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Relationship Between Clinical Test Results and Morphologic Severity Demonstrated by Sitting 3-D CT in Patients With Patulous Eustachian Tube

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Objective: To investigate the correlation of sitting 3-D computed tomography (CT) scans of the Eustachian tube (ET) with subjective and objective findings in patients with patulous Eustachian tube (PET).
Study Design: Retrospective.
Setting: Tertiary referral center.
Subjects: A retrospective survey of medical records in Sen-En Hospital identified 40 patients and 62 ears with PET between September 2014 and June 2015.
Method: Diagnosis of PET was based on the presence of three characteristic aural symptoms (autophony of voice or breathing sounds, and aural fullness), as well as verification of synchronous movement of the tympanic membrane in response to forced breathing under an endoscope. Any pressure changes in the external auditory canal (EAC) elicited by deep breathing and sniffing were detected by tubotympanoaerodynamography (TTAG). In addition, sonotubometry was performed where two parameters were used determined to evaluate ET function. Patients were examined by 3-D CT (Accuitomo; Morita, Kyoto, Japan) in the sitting position. The length of the closed ET lumen section was measured. Ears were divided into three groups as follows: completely open, closed-short (3 mm or less), and closed-long (longer than 3 mm).
Results: The median length of the closed section of the ET lumen was 1.85 ± 2.69 mm in positive findings of PET. The three groups were significantly different in both aural fullness ($p = 0.023$) and, similarly, the difference in tympanic membrane movement ($p = 0.032$) among these three groups was also significantly different ($p = 0.032$). However, for autophony of breathing sounds, there was no significant difference with regard to autophony of breathing sounds among these three groups ($p = 0.324$). Although TTAG findings were did not reveal any significantly difference among these three groups ($p = 0.589$), the difference was significant ($p = 0.001$) in degree of EAC pressure change in TTAG. The difference among the three groups was significant ($p = 0.001$) based on sonotubometry findings.
Conclusion: Under resting conditions, the lengths of the closed area of the ETs in PET groups are clearly shorter than in groups without PET based on sitting position CT scans in resting condition. Among the symptoms and clinical test findings including the ET function test results, the presence of tympanic membrane movement induced by respiration, the high degree of EAC pressure change in TTAG, as well as the positive results of sonotubometry are significantly correlated with the positive findings of sitting CT revealing the open ET. **Key Words:** Computed tomography—Patulous Eustachian tube—Sonotubometry—Tympanic membrane.

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The Eustachian tube (ET) is a narrow canal that connects the middle ear with the nasopharynx. It consists of an osseous portion comprising the lateral one-third and a cartilaginous portion comprising the medial two-thirds (1). The ET is usually closed, but opens briefly for approximately 200 to 500 ms during swallowing, chewing, or yawning.

Patients with patulous Eustachian tube (PET) suffer from symptoms such as aural fullness, and autophony of voice or breathing sounds because of persistent opening of the normally closed ET (2,3). Posture is a very important factor in the pathophysiology of the ET because the ET lumen is dilated in the sitting and standing position. PET symptoms are usually masked in the recumbent position (3), which detract advantages of modern imaging for the diagnosis of the PET because computed tomography (CT) and magnetic resonance imaging (MRI) are performed in the recumbent

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position (4). The first published use of recumbent CT for PET patients was by Tolley and Phelps (5) who visualized tube patency in one patient with characteristic symptoms, and three patients with macrosomia. Oonk et al. (6) also reported bilateral completely open ET along the entire length in PET patients using recumbent CT. However, the horizontal CT system, such as sitting position three-dimensional CT (3-D CT), was recently developed, and its usefulness in the diagnosis of PET has been verified by our earlier studies (7–9). Diagnosis of PET is usually confirmed based on several subjective and objective findings. However, there has been no study correlating the radiographic morphology of the ET lumen with subjective or objective findings in PET patients.

In this study, we evaluated the correlation of sitting 3-D CT findings of ET with subjective complaints and objective test findings in PET patients.

