Quantitative Description of Eustachian Tube Movements During Swallowing as Visualized by Transnasal Videoendoscopy

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IMPORTANCE Eustachian tube (ET) dysfunction predisposes ears to otitis media, tympanic membrane retraction, retraction pocket and perforation, or cholesteatoma.

OBJECTIVE To develop a method to quantitatively measure the eustachian tube (ET) component movements and their interactions captured by transnasal videoendoscopy of the ET during swallowing.

DESIGN, SETTING, AND PARTICIPANTS A blinded analysis of ET mechanics in 33 adults, aged 18 to 54 years, with no middle ear disease at present but without (group 1 [n = 16]) or with (group 2 [n = 17]) history of disease, conducted at a clinical research laboratory.

INTERVENTIONS Videoendoscopy of the ET orifice at the nasopharynx.

MAIN OUTCOMES AND MEASURES Eustachian tube component translations and structural interactions during a swallow and the between-group differences in those variables. After topical anesthesia of the nose, a 45° telescope was introduced unilaterally and focused on the ipsilateral ET orifice. A video recording of ET component movements was made during 3 swallows. Swallow and ET opening durations and times to selected events were calculated. Images at 3 time points were analyzed by measuring the apex angle, the medial-lateral luminal width, and the medial angles between a frame-normal horizontal line through the apex and fixed points on the torus and medial and lateral luminal walls. Linear and angular variables during a swallow were expressed as change from baseline.

RESULTS Luminal opening was driven by soft palate elevation–related medial rotation of the torus and medial wall, coupled with lateral wall fixedness. The magnitude of the change from baseline for most variables was statistically greater than 0. Swallow time, palatal elevation time, time interval between maximum palatal elevation, and maximum eustachian tube opening time were not different between groups 1 and 2. Opening time was longer (mean [SD], 0.49 [0.28] vs 0.67 [0.51] seconds; P = .03) in group 2. Higher magnitude of torus rotation (mean [SD], 36.05° [12.96°] vs 27.72° [9.45°]; P = .002) with maximum soft palate elevation in group 1 resulted in greater degree of eustachian tube orifice widening (mean [SD], 0.34% [0.47%] vs −0.02% [0.49%]; P = .001) compared with the resting position in that group.

CONCLUSIONS AND RELEVANCE This methodology has application in developing quantitative descriptions of ET mechanics in groups of persons without and with history or suspected ET dysfunction. A lesser degree of soft palate elevation during swallow that derives the ET medial lamina rotation and widening of the ET orifice may be associated with poor ET function and higher risk for otitis media. Videoendoscopic evaluation of the ET orifice may assist in diagnosing presence and mechanism of ET dysfunction.
Middle ear (ME) pressure regulation is a homeostatic mechanism that maintains a quasi-stable equilibrium between total ME gas pressure and ambient (atmospheric) pressure. While an approximate ME ambient pressure equivalence is a prerequisite for normal hearing and for maintaining a gas-filled ME cavity, those compartments are, at most times, functionally decoupled such that their pressures change independently. Periodic opening of the usually closed eustachian tube (ET) lumen during swallowing, and other maneuvers transiently couples the ME and ambient environment in the air phase. This allows for gradient-driven trans-ET gas flow between the nasopharynx (approximate ambient pressure) and ME, which decreases the magnitude of any preexisting ME ambient pressure gradient. Thus, functional ET opening is the effector mechanism responsible for ME pressure regulation, and the efficiency of active ET opening limits the efficiency of ME pressure regulation. As a consequence, active ET opening efficiency is an inverse predictor of the risk for some types of hearing losses and ME diseases.

For these reasons, a variety of tests have been developed to assess the presence or absence of ET openings during swallowing (and other maneuvers). The most accurate of these estimates active ET opening efficiency quantified as the trans-ET gas conductance (volume gas flow divided by extant pressure gradient). Determining that parameter requires that an ambient ME pressure gradient be established and then measured before and after a swallow (or other maneuver). Such gradients can be easily created and directly measured in MEs with a direct environmental communication (eg, a nonintact tympanic membrane), and for MEs with intact tympanic membranes, targeted pressure gradients can be created within the environment of a pressure chamber and then measured using tympanometry or related methods. However, these tests require specialized instruments not available in most clinical settings.

In developing treatment plans for patients with ME diseases attributable to low ET opening efficiency, it is necessary not only to identify affected cases but also to characterize the underlying cause of the functional impairment, when possible. Transnasal videendoscopy is an accepted, relatively noninvasive examination procedure that has a demonstrated utility for diagnosing regional pathologic conditions near or within the nasopharyngeal orifice of the ET that could affect ET functional efficiency. While some investigators suggested that videendoscopic observations made during swallowing and/or yawning can detect the presence or absence of a concomitant luminal opening capable of pressure regulation, "continency table" analyses of concurrent opening assignments made by videendoscopy and more standard test methods question this assertion. More promising is the potential for videendoscopy to characterize the ET system mechanics underlying luminal dilation during swallowing and other maneuvers with the expectation that abnormal mechanical relationships will characterize and/or explain functional deficiencies.

