Published in final edited form as:

Laryngoscope. 2016 December ; 126(12): 2778–2784. doi:10.1002/lary.25928.

Correlations between videoendoscopy and sonotubometry of Eustachian tube opening during a swallow

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Abstract

Objective—Describe the relationship between the magnitude of Eustachian tube (ET) dilation during swallowing observed on trans-nasal videoendoscopy and quantified by sonotubometry.

Study Design—Descriptive observational study

Methods—Simultaneous trans-nasal videoendoscopic and sonotubometric recordings were done on 33 adults with no middle-ear disease. Briefly, microphones were placed in the ear-canals, a 45° telescope introduced through one side of the nose to visualize and record ipsilateral ET movements, and the probe from a sound generator placed in the opposite nostril. At a generated nasopharyngeal sound-level, ET movements and ipsilateral microphone signals were continuously recorded while the subject performed a series of 3 swallows. For each swallow, relational movements among ET structures observed on video-recordings and characteristics of the sonotubometry signal envelope at the ear-canal were quantified at 3 times, swallow onset (T1), maximum soft-palate elevation (T2), and maximum ET luminal dilation (T3).

Results—A total of 99 swallows were analyzed. The average medial rotation of the ET cartilage and lateral wall over the T1-T2 interval were $-32.7 \pm 14.9^\circ$ and $7.2 \pm 25.1^\circ$, and over the T2-T3 were $4.6 \pm 7.7^\circ$ and $6.2 \pm 14.6^\circ$, respectively. The trans-tubal sound transmission during a swallow peaked at an amplitude of 30.5 ± 35.7 mV during the 572.5 ± 292.6 msec of elevated sound-pressure time. Correlational analysis documented significant linear associations between the relational measures of ET component movements from videoendoscopy and the signal envelope measures from sonotubometry.

Conclusion—There is a direct linear relationship between the degree of ET luminal dilation visualized on videoendoscopy and represented in the sonotubometry signal envelope.

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Work Conducted at: Middle Ear Physiology Laboratory, University of Pittsburgh, Pittsburgh, PA, USA

Conflict of Interest: The authors have no conflicts to disclose.

Financial Disclosure Information: The authors have no financial disclosures.

Presented in part: At the 18th International Symposium on Recent Advances in Otitis Media, National Harbor, MD., June 7–11, 2015

Level of Evidence: NA

Keywords

Eustachian tube; Sonotubometry; Videoendoscopy; Swallowing

INTRODUCTION

Trans-nasal videoendoscopic observation of the ET component movements (medial wall, lateral wall, cartilage) at the level of the nasopharynx (NP) is becoming a common assessment procedure in the clinical setting.¹⁻¹² The technique has evolved from qualitative to semiquantitative⁶ to quantitative.^{5,7} This technique allows real-time visualization and recording of the ET component rotations and displacements caused by the synchronized activities of the levator (mLVP) and tensor veli palatini (mLVP) muscles effecting luminal opening during swallowing.¹³ When appropriately synchronized, these muscle-driven relative wall movements dilate the lumen over its full length allowing for gas exchange between the ME and NP at times of an extant pressure-gradient.¹³ However, the question remains whether specific configurations of these wall movements correspond to a full luminal opening enabling NP-ME gas-exchange and MEPR.

Sonotubometry is a method that first creates a super-ambient, characteristic sound-pressure level in the NP, i.e. a NP to ME sound pressure-gradient, and then measures the change in sound-pressure at the level of the ear-canal during swallowing or other maneuvers typically associated with ET opening.¹⁴⁻²⁴ Features characteristic of the pattern of that change such as duration and magnitude are extracted to represent the magnitude and duration of ET opening. Recent studies attempted to acquire concurrent multimodal data in order to assess the association between the videoendoscopic findings and the sonotubometry.^{13,25}

In this study, the techniques of sonotubometry and videoendoscopy were used to simultaneously capture ET anatomical movements and the change in ear-canal sound pressures during swallows. A correlational analysis was done on that dataset to identify elements of component movements that correlate well with the sonotubometric parameters reflecting luminal opening and, thereby, identify the relational movements associated with an opening.