METHODS

A retrospective survey of medical records in Sen-En Hospital identified 40 patients, 14 men and 26 women aged 14 to 83 years (51.8 ± 19.5 years), and 62 ears (34 right ears and 28 left ears) with PET between September 2014 and June 2015. This study was approved by the Sen-En Hospital Institutional Review Board.

A retrospective survey of medical records in Tohoku University Hospital identified 414 patients with PET, 187 men and 227 women aged 8 to 85 years (43.7 ± 19.6 years), treated between September 2001 and October 2009.

Diagnosis of PET was based on the proposal on PET diagnosis criteria announced by the Otological Society of Japan in 2012. It is published in Japanese and can be summarized as follows.

1) The presence of at least one of three characteristic aural symptoms (autophony of voice or breathing sounds, and aural fullness) with marked improvement upon positional change from sitting/standing to a supine or prone position.

2A) Verification of synchronous movement of the tympanic membrane in response to forced breathing under an endoscope or microscope (10).

2B) Positive findings based on ET function tests (TTAG and sonotubometry).

Positive Findings of 1 Plus 2A and/or 2B were Defined as PET

The symptoms were usually improved upon by postural change from sitting/standing to a recumbent position. However, there are exceptions and in some relatively severe cases, these symptoms are not diminished even in the recumbent position. In such cases, PET was defined as a positive finding if the evidence of the open tube was obtained by one the following: findings, such as movement of the tympanic membrane, tubotympanoaerodynamography (TTAG), sonotubometry or CT findings, it was defined as positive findings of PET.

The ET function tests (TTAG and sonotubometry) were conducted using a commercially available machine (JK05A; Rion, Tokyo, Japan). Pressure changes in the external auditory canal (EAC) and the nasal cavity (nasopharynx) were simultaneously recorded using the manometry mode of the tubotympanoaerodynamography (TTAG). Positive findings of TTAG were defined as an EAC pressure change synchronous with that in the ipsilateral nasal cavity or nasopharynx (11). Positive findings of TTAG were divided into two groups in this study. In group A, the ratio of nasopharyngeal pressure to EAC pressure was 10% or more, while in group B this was less than 10% (Fig. 1). Sonotubometry mode of the commercially available ET function test machine (JK05A; Rion, Tokyo, Japan) automatically measures the input sound pressure level (SPL) at the nostril, which enables predetermined 50 dB SPL output in the external auditory canal. Diagnosis of an open tube by sonotubometry was made when the ET opened upon swallowing and remained continuously open thereafter (12,13), or if the input SPL of the test tone applied to the nostril was lowered to less than 100 dB (Fig. 2).

Patients were also examined by 3-D CT (Accuitomo; Morita, Kyoto, Japan) in the sitting position as previously reported (7,14). Images of the sagittal, coronal, and axial sections were

