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A Novel Imaging Method for the Cartilaginous Eustachian Tube Lumen: Computerized Tomography During the Forced Response Test

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Abstract

Objectives: *In vivo* imaging of the open cartilaginous Eustachian tube (ET) lumen by computed tomography (CT) scan during ET function (ETF) testing to establish new methodology.

Methods: Five adults underwent unilateral ETF testing of an ear with a non-intact tympanic membrane using forced response test (FRT) to measure the opening pressure (PO), steady state pressure (PS) and flow conductance (CS). Then at baseline and during the PS phase of the FRT, a temporal-bone CT scan with continuous 0.625 mm thickness was obtained. Multiplanar oblique reformats along the axis of ET were created and point value and region of interest (ROI) Hounsfield Unit measurements were recorded from the location of the ET lumen.

Results: At the FRT flow rate of 11 ml/min, the average PO, PS and CS were 370.5 daPa, 119.6 daPa and 0.16 ml/min/daPa respectively. For flow rates of 23 and 46 ml/min, these values were 236.2, 204.2, 0.12 and 385.5, 321.1, 0.18 respectively. Although areas with lower attenuation were suggestive of air density, a distinct air filled cartilaginous ET lumen could not be confirmed.

Conclusions: While the current imaging parameters failed to resolve the air-soft tissue interface throughout the open cartilaginous ET, further advances in imaging may obviate this limitation.

Keywords

Eustachian Tube; Eustachian tube function; CT scan; Imaging

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DECLARATION OF CONFLICTING INTERESTS

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INTRODUCTION

Adequate Eustachian tube (ET) function is essential to normal middle ear (ME) physiology, while dysfunction leads to the development of otitis media, its complications and sequelae, including tympanic membrane (TM) retraction, retraction pockets and cholesteatoma. Anatomical and functional abnormalities of the cartilaginous ET have therefore been of interest to clinicians and researchers. Traditional methods of assessing the ET and its function include history, otologic examination and tympanometry. Additional testing, utilized mostly in research centers, has included the 9-step test, sonotubometry, tubomanometry, and inflation-deflation, forced response and pressure chamber tests. Recently questionnaires, nasal and nasopharyngeal endoscopy and imaging of the ET have been added to this list. Although there have been efforts for several decades to obtain both static and functional images of the ET, relatively low temporal and spatial resolution and concerns regarding the safety of using contrast have limited progress [1].

The anatomical dimensions of the ET are very small compared to other organs. With respect to *in vivo* imaging this characteristic is exacerbated by its para-central position in the head and its proximity to the skull base, temporal bone and other bony and soft tissues of the head and face [1, 2]. The introduction of helical computed tomography (CT) scanning with isotropic imaging and multiplanar reformat capability has enhanced the ability to image the anatomy of small structures such as the ET. However, imaging of the functional segment of the ET lumen poses further challenges; in addition to its small dimensions, it lacks a tissue-air interface at rest, and opens intermittently for only a few hundred milliseconds. As reviewed in Smith et al [3] prior studies suggest that the primary issue is the lack of contrast between the lumen and surrounding tissues since CT imaging of the lumen has been possible when the ET is patulous [4–7] or when the lumen is dilated during swallowing [8, 9] or nasopharyngeal maneuvers such as Valsalva [5]. Here we designed a pilot study to explore a new imaging technique in which the temporal bone CT scan is performed while the cartilaginous ET is simultaneously held open by a continuous airflow during the forced response test (FRT).

MATERIALS AND METHODS

This pilot study was approved by the University of Pittsburgh Institutional Review Board. Five subjects with at least one patent ventilation tube and a history of simple ET dysfunction and/or chronic otitis media with effusion were enrolled in the study. Only one ear/ET with a perforation or a ventilation tube per subject was selected for testing and imaging. Exclusion criteria included a history of any type of cancer, radiation treatment, chronic suppurative otitis media, ossicular chain reconstruction, inner ear diseases, patulous ET and pregnant or nursing females.