METHODS

Population (human subjects)

Subjects were recruited by advertisement and referral. Respondents interested in study participation presented to the University of Pittsburgh Middle Ear and Eustachian Tube Center and were in good health by history, had normal tympanic membrane mobility, lacked tympanic membrane pathology, had normal MEP and did not have extant ME effusion and/or other ME pathologies by ENT examination which included bilateral pneumatic otoscopy and tympanometry. Thirty-three healthy adults with no current or recent ME disease were enrolled and tested+/- at the same visit. The study protocols were reviewed and approved by the IRB at the University of Pittsburgh and written informed consent was obtained from all subjects prior to performing any procedure including screening.

Protocol

The subject's nasal passages were topically anesthetized and decongested, first, with a sprayer and, then, with cotton gauze (Medtronic Neuray® Neurosurgical Patties, ½ in. × 2 in., Medtronic Xomed, Inc., Jacksonville, FL) both containing a 1:1 solution of 4% Lidocaine Hydrochloride (Roxane Laboratories Inc., Columbus, OH) and 0.05% Oxymetazoline Hydrochloride (Major® Soothing 12 Hour Nasal Decongestant Spray, Major Pharmaceuticals, Livonia, MI). For initial examination, a 0° endoscope (Hopkins, 2.7 mm. 18 cm, Karl Storz Endoscopy, Germany) and attached video-camera (DigiCam 2.0, JedMed Instrument Co., St. Louis, MO) whose output was routed at 24 frames per second (FPS) to the memory of a personal computer (PC) running Lab Chart software 7.3.6 (AD Instruments, Bella Vista, NSW Australia) was used to view the nasal passages, NP and ET orifices. That endoscope was replaced with a 45° telescope (Hopkins, 2.7 mm. 18 cm, Karl Storz Endoscopy, Germany) and was inserted into the least resistant nasal passage (16 right-side), advanced to the NP and focused on the ipsilateral ET orifice. A plastic probe containing the pick-up microphone (Knowles Electronic BT-21834-000-Itasca, Illinois, USA) of a previously described [23, 36], custom-built, sonotubometer was fitted within the ear-canal ipsilateral to the ET under view and then covered with a standard ear-protector (EARMUFF 1000-Aearo Technologies, Indianapolis, IN). The microphone signal was routed to a PL3504 PowerLab 4/35 data acquisition system (AD Instruments, Bella Vista, NSW Australia) for conditioning and then to the same PC for storage, display, filtering and analysis. Then, the nasal probe attached to a hand-held plastic box containing the sound-source speaker (Piezo Electric Tweeter SS-990-Herald Electronics, Lincolnwood, IL) for the sonotubometer was inserted part-way into the contralateral nostril. Finally, while continuously and simultaneously recording the microphone signals and video images of the ET orifice, the speaker was activated delivering a 110 dB white noise (at probe tip) to the NP and the subject performed three saliva swallows at intervals of approximately 5 seconds.

Study Data

The data available for analysis were the video recording of the ET component movements and synchronous microphone signals over the swallow time for each of the 3 swallows of the 33 subjects. Previously, using a subset of these data, we developed and reported procedural methods to parameterize the sonotubometric microphone signal-envelope²⁶ and to quantify the ET component movements captured by videoendoscopy⁷ throughout a swallow. These procedures were followed and the data from the 2 sources abstracted independently by 2 investigators and then reconciled.

Briefly, the microphone signal for a swallow was high pass filtered at 1000 Hz, smoothed using an arithmetic function and analyzed using the Peak Analysis Module of the Lab-Chart software. Six 'shape' features (See Table I) for each signal envelope were extracted as analysis variables (see Figure 1). For the analysis of video-recording each frame for a swallow was examined to identify the times of swallow onset (T1) and end (T4), maximum soft palate elevation (T2) and maximum luminal opening (T3), and ET opening onset (TO) and termination (TC). From these times, 4 variables were calculated: swallow time (ST=T4-T1); palatal elevation time (PT=T2-T1), ET opening time (OT=TC-TO), and the time interval between maximum palatal elevation and maximum ET opening (IT=T3-T2). Then,