Since its introduction, the study of ET system mechanics by videendoscopy has evolved from simple qualitative descriptions of the relative movements of the various ET components during swallowing and yawning, to the assignment of observed mechanical patterns to functional classes (eg, grades), to recent attempts at quantifying the relative magnitudes of component movements over time. The purposes of the present exploratory study were to develop an externally referenced, quantitative method to characterize the ET system component movements captured by videendoscopy during a swallow and to compare component movements between groups of adults with no extant ME disease but with and without a history of otitis media (OM) defined by past ventilation tube insertion.

### Methods

#### Participants

The study was reviewed and approved by the institutional review board at the University of Pittsburgh, and written informed consent was obtained from all participants prior to performing any procedure. Participants were recruited by advertisement and referral. A total of 33 otherwise healthy adults with no extant ME disease—16 without (group 1) and 17 (group 2) with a history of OM defined by ventilation tube insertion—were enrolled. After recruitment, the participants presented to the Middle Ear Physiology Laboratory at the University of Pittsburgh, and a general history was taken, an ear, nose, and throat (ENT) examination was performed, and the ears were examined bilaterally using pneumatic otoscopy and tympanometry to confirm normal tympanic membrane mobility, the lack of tympanic membrane pathology, normal ME pressures, and the lack of extant ME effusion and/or other ME pathologic conditions. Bilateral ET function testing was performed to assess active ET opening efficiency using sonotubometry, and the results for the sonotubometric testing of these participants were reported in an earlier publication.

#### Procedures

Eligible participants who provided consent had their nasal passages topicaly anesthetized and decongested first with a spray and then with cotton gauze (Medtronic Neuray Neurosurgical Patties, 0.5 in × 2.0 in; Medtronic Xomed Inc) containing a 1:1 solution of lidocaine hydrochloride, 4% (Roxane Laboratories Inc), and oxymetazoline hydrochloride, 0.05% (Major Soothing 12-Hour Nasal Decongestant Spray; Major Pharmaceuticals). A 0° endoscope (Hopkins, 2.7 mm × 18 cm; Karl Storz Endoscopy) attached to a high-speed digital camera (DigiCam 2.0; JedMed Instrument Co) was used to examine the nasal passages. Then the endoscope was advanced through the most patent side of the nasal cavity to the level of the nasopharynx (8 right sides for both groups 1 and 2), the ipsilateral ET was visualized, and the region was examined for pathologic conditions. The endoscope was removed; a 45° telescope (Hopkins, 2.7 mm × 18 cm) with attached video camera was inserted into the same side, advanced to the nasopharynx, and focused on the ipsilateral ET orifice. Movements of the ipsilateral ET and associated structures were visualized and captured while the participant performed 3 sequential swallows. Continuously, camera signals for the 3 swallows were split routed to an online monitor and to the memory of a personal computer for storage and analysis.
PM, and PL for each still-frame image were mapped using a
the midline (point T [PT]), and the medial (point M [PM]) and
lateral (point L [PL]) luminal borders were identified

Within each recording, the lens to surface orientation
system is externally referenced and, using different
magnifications, the change in absolute point locations, it is only necessary to specify
the change in the angle coordinate because the radial
coordinates are identical at all times for each recording
(point change lies along an arc of fixed radius). There, using
the absolute location of Pp, PM, and Ps were calculated as the difference between T2 and T1 and between T3 and T1 (ΔT3W), noting that angular measures are
independent of magnification. To capture the change between specified times in absolute point locations, it is only necessary to specify the change in the angle coordinate because the radius
coordinate is identical at all times for each recording (point
change lies along an arc of fixed radius). There, using
the absolute location of Pp, PM, and Ps were calculated as the difference between T2 and T1 and between T3 and T1 in ΔT2AMJL, ΔT3AMJL, and ΔT4AMJL, respectively. For example, the T2 − T1 change in Ps location is given by ΔT2Ps = ΔT2AMJL + ΔT1M (T2 − T1). When multiplied by −1, those differences in AHJM, AHIJM, and AIJM reflect the absolute magnitudes of medial rotation (degrees) of the torus, medial luminal wall, and lateral luminal wall, respectively, at T2 and T3.