Experimental protocol:

At their first visit, subjects had their medical history taken, underwent an ENT exam and tympanogram and had ET function tested using the FRT performed in sitting and recumbent positions, as described previously [10]. Briefly, for the FRT, tubing from a step pump (Harvard Apparatus, Holliston, Massachusetts, USA) connected to custom probe was sealed

in the external auditory canal (EAC) of the test ear. A constant flow of air increases the pressure in the tubing, ear canal and the ME, until the cartilaginous ET opens, termed opening pressure (PO). With continued air flow the ET reaches an equilibrium state (i.e. a steady state) which can be perturbed by a voluntary swallow that induces a transient increase in the air flow with a simultaneous reduction of the pressure; after the swallow, the system returns to the equilibrium state. Stopping the pump allows the pressure gradient between the ME and environment to dissipate yielding the cartilaginous ET closing pressure (PC). Using the pressure and flow values from these events, the ETF parameters steady state conductance (CS), steady state pressure (PS), active conductance (CA) and dilatory efficiency (DE) can be calculated. The data streamed from the pressure and flow sensors were digitized in a PowerLab 4/30 data acquisition system and displayed and analyzed in LabChart (AD Instruments North America, Colorado Springs, CO). Once an ear was selected for the imaging experiment, an impression of the EAC was made to fabricate a custom ear plug to be used during the CT scan.

Forced Response Test during CT scan:

At the scheduled time, the subjects presented to the Presbyterian University Hospital Radiology Department, had a ENT exam, the custom probe was sealed into the EAC of the test side and the submental surface EMG electrodes were placed and connected to the data acquisition system. The setup was tested to ensure that swallows were being recorded correctly and that the probe was sealed in the EAC and the subject was positioned supine on the CT scan table. Because the duration of a cartilaginous ET dilation (~ 300 msec) during a swallow is too short to resolve during a CT scan, imaging was performed during the equilibrium phase of the FRT, when there is a continuous air column dilating the cartilaginous ET lumen between the ME and nasopharynx. Initially three scans were performed: the first (Scan A) at rest without FRT served as the baseline, a second (Scan B) during the equilibrium phase of the FRT at a low pump flow rate, and a third (Scan C) during the equilibrium phase of a second FRT with a higher flow rate.

CT Scan Protocol:

All imaging was performed on a 64-channel multidetector helical CT scanner (GE LightSpeed VCT; GE Healthcare, Milwaukee, WI) with the subjects in supine position. A modified low dose temporal bone CT protocol approved by the Radiation Safety Committee at the University of Pittsburgh was employed. It was developed and tested using a real bone RANDO phantom to ensure adequate soft tissue and spatial resolution. The imaged field of view extended from the tegmen of the temporal bone through the pterygoid processes. The baseline CT scan parameters were: mAS 180, kVp 100, rotation time 0.6 sec, 0.625 mm thickness, 0.969 pitch, FOV 160 mm. CT scan parameters modified for imaging during the FRT steady state included changing mAS to 200, and pitch to 0.531. The total radiation exposure (for the total of 3 scans) is set to be within the 0.88 – 0.96 millisievert (mSv) range, which is a 24% reduction in ionizing radiation compared to one standard temporal bone CT scan (1.18 mSv) [11]. The estimated scan time for each acquisition was 15–30 seconds. Air served as the contrast media.

Image Analysis

Standard 1 mm thick coronal reformats were created for each acquisition using the GE Lightspeed VCT software. Additionally, multiplanar oblique reformats parallel and perpendicular to the long axis of the cartilaginous ET were created for each acquisition using Vitrea®Core software (Vitrea® Core; Vital Images, Minnetonka, Minnesota, USA) by a neuroradiologist experienced in head and neck imaging (TJR). The junction of the bony and cartilaginous ET, the torus tubarius and the nasopharyngeal ET orifice served as landmarks specifying the plane parallel to the ET lumen. For each CT scan, a 1 mm² region of interest (ROI) Hounsfield Unit (HU) from the nasopharyngeal space was measured [-969.6 ± 20.0 (range -943.7 to -1017.1 HU)] and used as the CT scan standard reference for air (Figure 1). To eliminate the potential technical variability between scans, all the measurements were adjusted to the average HU measurement for the air.

For all CT acquisitions using the Vitrea®Core software, three 1 mm² ROI HU measurements were recorded from the area where air was suspected visually along the axis of the ET lumen and at least 5 mm away from the bony ET and the nasopharyngeal orifice (Area 1, Area 2 and Area 3, one area shown in the figure) (Figure 1). Similarly, 3 lowest point value (LPV) HU measurements were recorded on the software “hair line” placed where air was suspected visually (Point 1, Point 2 and Point 3, one point shown in the figure) (Figure 2).

