perilabyrinthine pneumatization (see Figure 1, C).

The petrous segment of the internal carotid canal is used for assessing the pneumatization of the petrous apex.

- **Group 1**: No pneumatization of the petrous apex (Figure 2, A).

**Table I. Inclusion and exclusion criteria**

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
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<tr>
<td>Complete visualization of:</td>
<td>Soft tissue or fluid levels</td>
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<tr>
<td>- External ear</td>
<td>- Sclerosis</td>
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<td>- Middle ear</td>
<td>- Destruction of the bony margins</td>
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<td>- Perilabyrinthine region</td>
<td>- Radiographic evidence of surgical procedure</td>
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<tr>
<td>- Petrous apex</td>
<td>- Articular eminence</td>
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<tr>
<td>- Articular eminence</td>
<td>- Destruction of the bony margins</td>
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<td>- Periarticular bone</td>
<td>- Radiographic evidence of surgical procedure</td>
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<td>- Periarticular bone</td>
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Group 2: Mild pneumatization of the petrous apex; there are irregularly evident small numbers of air cells on either side (medial or lateral) of the carotid canal (see Figure 2, B).

Group 3: Complete pneumatization of the petrous apex; pneumatization is present surrounding the carotid canal (see Figure 2, C).

Direct communication of peritubal cells with the ET was also assessed to determine possible correlation with the degree of pneumatization. Presence of peritubal cells was assessed to see its correlation with the degree of pneumatization of the temporal bone, and further incidence of direct communication (Figure 3, A-C) of peritubal cells with the bony portion of the eustachian tube was also analyzed.

**Calculation of volume**

Pneumatization in the temporal bone is mainly present in the mastoids, the perilabyrinthine region, the middle ear/tympanic cavity, and the petrous part of the temporal bone. Measurements of pneumatization of the temporal bone included in this study were in the middle ear cavity (including the eustachian tube), the perilabyrinthine region, and the petrous apex.

The acquired data were stored in DICOM-2 format and imported into the CB Works 3.0 (Hitachi Medical Systems America Inc) at slice thickness of 0.5 mm.

The areas of interest were segmented using lower and upper window levels of −1024 and −290 pixel intensity values to mark the pneumatized spaces. The windowing function in CT enables the operator to narrow the shades of gray. The typical human eye is capable of distinguishing around 32 shades of gray, whereas CT data has a range of 4096 shades of gray per pixel. In the thresholding process, the window width and level settings map the measured attenuation of each voxel to a corresponding grayscale value to appropriately mark the tissue of interest.

All other regions, such as the articular eminence, part of the sphenoid sinus, and the external auditory canal, were excluded using the region of interest tool (Figure 4). In Figure 4, A, the initial process of thresholding shows marking of all air cavities in the craniofacial area, which includes the paranasal sinuses, nasal cavity, air cells in the skull base/pneumatized bone in the skull base, and airway. Since extension of pneumatization varies with each patient, we used our reference structures to limit the region of interest on multiplanar sections. As with MSCT data, CBCT data sets can be easily used to perform thresholding and segmentation of bone and air cavities.

Once all the air cavities are marked, the region of interest tool is applied to limit our area of interest as described above. Since CBCT utilizes isotropic voxels, multiplanar views (axial, sagittal, and coronal), which precisely mark the area of interest, can be used to limit or extend the area of volume measurement accordingly.
Once air spaces are selected, the software automatically calculates the volume of area of interest (see Figure 4, C).

**Data and statistical analysis**

Data analysis to evaluate the pattern of pneumatization was done by one OMF radiology faculty member (A.T.) and one third-year OMF radiology resident (A.J.) working together. Volumetric measurements were done twice using 2 reference structures (i.e., labyrinthine and carotid canal). Differences in the volumes of temporal bone pneumatization according to the degree of pneumatization between the groups for each reference structure were investigated using 1-way analysis of variance (ANOVA) and a post hoc test using the Tukey honestly significant difference test. A Student t test was performed to assess possible differences in volume between right and left temporal bones in the same subject. Correlation of direct communication of peritubal cells with ET was analyzed using Pearson correlation. All statistical analyses were done using IBM SPSS version 21 (IBM Inc)

<value so of \( P \) < .05 were considered statistically significant.