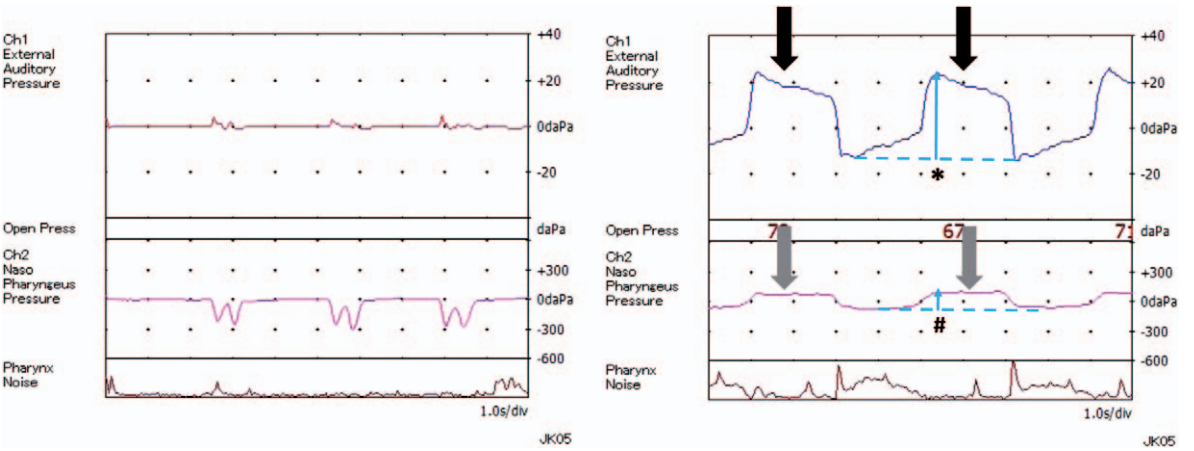

FIG. 1. Negative TTAG finding (*left*) and positive TTAG finding (*right*). *Upper figures* show external auditory pressure and *lower figures* show nasopharyngeal pressure. External auditory pressure was not changed in negative TTAG. Positive TTAG is defined as external auditory pressure changes (*upper right: black arrows*) that are synchronized with nasopharyngeal pressure changes (*lower right: gray arrows*). The ratio of nasopharyngeal pressure to EAC pressure is defined as */#. EAC indicates external auditory canal; TTAG, tubotympanoaerodynamography.

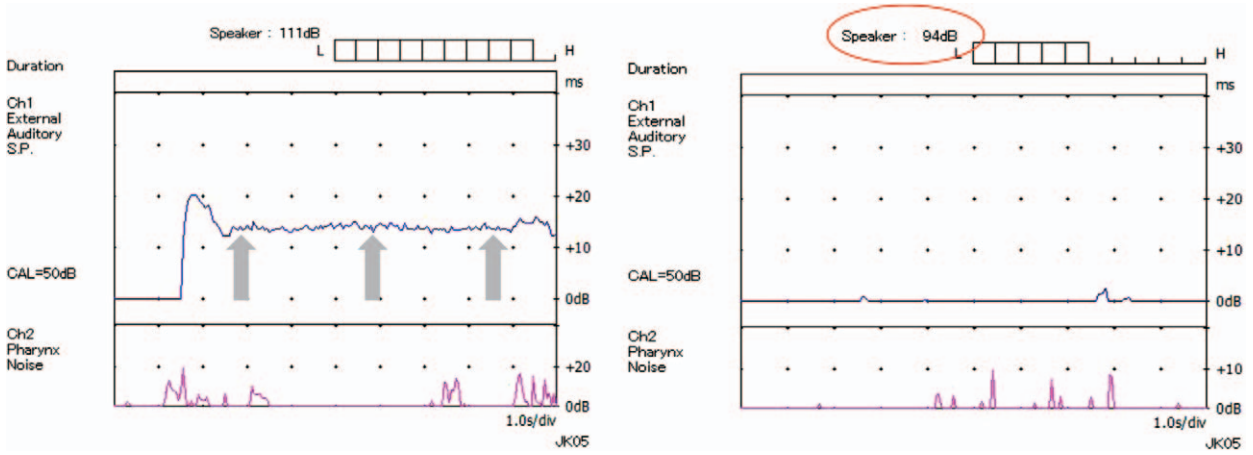

FIG. 2. Positive sonotubometry findings are characterized by either of the finding that the ET opens well when swallowing and remains continuously open thereafter (*left: gray arrows*), or lowering of the applied SPL to less than 100 dB (*right: circle*). ET indicates Eustachian tube; SPL, sound pressure level.

obtained, followed by analysis with the integrated software (Integrated Information System i-VIEW; Morita, Kyoto, Japan). The multiplanar reconstruction (MPR) technique was used to reconstruct 1-mm-thick gapless images, which that are parallel and perpendicular to the ET long axis. The ET lumen was observed in each 1-mm section perpendicular to the ET long axis. Anatomical portions of the ET, including the pharyngeal and tympanic orifices, the isthmus, and the cartilaginous and bony portions were defined as described previously (8,9). In the analysis of the cross-sectional images perpendicular to the long axis of the ET, the pharyngeal orifice of the tube was defined as the point nearest to the pharynx where the ET lumen appears round. The isthmus was defined as the point farthest from the pharynx where the circumference of ET lumen was surrounded by both soft tissue and bony tissue. The tympanic orifice was defined as the point where the EAC appears near the tympanum on the cross-sectional image. The cartilaginous portion of the ET was defined as the portion from the pharyngeal orifice to the isthmus, and the boney portion was defined as the tympanic orifice to the isthmus (7). The opened section of the ET lumen was easily identified as a hyperlucent area (Fig. 3 A and B).