RESULTS

One ear of 5 subjects (4 males and 1 female) between 36 to 54 years of age was selected for this pilot study. Based on the initial supine FRTs, flow rates were chosen for use during the CT scanning portion of the study. The first two subjects were imaged at baseline and during the equilibrium phases of the FRT at standard flow rates of 11 and 23 ml/min [12, 13]. Baseline images did not demonstrate any visible air column consistent with ET lumen (Figure 3). Preliminary assessment of the images of the first two studies at 11 ml/min (average PO of 370 daPa and CS of 0.16 ml/min/daPa) lacked an identifiable air-filled ET lumen. Review of the images at 23 ml/min with the average 0.12 ml/min/daPa CS did not demonstrate a clear air-filled lumen either. For the subsequent 3 subjects, the protocol was modified to perform the CT scan at the highest comfortable flow rate less or equal to 46 ml/min. Furthermore, since there was no clear evidence of a ET lumen at the lower flow rates, only two CT scans were performed (Scan A and C) avoiding unnecessary radiation exposure. The FRT parameter values measured during CT scanning for the 5 subjects are listed in Table 1. Opening pressures ranged between 234 and 481 daPa, the steady state pressures ranged between 52 and 505 daPa, and the steady state conductance ranged between 0.10 and 0.29 ml/min/daPa. For the higher flow rates (average 44.7 ml/min), the average PO was 385.5 daPa and the average CS was 0.18 ml/min/daPa. At these increased flow rates, small foci of air were suspected in the Eustachian tube but the expected continuous air-filled channel was not appreciated (Figure 4a and 4b).

Quantitative values of the measured HU along the expected course of the ET long axis are listed in Table 2. There is a pattern of decreased HU measurements during the equilibrium airflow through the ET, compared to the baseline CT scan. The trend toward lower HU during FRT suggested the presence of increased air within the tubal lumen, though a discrete

air filled distended lumen with HU approaching that of the measured nasopharyngeal air standard was never seen (Figure 5). As expected both PS and CS increase with increasing flow rate. With respect to these trends in FRT parameter values, the quantitative changes in image ROI and point intensities are inversely proportional to PS and CS (Figure 6: slope = $-525 \text{ HU/ml/min/daPa}$, $r^2 = 0.31$). This result is consistent with increasing amounts of air in the tubal lumen despite an inability to appreciate this change visually.

DISCUSSION

Imaging of the cartilaginous ET and the para-tubal structures has been a challenge. While magnetic resonance imaging of the ET and para-tubal structures provides much better soft tissue discrimination than CT, absence of signal from air and the larger voxel sizes pose additional limitations for visualizing the ET lumen [3, 14–16]. Currently, the cartilaginous ET lumen can only be identified with CT when it is open, a result of the significant contrast differences between the HU levels of air and soft tissue. However, at rest in normal individuals, the walls of the functional section of the cartilaginous ET lumen are apposed and thus not visible on CT scan.

The Middle Ear Physiology Laboratory of the Children's Hospital of Pittsburgh of UPMC uses FRT to routinely evaluate ET function in patients with TM perforations or ventilation tubes. During that test, a running pump keeps the ET lumen in an open steady-state which should allow an assessment of the ET lumen with the current temporal bone CT scanning protocols. In this pilot study at lower FRT flow rates (11 and 23ml/min), the widened ET lumen could not be appreciated when compared to the baseline scan. Assuming the minimal lumen diameter at steady-state is directly related to the ratio of steady-state flow to pressure (Poiseuille's equation), the FRT protocol was modified to use the highest tolerated pump speed up to 46 ml/min in subjects 3, 4 and 5. Despite various pump speeds with concomitant wider diameters, a complete column of air filling the cartilaginous ET lumen could not be visualized in the CT images. Interrupted areas of low attenuation which could represent tiny foci of air were detected along the axis of the ET from the nasopharyngeal opening to the bony ET. However, these areas were not composed solely of air as demonstrated by their density (HU) with reference to the nasopharyngeal air standard. This is likely related to partial volume averaging of the voxels, with the adjacent soft tissues increasing the density of the "ET lumen". It is also possible that the areas and points selected may not reflect the ET lumen. However, the trend toward decreasing density with increased air flow during the FRT is consistent with the selected areas and point values including the ET lumen.

The advent of high-resolution CT with multi-planar reconstruction and the introduction of ET surgical treatments led to a proliferation of ET imaging studies over the last decade. The smaller isotropic voxels in the context of multiplanar reconstruction algorithms maximizes the possibility of discriminating the ET lumen from surrounding structures by maximizing its in-plane size. Despite these improvements, two questions remain with respect to the cartilaginous ET. First, is the ET functional segment cross-section large enough to be resolved with CT? And, if it is, are the tissue contrast differences sufficient to make that discrimination possible?