**RESULTS**

This study population consisted of 78 patients: 27 men and 51 women with ages ranging from 18 to 70 years and with a mean age of 56 years. A total of 155 temporal bones were analyzed to classify the pattern of pneumatization: 78 on the right side and 77 on the left side. The mean volume of temporal bone pneumatization was 1339.9 mm\(^3\) and 1338.8 mm\(^3\) when the carotid canal and the labyrinthine were used as a reference structure. The difference between right and left sides was not statistically significant (\( P = .930 \)) (Table II).

**Classification of temporal bone pneumatization and its corresponding volumetric analysis**

Evaluation of temporal bone using labyrinthine as a reference structure. Cases were classified into 3 groups. Group 1 consisted of 62 cases, with a mean volume of 822 mm\(^3\) and a volume range of 450 mm\(^3\) to 1325 mm\(^3\). Since group 1 indicates no pneumatization of the temporal bone, the calculated value represents the volume of the middle ear cavity. Group 2 consisted of 41 cases with a mean volume of 1269 mm\(^3\) and a volume range of 760 mm\(^3\) to 2185 mm\(^3\). Group 3 consisted of 52 cases with a mean volume of 2008 mm\(^3\) and a volume range of 1010 mm\(^3\) to 3050 mm\(^3\).

Overlapping of volumetric measurements between the 3 groups was observed in this study, owing to the large size of the air cells in a few cases. Despite this, cases were segregated according to their extension and not based on their volumetric measurements.

Using ANOVA, the 3 groups showed statistically significant differences (\( P < .0001 \)) in their mean volumes (Figure 5, A). A post hoc test was performed to see the source of significant differences in the groups. Significant differences existed between all groups (\( P < .0001 \)) (Table III).

Evaluation of temporal bone using the carotid canal as a reference structure. Cases were again classified into 3 groups. Group 1 consisted of 51 cases with a mean volume of 781 mm\(^3\) and a volume range of 443 mm\(^3\) to 1325 mm\(^3\). Since group 1 indicates no pneumatization of the temporal bone, the calculated value represents the volume of the middle ear cavity. Group 2 consisted of 57 cases with a mean volume of 1268 mm\(^3\) and a volume range of 840 mm\(^3\) to 2780 mm\(^3\). Group 3 consisted of 47 cases with a mean volume of 2033 mm\(^3\) and a volume range of 1178 mm\(^3\) to 3021 mm\(^3\).

Overlapping of volumetric measurements between the 3 groups was observed in this study, owing to the large size of the air cells in a few cases. Despite this, cases were segregated according to their extension and not based on their volumetric measurements.

Using ANOVA, the 3 groups showed statistically significant differences (\( P < .0001 \)) in their mean volumes (see Figure 5, B). The post hoc test showed statistically significant differences between the volumes of all 3 groups (\( P < .0001 \)) (see Table III).

**Difference in volume of temporal bone between reference structures**

No statistically significant differences (\( P = .966 \)) exist between the volumes of the temporal bone when
calculated using 2 reference structures (see Table III). This indicates that either of the reference structures can be successfully used to classify and calculate the volume of temporal bone pneumatization.

**Presence of peritubal cells and its correlation with degree of pneumatization**

Of the 155 temporal bones, 99 temporal bones (63.9%) showed the presence of peritubal cells, whereas 56
difference was not statistically significant ($P = .930$).

(36.1%) had no evidence of peritubal cells. A statistically significant correlation ($P < .0001$) was found between degree of pneumatization and presence of peritubal cells. The presence of peritubal cells was further categorized on the basis of direct communication with the bony part of the ET. Direct communication of peritubal cells at the lateral aspect of the bony segment of the ET occurred in 41.3% of the temporal bones. Communication on the medial aspect of ET was seen in 12.3% of the temporal bones, while 10.3% showed communication at the anterior third of the bony segment of the ET.