still-frames at T1, T2 and T3 were marked at 4 points corresponding to the juncture of the medial and lateral lamina (Point J), the inferior torus at the midline (Point T), and the medial (Point M) and lateral (Point L) orifice luminal borders, a line parallel to the superior frame-border through Point J constructed, and Point H was marked along that line at an arbitrary distance medial to Point J (see Fig 2). Using OsiriX v.5.8.5 software (Pixmeo, Geneva, Switzerland), the angles ($\angle$) $\angle$ HJT, $\angle$ HJL and $\angle$ HJM, and the apex angle, $\angle$ MJL were measured (See Figure 3). From these, additional analyzed variables were defined as the changes in these angles corresponding to medial rotations of the referenced points from T1 to T2 and T2 to T3 (See Table II).

The analyzed variables for sonotubometry and videoendoscopy were entered into an Excel work-sheet. For each variable, the average and standard deviation of the values for the 99 swallows were calculated. Then, for all available paired observations included in the 2 data sets (sonotubometry and videoendoscopy), the Pearson correlation coefficient was calculated using the method of least squares to estimate the degree of relatedness between the selected sonotubometry and videoendoscopy variables. The probability that the calculated coefficient was not equal to 0 was calculated using a Z statistic and statistical significance was evaluated at alpha .05, and at alpha .1. All analyses were done using the NCSS 9 statistical software (Kaysville, Utah) and, in all data summaries, the format average $\pm$ standard deviation is used.

RESULTS

The 33 subjects ranged in age between 8 and 54 (average 32.9 ± 10.4) years, 15 were male, and 23 reported their race as being “white”. Sixteen subjects reported a negative and 17 a positive history for OM in childhood, 7, of whom, had had ventilation tubes inserted. In addition, 9 subjects reported a history of allergy and 3 had gastroesophageal reflux disease. None had existing or recent ME disease and all MEs were “normal” on examination.

Table I lists the averages and standard deviations for 6 features extracted from the sound signal envelopes of the 99 swallows. Of these, 3 key features describe the overall geometry of the signal envelope, the duration of the elevated sound pressure (Width), 572.5 ± 292.6 msec, time to the signal peak (Time to Peak), 223.1 ± 153.5 msec, and the peak-amplitude (Peak), 30.5 ± 35.7 mV. Additionally, 3 other variables provide additional information regarding the peak characteristics these include peak area, and width at 50% and 90% peak height (Width-50 and Width-90, respectively).

Table II lists the average and standard deviations for the 11 parameters extracted from the videorecordings for the 99 swallows. The first 5 variables establish event timing within a swallow, and the remaining 6 variables capture the magnitude of ET component rotations over specified time-periods during swallowing. To summarize, those results show that, tubal opening is a relatively short event lasting 529.4 ± 323.5 msec. starting at T2 (1384.7 ± 108.8 msec) in the swallow cycle (2398.7 ± 1031.7 msec). From the onset of the swallow to the maximum soft palate elevation, the torus cartilage and medial lumen wall points rotated posteriorly an average of 32.7 ± 14.9 and 15.7 ± 16.7 degrees, respectively, while the lateral wall point rotated much less at 7.2 ± 25.1 degrees. After maximum posterior rotation of the

ET cartilage, as the ET orifice opens, the ET cartilage and adjacent medial luminal wall slowly rotate back anteriorly at 9.2 ± 10.7 and 4.6 ± 7.7 degrees respectively, while lateral orifice wall rotates anteriorly 6.2 ± 14.6 degrees.

Correlation analysis between measures from these 2 tests identified significant relationships between 7 of the 11 image variables and 6 of the 6 sonotubometry variables at the $p < 0.05$ level. When a more loose significance criterion of $p < 0.1$ was applied, additional 7 correlations were noted between 8 image variables and the 6 sonotubometry variables. Table III summarizes these results by listing, for each paired combination, the number of swallows analyzed, the Pearson Product-Moment Correlation Coefficient and the probability that the coefficient is not equal to 0.