With respect to the first question, the cartilaginous ET lumen is clearly visible and thus measurable under two conditions. First, the ET lumen is visible throughout its length in patients with pathologically open ETs, that is with patulous ETs [6, 7, 17]. The ET lumen is also evident in most subjects/patients at the nasopharyngeal orifice and at the junction with the protympanum, both regions in which it is normally patent. Measurements of lumen size in these regions correlate well with those derived from histologic studies; the height for adult controls at the nasopharyngeal orifice is 8.9 mm for CT [7] compared to the 8.5 mm size in histologic studies [18, 19], and the lumen of the protympanum is 1.8 mm and 3.5 mm, respectively. The expected lumen height of the ET functional segment should be intermediate between these two values; for the histologic specimens this is approximately 6 mm [18]. Thus, when completely open, the cartilaginous ET lumen should be large enough to be demonstrated using CT. Our inability to see the cartilaginous ET lumen during the FRT suggests that the air column produced by the test is even smaller than the protympanic portion of the ET.

Given that the ET functional segment is large enough, but being unable to visualize the ET lumen in this study suggests that tissue contrast among the ET structures is insufficient to allow that discrimination, a not unexpected result. The logical response to this problem is to employ contrast agents to differentially alter voxel intensities. The ET lumen has been demonstrated by instilling a CT contrast agent either into the ME via a ventilation tube [20] or into the nasopharynx employing postures that maintain the contrast at the ET nasopharyngeal orifice during swallowing or yawning [21]. Generally, these procedures are contraindicated because of the potential for cochlear toxicity when contrast agents are introduced to the ME. Visual contrast has also been developed by introducing air into the lumen either via a nasopharyngeal maneuver or by scanning the ET fast enough during swallowing to image the actively dilated lumen. Valsalva has been used to examine the differences in ET length between “patulous” and controls, both in the sitting and supine positions [5, 22, 23]. Of the controls examined, only about one-third showed the ET functional segment dilating during the maneuver [23]. The second strategy, scan fast enough to visualize the actively dilated ET, has been employed in two descriptive studies. One using cine-CT showed movements of the cartilaginous ET, but never documented a patent lumen in the ET functional segment [9]. Review of the supplemental data movies showed movement at the nasopharyngeal orifice and smaller movements at the junction with the protympanum but the tissues of the ET functional segment remained undifferentiated. The best documentation of the ET functional segment lumen was obtained using a specialized 320 detector CT machine and optimal subject positioning. Yoshioka and colleagues demonstrated the ET opening, both morphologically and temporally, with the ET functional segment being patent for approximately 0.4 sec [24]. Employing the same testing instrumentation, they observed the collapse of the patulous cartilaginous ET lumen in response to sniff induced nasopharyngeal sub-ambient pressures. Unsurprisingly, with this collapse it was no longer possible to differentiate the lumen from the surrounding tissues [25]. Clearly, tissue and air-filled-lumen contrast is critical to identifying and quantifying the size of the ET lumen.

In this pilot study, we explored a novel imaging method using CT scanning when the ET lumen is stented open with the continuous air flow during the FRT. The limitation of the

FRT is that it can only be used in cases with a non-intact TM due to a ventilation tube or perforation. Unfortunately, higher air flow during FRT did not necessarily create a steady pressure on the ET walls to keep them apart wide enough to be clearly visualized. This could be due to the need for higher pressure to overcome the high PO in the ears with more significant ET obstruction. When the initial protocol did not accomplish demonstration of air filled lumen, the protocol was modified to protect the subjects from unnecessary radiation exposure. Such modification resulted in subjects being tested at different flow rates, limiting the interpretation of changes in the imaging variables. Moreover, the supine position used for the CT scan is not ideal, as it increases pressure of the surrounding tissues and hinders ET luminal dilation, although, due to a number of uncontrolled variables this effect was not observed consistently.

In the CT images, punctate foci of low attenuation suggestive of air were visualized, but the HU density measurements of these foci were less than that of the nasopharynx, most likely a consequence of inadequate spatial resolution resulting in partial volume averaging with the adjacent soft tissue. Current image analysis method relies on placement of the HU measurements from the areas (ROI) and cross section of hair-lines (LPV) that appear to have the lowest density as perceived by the study radiologist. To capture the HU values that represent the lumen, larger areas of ROI were avoided. There is also a chance that oblique axial plane chosen to take the HU measurements may have partially missed the pixels with lowest density. Alternative image analysis methods of taking measurements from larger size ROI's on multiple adjacent CT image planes along the ET lumen and analyzing the distribution of histogram of HU measurements within the tissue volume may improve the likelihood of capturing the air-filled ET lumen.