The closed section of ET lumen was measured and ears were allocated into one of three groups as follows: completely open group, closed-short (3 mm or less) group, and closed-long (longer than 3 mm) group. Chi-square test and one-way ANOVA were used to evaluate differences between individual conditions using the statistical software SPSS version 20 (IBM, Chicago, IL, U.S.A.). Differences with a corrected p-value of less than 0.05 were considered significant. Data are presented as means ± standard deviations.

RESULTS

Total Results

There were 34 ears in the completely open group (54.8%), 15 in the closed-short (3 mm or less) group (24.2%), and 13 in the closed-long (longer than 3 mm) group (21%). The median length of the closed section of the ET lumen was 1.85 ± 2.69 mm in positive findings of PET.

Aural Symptoms

Correlation of autophony of voice with CT findings of the ET could not be evaluated because almost all patients (38 of 40) had this symptom. Aural fullness was observed in 21 of 62 ears. The median length of the closed section of the ET lumen was 3.14 ± 3.21 mm in the group with aural fullness and 1.18 ± 2.16 mm in the group negative for aural fullness. The difference among the three groups (open, closed-short, and closed-long) was significant (Chi-square test, $p = 0.023$). Autophony of breathing sounds was observed in 28 of 62 ears. The median length of the closed section of the ET lumen was 1.86 ± 2.76 mm in the group with autophony of breathing sounds and 1.85 ± 2.72 mm in the group negative for autophony of breathing sounds. There was no significant difference among the three groups (open, closed-short, and closed-long) (Chi-square test, $p = 0.324$) (Table 1).

Endoscopic Findings of the Tympanic Membrane

Movement of the tympanic membrane was observed in 34 of 62 ears. The median length of the closed section of the ET lumen was 1.29 ± 2.65 mm in ears with tympanic movement and 2.56 ± 2.68 mm in those negative for tympanic movement. The difference among the three groups (open, closed-short, and closed-long) was significant (Chi-square test, $p = 0.032$) (Table 1).

ET Function Test

Forty-five of 62 ears were positive for TTAG. The median length of the closed section of the ET lumen was 1.56 ± 2.41 mm in positive TTAG findings and 2.65 ± 3.28 mm in negative TTAG findings. There was no significant difference among the three groups (open, closed-short, and closed-long) (Chi-square test, $p = 0.589$). Furthermore, the median length of the closed section of the ET lumen was 0.19 ± 0.6 mm in group A of positive TTAG findings, and 3.44 ± 3.56 mm in group B