The change in medial orifice wall angle in the time interval between the maximum ET cartilage rotation and maximum opening of the ET orifice was significantly correlated with the highest number of sonotubometry variables (4 out of 6 at the $p < 0.05$, or 5 out of 6 at the $p < 0.1$). These correlations were negative indicating that a smaller the angular change between those time points, that is the longer the large angle persisted before relaxation, the more sound was transmitted through the ET. Width at 90 % and 50% of the peak height also correlated negatively with 3 (5 at $p < 0.1$) and 2 video-analysis variables respectively. A smaller angular change between T2 and T3 (IT) was correlated with a wider sound peak at 90% of the peak height. ET opening time was the only video endoscopic variable positively correlated with sonotubometry variables, including Peak Area and Width at 50% height.

DISCUSSION

Endoscopic examination of the ET orifice is one of the relatively commonly utilized methods to assess the anatomy, function and related pathology of the ET. However, there are limitations to using the endoscopic appearance of the ET nasopharyngeal orifice to verify opening of the entire ET lumen. Widening of the ET orifice does not necessarily accurately indicate an opened ET. Combining functional information from sonotubometry and endoscopic evaluation is reported to improve the accuracy of each of these tools.²⁵ Recent reports of a more detailed quantitative description of peri-tubal movements and the shape and magnitude of the transferred sound allow a more sophisticated analysis of the ET function during swallowing.^{7,26}

A recent report compared the angular and spatial changes of the ET nasopharyngeal anatomical structures during swallowing between subjects with or without a history of significant middle ear disease as indicated by ventilation tube insertion.⁷ That study provided insight into the factors underlying the effectiveness of swallowing for ET dilation. Among those factors, the magnitude of the angular rotation of the ET cartilage medial lamina posteriorly during the maximum elevation of soft palate, the sustained deflection of the ET cartilage as the soft palate was relaxing, and the anterior movement of the ET lateral orifice wall as the soft palate was starting to relax appeared to contribute to achieving and maintaining a broader apex angle (the angle between the lateral and medial laminae) and was associated with a more effective ET dilation. A second report employing sonotubometry data from the same experiment reported differences between the two groups, with or without

a history of ventilation tube insertion, with respect to the efficiency of sound signal transmission through the ET during swallowing.²⁶ There, on the basis of sonotubometry parameters, the healthy adults with a past history of ventilation tube insertion had poorer ET function, compared to those without such a history.

A number of significant correlations are found between the dissected physiological changes and sonotubometry variables. Angular changes in the peri-tubal structures during swallowing demonstrated that the most critical variable associated with the sonotubometry variables was the change in the medial orifice wall angle between T2 and T3. The typical sequence of events at the ET orifice in a swallow begins with the maximum elevation of the soft palate with the constriction of mLVP resulting in maximum posterior rotation of the ET cartilage (medial lamina) which is the described time point of T2. Following this is constriction of the mTVP, resulting in lateral rotation of the lateral wall of the orifice as the soft palate relaxes and the medial lamina starts to rotate back to the original angle, reaching the widest state of the ET orifices, defined as T3.^{5-7,13} The relaxation of soft palate between T2 and T3 was inversely correlated with the sonotubometry variables in that the less the medial lamina rotated back from the T2 position (maximum rotation with maximum soft palate elevation) to the T3 position (maximum orifice opening), the better was the sound transmission through the ET as measured by sonotubometry.

Previous analysis had shown that subjects with a history of ventilation tube insertion in the past had a longer duration of swallow.[9] In the current study, Width-90 was the sonotubometry variable with highest number of significant correlations. The total duration of swallow had a significant negative correlation with the Width-90, which suggests that shorter swallows tend to be more effective in sound transmission. Time to ET opening (TO) is inversely correlated with Width-90, suggesting again that the sooner the ET lumen widening is observed, the more sound volume is transmitted through the ET. Similarly, time to reach the maximum orifice widening (T3) is inversely correlated with a good and wide peak, i.e., full opening of the ET (Width-90). More specifically, the strong inverse correlation ($p=0.006$) between the time interval between T3-T2 and Width-90 implies that the shorter the time interval between the firing of the mLVP and mTVP, the better was the maximum transmitted sound envelope duration. Together, those two variables imply that muscular coordination is an important factor for optimal ET opening, as hesitant, fasciculating or double/triple overlapping soft palate movements prolong the swallow duration and time to lumen widening. On the other hand, the duration of ET opening as assessed by videoendoscopic image analysis was directly correlated with sonotubometry variables, including Peak Area, and Width-50.