**DISCUSSION**

CBCT technology, also known as volumetric tomography, was developed in the early 1970s and was utilized in vascular imaging until the early 1980s. This initial prototype was based on a C-arm instrument. In 1995, 2 Italian inventors introduced CBCT to dentistry, and the NewTom DVT 9000 (QR srl) was launched in European markets in 1999. Apart from dentistry, this technology has gained popularity in the field of otolaryngology, especially for imaging of paranasal sinuses and the temporal bone.

The working model of CBCT is based on a rotating gantry with a fixed source of x-rays and a detector. During rotation, multiple planar projection images are acquired in an arc of more than 180°. CBCT technology uses a cone-shaped beam (vs a fan-shaped beam in conventional CT). Orthogonal planar images are secondarily reconstructed from multiple-basis projection in CBCT, whereas in conventional CT, primary reconstruction produces axial images and then secondary reconstruction generates orthogonal slices.

To date, numerous studies have been published on the use of CBCT technology for imaging of the temporal bone, specifically middle and inner ear structures. CBCT not only is being used in presurgical evaluation of the temporal bone but also is now being tested intraoperatively for surgery of the skull base and the temporal bone. Multiple commercial CBCT systems are available, from limited fields of view to large fields of view. Most of the new-generation CBCT machines give the operator flexibility to choose from various FOVs targeted to the area of interest.

Pneumatization in the temporal bone is divided into 5 major regions: middle ear, mastoid, petrous apex, perilabyrinthine, and accessory. In this study, we examined pneumatization only in the middle ear, perilabyrinthine region, and petrous apex. In maxillofacial CBCT imaging, these are the primary regions that usually appear on large-FOV scans, as opposed to dedicated temporal bone studies, which include the entire temporal bone. Pneumatic spaces in the tympanic cavity arise independently of the mastoid antrum, whereas perilabyrinthine and petrosal apex cells originate from extensions of the mastoid air cells. The supralabyrinthine region is pneumatized by the posterior superior and subarcuate tracts, and the infralabyrinthine region is pneumatized by hypotympanum, posteroemedial, and peritubal cells. The petrous apex is pneumatized by cells from the perilabyrinthine region and peritubal tracts.

There are numerous studies of pneumatization of the temporal bone and its volumetric analysis using conventional radiography and CT. A study conducted by Han et al. showed a mean volume of 15.28 ± 5.34 cm³ using CT. Stieglitz et al. reported a mean petrous bone air cell volume of 10.97 mL based on MSCT imaging. In our study, the mean volume of temporal bone pneumatization was 1339.9 mm³ when the carotid canal was used as a reference, and when labyrinthine was used as a reference structure, the volume was 1338.8 mm³. These numbers are lower than those in the popularly referenced studies by Han et al. and Stieglitz et al., because we did not include the mastoid air cell system in the classification system and the volumetric analysis.

In this study, we used 2 reference structures and classified the pneumatization into 3 groups. By grouping pneumatization, we were able to show the repeated patterns of extension of air cells in the temporal bone. In regard to reference structures, the labyrinthine and the carotid canal are easily locatable anatomic landmarks on CBCT scans. The numbers of cases in each group are different for the 2 reference structures, but the calculated mean volume for each group is not statistically different. In this study, we showed that either of the reference structures can be used to classify and perform volume analysis of the pneumatization pattern in the temporal bone.