Future studies may overcome the identified limitations of this technique and CT-FRT could become an important diagnostic tool for the understanding of ET anatomy and physiology. This diagnostic tool may also be utilized to measure the outcome of new treatment procedures for ETD, such as the comparison of the lumen diameter pre and post ET balloon dilation. It is unlikely that the ET lumen will be measurable during pre-balloon dilation FRT, however demonstration of an air-filled lumen after balloon dilation and correlation of this size with the functional and clinical outcome data may be valuable.

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Figure 1. Hounsfield unit measurements on the left oblique axial temporal bone computerized tomography scan during the forced response test. The 1 mm^2 region of interest (ROI) was measured at the nasopharyngeal airway, to serve as a standard reference for air, and where air was suspected in the mid left cartilaginous Eustachian tube (ET) (oval marks and legend). Black arrow with white rim: nasopharyngeal opening. White arrow with black rim: bony Eustachian tube.

Figure 2. Hounsfield unit measurements on the left oblique axial temporal bone computerized tomography scan during the forced response test. Example of 1 lowest point value (LPV) measurement along the cartilaginous Eustachian tube axis where air was suspected in the Eustachian tube lumen. Black arrow with white rim: nasopharyngeal opening. White arrow with black rim: bony Eustachian tube.

Figure 3.

Left oblique axial temporal bone computerized tomography scan at baseline, prior to running the pump for the forced response test. As expected for the closed cartilaginous Eustachian tube at rest, the Eustachian tube lumen could not be identified. Black arrow with white rim: nasopharyngeal opening. White arrow with black rim: bony Eustachian tube.

Figure 4.

(a) Oblique axial and (b) oblique coronal reformatted computerized tomography scan images of the left cartilaginous Eustachian tube (ET) during the forced response test at 46 ml/min. A linear area of low attenuation could be traced along the cartilaginous ET axis from the nasopharyngeal opening (black arrow with white rim) to the bony ET (white arrow with black rim) with an area suggestive of tiny foci of air (asterisk). However, areas and points of low attenuation were not consistent with Hounsfield units (HU) representing air.

Figure 5. During the forced response test at 46 ml/min, the linear area of low attenuation traced along the cartilaginous Eustachian tube (ET) axis appeared to be consistent with a distinct air column (asterisk); however, Hounsfield unit measurements for the areas and points chosen did not confirm a distinct measurable air column. Black arrow with white rim: nasopharyngeal opening. White arrow with black rim: bony Eustachian tube.

Figure 6.

There is an inverse relationship between average region of interest (ROI) intensity and forced response test (FRT) conductance. As expected, ROI intensity decreases as the FRT flow rate and the amount of air in the ET lumen increase.

Table 1.

Forced response test parameters recorded during CT scan for all 5 subjects.

Subject Number	Scan Series	FORCED RESPONSE TEST DATA				
		Flow Rate (ml/min)	Measured Flow Rate (ml/min)	Opening Pressure (daPa)	Steady State Pressure (daPa)	Steady State Conductance (ml/min/daPa)
1	A	0	0	x	x	0.00
	B	11	12.9	299	52	0.25
	C	23	23.4	236	189	0.12
2	A	0	0	x	x	0.00
	B	11	12.8	442	187	0.07
	C	23	25.4	y	219	0.12
3	A	0	0	x	x	0.00
	B	46	47	234	158	0.29
4	A	0	0	x	x	0.00
	B	42	42.6	442	300	0.14
5	A	0	0	x	x	0.00
	B	46	50.9	481	505	0.10

x: Opening pressure is not available in baseline forced response test (FRT), but were displayed as 0 in the graph.

y: Opening pressure is not available, due to a continuous transition from 11 ml/min to 23 ml/min flow rate.

Table 2.

Image Analysis Data of the CT Scans

Subject Number	Forced Response Test Pump Rate [ml/min]	IMAGE ANALYSIS DATA (Hounsfield units)					
		Region of Interest (1 mm ²)			Lowest Point Value		
		Area 1	Area 2	Area 3	Point 1	Point 2	Point 3
1	0	-120	-65	-80	-238	-242	-151
	11	-246	-461	-364	-443	-542	-569
	23	-323	-302	-306	-301	-352	-370
2	0	-76	-72	-102	-115	-102	-144
	11	-70	-101	-80	-150	-128	-134
	23	-129	-102	-123	-164	-184	-166
3	0	-81	-85	-86	-171	-152	-268
	46	-107	-109	-124	-212	-184	-209
4	0	-80	-70	-64	-95	-96	-92
	42	-91	-91	-103	-119	-98	-93
5	0	-77	-86	-93	-201	-179	-162
	46	-150	-135	-151	-205	-184	-216