Concurrent recording of videoendoscopy and sonotubometry is a useful technique, with the potential to improve the accuracy of both assessment tools.²⁵ However, interpretation of sonotubometry output with respect to opening of the ET lumen is not straightforward.²⁷⁻²⁹ A recent analysis demonstrated an accuracy of 73.3% for sonotubometry in assessing ET opening/non-opening by swallowing, based on tympanometry.²⁴ There is substantial overlap in values between the average duration of ET orifice widening by image analysis (529 ± 323 msec.) and the increase in sound pressure level by sonotubometry (572 ± 292 msec). This duration is consistent with the 0.44 sec reported by Hanzel et al.²⁵ and 0.43 ± 0.138 sec

reported by Mondain et.al.³⁰ Within this time frame, there is actually a gradual widening, a peak of maximum width followed by a gradual narrowing of the ET orifice, consistent with the shape of the sonotubometry data. Videoendoscopy is able to record and detect only the changes in the nasopharyngeal orifice of the ET. The 45° telescope, positioned facing the ET lumen, theoretically has a visual direction co-axial to the ET lumen. However, the visual penetration of light into the lumen and the quantity of reflected light for adequate perception of the lumen size decreases exponentially.²⁵ Despite this weakness, understanding the changes in most mobile part of the ET provide useful information on the effect of peri-tubal muscles.

The current analytic approach to the “swallow” provides insight into successful and unsuccessful swallows with respect to ET opening. Identifying certain swallowing patterns associated with ETD could allow for swallow modification and provide a novel approach for treating this condition.

Acknowledgments

Source of Funding: NIH Grant DC007667

The authors thank Drs. William Doyle and Ellen Mandel for editorial review of the manuscript drafts and Ms. Julianne Banks, Ms. Jenna El-Wagaa and Dr. Selma Cetin-Ferra for assisting with subject recruitment and testing.

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Figure 1.

An idealized ear-canal signal envelope recorded from the ear-canal microphone data stream (mV) as a function of time (ms) and bracketed for the period of a swallow. The six analyzed “shape” parameters are labeled as: Width, the time between onset and termination of an increase in signal amplitude; Peak, the maximum signal amplitude above baseline; Time to Peak, length of time between start and the Peak; Area, the integrated area under the amplitude-time curve; and Width50 and Width90, the lengths of time within a defined change in amplitude at 50% and 90% of Peak, respectively.

Figure 2.

Still-frame image of the left Eustachian tube (ET) orifice at T2 (time of maximum soft palate elevation) for one patient showing the identified points, measured line segment, and measured angles used in the calculations. Point J is located at the juncture of the medial and lateral lamina; point T, at the midline of the inferior portion of the torus; point M, at the medial border of the ET nasopharyngeal orifice; and point L, at the lateral border of the ET orifice. The H line segment is a frame-referenced horizontal line constructed to intersect point J.

Figure 3.

A, Still-frame images and point locations for that patient at T1, the onset of a swallow; B, at T2, the time of maximum soft palate elevation and medial lamina rotation; and, C, at T3, the time when the left Eustachian tube orifice is maximally dilated. See the Figure 2 caption for an explanation of the points and lines.

TABLE 1

Sample size (n), averages and standard deviations of the analyzed variables from sonotubometry.

SONOTUBOMETRY VARIABLES	N	Average	Std. Dev.
Width (msec)	99	572.5	292.6
Time to Peak (msec)	99	223.1	153.5
Peak (mV)	99	30.5	35.7
Peak Area (mV.msec)	99	4705.3	7588.4
Width-50 [at 50% of Height] (msec)	99	207.6	135.8
Width-90 [at 90% of Height] (msec)	99	48.4	27.4

TABLE 2

Sample size (N), averages and standard deviations of the variables abstracted from videoendoscopy recordings.