CBCT uses isotropic voxels with slice thickness of less than 0.4 mm and has higher spatial resolution than MSCT. This makes CBCT technology superior to MSCT when looking at bone and air cavities, where high contrast resolution is not indicated. In the present study, we calculated the volume of temporal bone air cells, including the middle ear cavity, with CBCT data. Group 1, which represents no pneumatization of temporal bone, showed a mean volume of 822 ± 50 mm³. This value indicates the volume of the middle ear.
cavity. Petrous apex cells and cells around labyrinthine were easily located when performing window thresholding, and hence labyrinthine was used as a reference structure. We found that the perilabyrinthine cells in group 3 were often extended to the posterior wall of the internal auditory canal. These air cells are of major concern in surgeries involving vestibular schwannomas, because they are known as the origin of CSF fistulas.21,22

Apical cells are anatomically located anteromedial to the internal auditory canal and posteromedial to the carotid canal, again consistently present in group 3. These cells significantly contributed to the total volume of the temporal bone in the present study. When the
The ET has important physiologic functions, including pressure regulation and protection of the middle ear from infectious pathogens from the nasopharynx.ET dysfunction can be caused by a variety of mechanisms, including upper respiratory tract infections, sinusitis, and adenoidal hypertrophy. The presence of peritubal cells and their communication with the ET were highly correlated with the degree of pneumatization in the present study. The relationship of peritubal cells to the bony segment of the eustachian tube plays a major role in the development of CSF rhinorrhea after skull base surgery.

Temporal bones in our study showed direct communication of peritubal cells with the ET in 63.9% of the cases. The most common communication was at the posterior lateral part of the ET toward the middle ear cavity. The ET is known as a common pathway for development of CSF rhinorrhea during translabyrinthine, suboccipital, and middle cranial fossa surgery for acoustic neuromas. In a study conducted by Jen et al., it was stated that direct communication of peritubal cells with the osseous portion of the ET plays an important role in the development of persistent CSF rhinorrhea after cerebellopontine angle surgery.

CBCT clearly showed the presence of air cells in the temporal bone due to high spatial resolution. Although there are many significant uses of CBCT in the imaging of the temporal bone, the low radiation dose, which increases noise and gives poor density resolution of soft tissues, may restrict the use of this imaging modality rather than MSCT and significantly affect its use for pre- and postoperative evaluation of skull base surgeries.

If the indication for using CBCT is correct, it can be used to reduce radiation exposure and cost of care. Hodez et al. showed that CBCT images of a well-pneumatized middle ear and temporal bone are comparable to high-resolution MSCT for visualizing ossicular erosions, traumatic lesions, osseous labyrinthine wall dehiscence, and bony dysplasias.

CONCLUSION

Repeated patterns of temporal bone pneumatization can be reliably evaluated using specific anatomic structures as a reference point. Our classification using the carotid canal and the labyrinthine area as reference structures allows for segregating the critical areas of the temporal bone and allows for quantifying the criticality of the area based on the pneumatization pattern. This study showed that CBCT can be effectively used to evaluate and classify the repeated pattern of the temporal bone pneumatization. The mean volume of air cells in perilabyrinthine, middle ear, carotid, and petrous regions was 1339.9 mm^3 when the carotid canal was used as a reference structure. The mean volume of air cells was 1338.8 mm^3 when the labyrinthine area was used as a reference structure. The petrous apex, labyrinthine area, and petrous segment of the carotid canal are critical structures which can be located easily on CBCT scans and used as references to assess the pneumatization patterns. For an OMF radiologist, it is important to define the normal appearances and patterns of the temporal bone pneumatization and to identify potential pathologic changes. In a variety of temporal bone conditions, pneumatization can be affected significantly; this study shows that analysis of air cells and their volume measurements can be done effectively using a lower-dose alternative like CBCT.

Because CBCT is being used widely and may be approaching standard-of-care status across the field of dentistry, especially for temporomandibular joint and orthodontic evaluation, it is important to identify early changes in the temporal bone, especially in the inner ear and central skull base regions, to make appropriate referrals to neuroradiologists and otorhinolaryngologists and to avoid long-term functional disability.

Future directions

Chronic inflammation of the middle ear, especially in children, can suppress pneumatization of the temporal bone.
bone. It causes bony erosion and disturbances in the ossicular chain. A comparative study of diseased bones vs normal bones needs to be done to correctly identify changes in the pneumatization pattern and differences in the degree of pneumatization.

REFERENCES

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