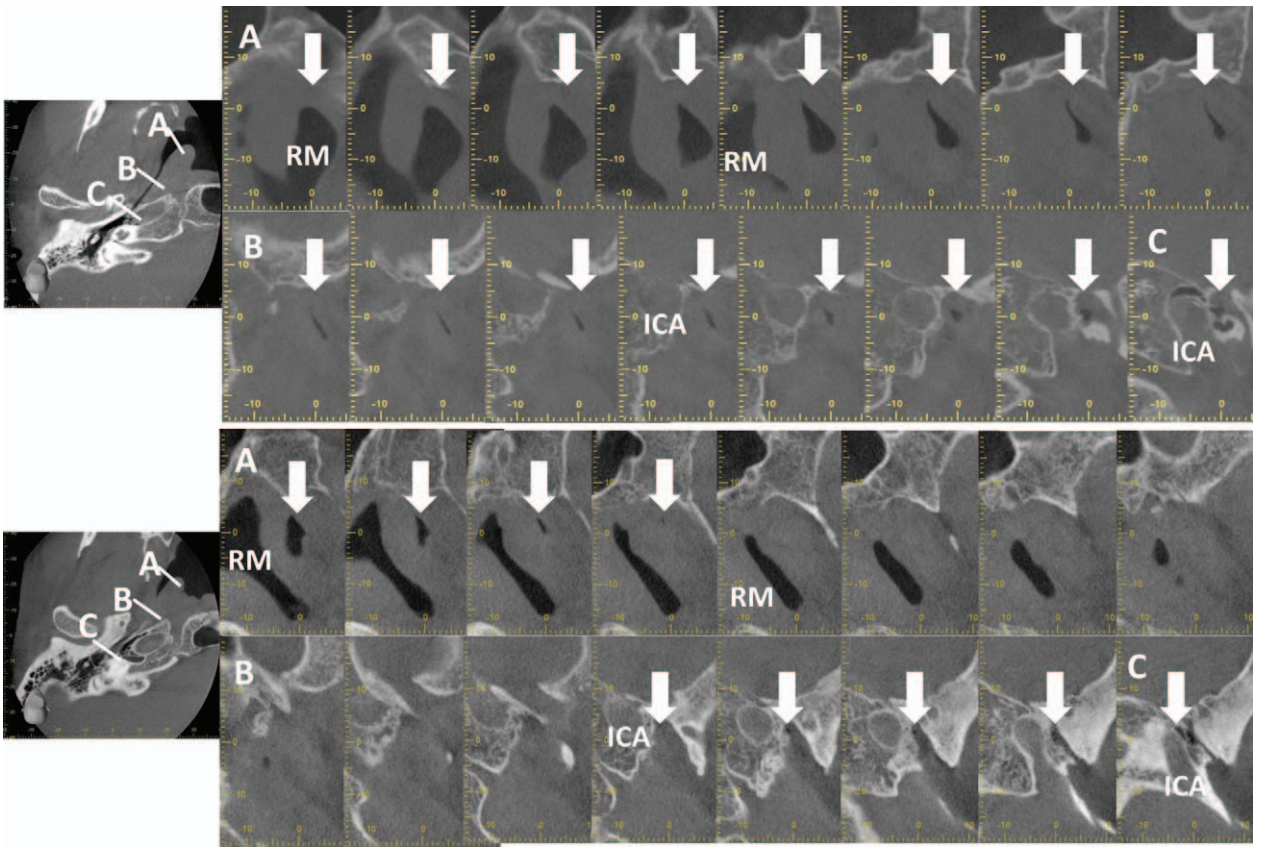

FIG. 3. Typical CT images in a patient (*upper row*) with PET showing the ET lumen (*white arrows*), which can be traced from the pharyngeal orifice to the tympanic orifice. Whereas in a normal subject (*lower row*), hyperlucency indicative of the lumen is interrupted at the cartilaginous portion of the ET. The hyperlucency (*white arrows*) indicative of air is detected along the ET. (*A*, pharyngeal orifice; *B*, cartilaginous portion; *C*, bony portion). CT indicates computed tomography; ET, Eustachian tube; ICA, internal carotid artery; PET, patulous Eustachian tube; RM, Rosenmuller recess.

of positive TTAG findings. The difference was not significant between group B and the group with negative TTAG findings (Chi-square test, $p = 0.465$). In contrast, there was a significant difference between group A and the group with negative TTAG findings (Chi-square test, $p = 0.007$).

Twenty-six of 62 ears had positive sonotubometry findings. The median length of the closed section of the ET lumen was 0.37 ± 1.00 mm in those with positive findings and 3.00 ± 3.02 mm in those with negative sonotubometry findings. The difference among the three groups (open, closed-short, and

TABLE 1. *Summary of overall results of the three groups: completely open group, closed-short (3 mm or less) group, and closed-long (longer than 3 mm) group*