IMAGE ANALYSIS VARIABLES	N	Average	Std. Dev.
Swallow Time (ST=T4-T1, msec)	99	2398.7	1031.7
Palatal Elevation Time (PT= T2-T1, msec)	99	1384.7	1008.8
Time to maximum ET opening (MO=T3-T1, msec)	98	1551.9	936
Eustachian tube opening time (OT=TC-TO, msec)	95	529.4	323.5
Time interval between maximum palatal elevation and maximum ET opening (IT=T3-T2, msec)	98	211.9	245.3
Change in Cartilage Angle during PT (<HJT between T2-T1, degrees)	99	-32.7	14.9
Change in Cartilage Angle during IT (<HJT between T3-T2, degrees)	99	9.2	10.7
Change in Medial Orifice Wall Angle during PT (<HJM between T2-T1, degrees)	99	-15.7	16.7
Change in Medial Orifice Wall Angle during IT (<HJM between T3-T2, degrees)	99	4.6	7.7
Change in Lateral Orifice Wall Angle during PT (<HJL between T2-T1, degrees)	99	-7.2	25.1
Change in Lateral Orifice Wall Angle during IT (<HJL between T3-T2, degrees)	99	6.2	14.6

* All angular changes are referenced to the medial/lateral direction

TABLE 3

Correlation Analysis between the Video Image and Sonotubometry variables.

PEARSON CORRELATION COEFFICIENT ANALYSIS (r:slope, p:significance, n:number of paired data)		Width	Time to Peak	Peak	Peak Area	Width-50	Width-90
Swallow Time (ST=T4-T1)	r	0.161	0.149	0.104	0.001	0.098	-0.253
	p	0.112	0.140	0.303	0.989	0.333	0.011 *
	n	99	99	99	99	99	99
Palatal Elevation Time (PT=T2-T1)	r	0.139	0.145	0.127	0.031	0.079	-0.186
	p	0.171	0.151	0.211	0.763	0.438	0.065 +
	n	99	99	99	99	99	99
Time to Maximum ET Opening (MO=T3-T1)	r	0.019	0.032	0.103	-0.025	-0.039	-0.267
	p	0.852	0.757	0.311	0.806	0.701	0.008 *
	n	98	98	98	98	98	98
Eustachian Tube Opening Time (OT=TC-TO)	r	0.144	0.181	0.150	0.210	0.203	0.061
	p	0.164	0.080 +	0.148	0.041 *	0.048 *	0.556
	n	95	95	95	95	95	95
Interval Time (IT=T3-T2)	r	-0.110	-0.051	-0.180	-0.169	-0.128	-0.277
	p	0.280	0.619	0.077 +	0.097 +	0.210	0.006 *
	n	98	98	98	98	98	98
Change in Cartilage Angle during PT (<HJT between T2-T1)	r	-0.143	-0.167	-0.013	0.057	-0.206	-0.105
	p	0.159	0.099 +	0.897	0.577	0.041 *	0.302
	n	99	99	99	99	99	99
Change in Cartilage Angle during IT (<HJT between T3-T2)	r	-0.093	0.009	-0.198	-0.188	0.032	0.001
	p	0.362	0.928	0.050 *	0.062 +	0.752	0.992
	n	99	99	99	99	99	99
Change in Medial Orifice Wall Angle during PT (<HJM between T2-T1)	r	-0.048	-0.089	0.058	0.049	-0.049	0.072
	p	0.635	0.384	0.567	0.631	0.633	0.481
	n	99	99	99	99	99	99
Change in Medial Orifice Wall Angle during IT (<HJM between T3-T2)	r	-0.274	-0.239	-0.227	-0.241	-0.156	-0.167

PEARSON CORRELATION COEFFICIENT ANALYSIS (r:slope, p:significance, n:number of paired data)						
Change in Lateral Orifice Wall Angle during PT (<HJL between T2-T1)	p	0.006 *	0.017 *	0.024 *	0.016 *	0.122
	n	99	99	99	99	99
		-0.084	-0.135	0.067	0.005	-0.110
	p	0.409	0.184	0.512	0.964	0.278
Change in Lateral Orifice Wall Angle during IT (<HJL between T3-T2)	n	99	99	99	99	99
	r	-0.081	-0.014	-0.165	-0.128	-0.092
	p	0.427	0.889	0.103	0.205	0.964
	n	99	99	99	99	99

* P 0.05, P 0.1