		Open		Moderate		Close		
Aural fullness	Y	7	33.3%	6	26.8%	8	38.1%	($\chi^2 = 7.558$, df = 2, $p = 0.023$)
	N	27	67.5%	8	20.0%	5	12.5%	
Breathing sound	Y	17	60.7%	4	14.3%	7	25.0%	($\chi^2 = 2.254$, df = 2, $p = 0.324$)
	N	17	51.5%	10	30.3%	6	18.2%	
TM movement	Y	24	70.6%	5	14.7%	5	14.7%	($\chi^2 = 6.887$, df = 2, $p = 0.032$)
	N	10	37.0%	9	33.3%	8	29.6%	
TTAG	Y	26	57.8%	11	24.4%	8	17.8%	($\chi^2 = 1.059$, df = 2, $p = 0.589$)
	N	8	47.1%	4	23.5%	5	29.4%	
TTAG A		19	90.5%	2	9.5%	0	5.0%	($\chi^2 = 9.836$, df = 2, $p = 0.007$)
TTAG B		7	29.2%	9	37.5%	8	33.3%	($\chi^2 = 1.532$, df = 2, $p = 0.465$)
Sonotubometry	Y	23	85.2%	3	11.1%	1	3.7%	($\chi^2 = 19.024$, df = 2, $p = 0.001$)
	N	11	30.6%	12	33.3%	13	36.1%	

closed-long) was significant (Chi-square test, $p = 0.001$) (Table 1).

DISCUSSION

It is generally well-known that no single test can be regarded as the gold standard for the diagnosis of ET dysfunction. Nevertheless, there is some evidence that diagnostic accuracy can be improved by combining data from different subjective and objective tests (15,16).

Posture is an important factor affecting ET function because the symptoms of PET usually diminish in the recumbent position. Humans tend to remain in the standing or sitting position for most part of the day. The Valsalva maneuver is useful in detecting abnormal ET opening in PET, which therefore explains the usual routine clinical use of the Valsalva maneuver in the diagnosis of PET (7,17). We previously reported that open tubal distance was significantly longer under the Valsalva condition than under the resting conditions (7). However, the Valsalva condition is not a physiological condition. In this study, we evaluated ET by sitting position CT in the resting conditions in this study because our to focus was on studying the most typical physiological condition of the human ET.

The objective finding of the tympanic membrane movement is closely related with the length of patency length of the ET lumen demonstrated by sitting position CT under in the resting conditions. The PET diagnosis of PET was confirmed by observing respiratory movements of the eardrum during forced breathing through one nostril. It is imperative that important to have the patient is in a sitting position as because a patulous tube is usually asymptomatic while in the recumbent position (18).

The group with positive TTAG findings was not significantly different from the group with negative TTAG findings. However, when the group with positive TTAG findings was divided into two subgroups based on the ratio of EAC pressure change to that of the nasopharyngeal pressure, a high degree of EAC pressure change in TTAG (Group A) was closely related to findings of open ET. These results suggest that it is important to consider not only the synchronous pressure change in EAC with that of the nasopharynx, but also the degree of EAC pressure changes.

The present study demonstrated that positive sonotubometry findings are closely related to findings of open ET. In this group, 96.3% had a completely opened or a closed-short ET in the resting conditions. These results suggest that although the sensitivity of sonotubometry to PET is not high based on the cut-off criteria of the present current Diagnosis Criteria, the specificity for severe cases of PET is higher than the other objective and subjective findings.

One limitation of this study is the well-known changeability of PET symptoms over time. However, the sitting CT is considered useful even in this respect because it can detect shortened distance of ET closure in patients with asymptomatic PET at clinic visits. Another limitation is the soft tissue contrast resolution of cone beam CT. As it has been reported to be inferior to standard CT (4), a slight discrepancy may exist between our study and other studies using standard CT to detect ET patency.

This study has demonstrated that the presence of tympanic membrane movement induced by respiration, a high degree of EAC pressure change in TTAG, and positive sonotubometry results are significantly correlated with the positive findings in sitting CT. Therefore, these three findings can be useful indicators for the presence of definite PET and can be applied in clinics where sitting CT is not available.

CONCLUSIONS

Among the symptoms and clinical test findings, including the ET function test results, the presence of the tympanic membrane movement induced by respiration, a high degree of EAC pressure change in TTAG, as well as positive sonotubometry results, are significantly correlated with the positive findings in sitting CT.

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