Data Analyses
The analyzed data set consisted of the swallow time, palatal
elevation time, ET opening time, time between maximum palatal
erection and maximum ET opening, the fractional change in
W at T2 and T3, the magnitude change in the apex angle, and
the medial rotations of Pt, Pm, and Pl at T2 and T3 referenced

Figure 1. Reference Points and Lines and the Measured Angles at T2
During a Swallow

Still-frame image at T2 (time of maximum soft palate elevation) for 1 patient
showing the identified points, measured line segment, and measured angles
used in the analysis. 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 eustachian tube (ET) pharyngeal opening; and point L, at the
lateral border of the ET pharyngeal opening. The H line segment is a
frame-referenced horizontal line constructed to intersect point J, and the W line
segment is the width of the ET pharyngeal opening.

Measurements
For each participant, the complete video recording was converted
to QuickTime format (SmartConverter v 2.0.2; The Shedworsx Team, Systemic Pty Ltd), and movies of each swallow
were created in normal- and slow-motion speeds (iMovie v 10.0.2; Apple Inc) for real-time and frame-by-frame analysis
(Macintosh HD OS X v 10.9.2; Apple Inc). Each movie was examined simultaneously by 2 investigators (C.M.A. and
M.S.T.) blinded to group assignment, who identified and
recorded the onset (T1) and termination (T4) times for each
of the 3 swallows and the times of maximum soft palate
elevation (T2), maximum ET luminal opening (T3), onset of
ET luminal opening (TO), and closure (TC). Still frames at T1,
T2, and T3 were studied simultaneously by those investiga-
tors, and 4 points corresponding to the juncture of the medial
and lateral lamina (apex or point J [PJ]), the inferior torus at
the midline (point T [PT]), and the medial (point M [PM]) and
lateral (point L [PL]) luminal borders were identified
(Figure 1). A horizontal line parallel to the superior frame border
was constructed through Pt, and an arbitrary point H was
located on that line medial to Ps. The absolute positions of Pt,
Pm, and Ps for each still-frame image were mapped using a
frame-independent, polar coordinate system referenced to PJ
such that the radius coordinate was set equal to the linear
distance in pixels between the point and PJ and the angle
coordinate set equal to the medial angle between the H-J line
segment and the point’s radius line. Note that this coordinate
system is externally referenced and, within each recording, is
time independent, since the lens to surface orientation
is not expected to change between swallows. Using

OsiriX v.5.8.5 software (Pixmeo), we directly measured the
linear distance between Pt and Ps, defined as line segment
W (ie, the medial-lateral width of the ET lumen, a standard-
ized horizontal reference angle (AHJT), and 2 internally
consistent angles (ATJM and ATJL). Then, the 2 internal angles
were referenced to the H-J line segment by summing each
with the standardized reference angle, ie, AHIJM = AHJT + ATJM
and AHIJM = AHJT + ATJL, and the internal angle (apex angle)
formed at the junction of the medial and lateral lamina at the
ET orifice was calculated as AML = AHIJM − ATJM (Figure 1).
Note that this method of external referencing allows for the
calculation of absolute rotations and translations in time for
each component independently.

Analysed Variables
Using the recorded event times, we calculated 4 relational
time variables for inclusion in the analyses: 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).

Other analyzed variables were constructed to reflect the relative
change in ET lumen width, absolute apex angle, and ab-
solute point locations between T2 and T1 and between T3 and
T1 (Figure 2). Specifically, the variables reflecting the change
in W at T2 (ΔT2W) and at T3 (ΔT3W) were calculated as frac-
tional changes in the measure using the following formula:

ΔT2W = [W(TX) − W(T1)]/W(T1),

where X = 2 or 3. Note that those variables are comparable
across recordings with different magnifications associated with
different lens to surface orientations, considering the follow-
ing formula:

MΔT2W = [MW(TX) − MW(T1)]/MW(T1) = ΔT2W,

where M is any magnification. The magnitude changes (refer-
ced to baseline) in apex angle were calculated as the simple
differences in AML between T2 and T1 (ΔT2AMJL) and between
T3 and T1 (ΔT3AMJL), noting that angular measures are inde-
pendent of magnification. To capture the change between

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to T1 (baseline). For the entire data set with all swallows considered to be independent observations, the relatedness among these variables was examined using principal component analysis with varimax rotation. There, a minimum 80%-explained total variance (total communality) cutoff was used to assign the maximum number of factors to be considered, and for each factor, a minimum variable loading communality of 20% (approximate percentage of variance in the variable explained by the factor) was used to assign factor structures. For the variables relating change in linear and angular measures, the significance of the change (referenced to baseline [T1]) at each time was evaluated using a 1-sample, 2-tailed t test that compared each mean value with 0 (no change), with significance assigned at a cutoff of P ≤ .01 to correct for multiple comparisons. To avoid the statistical problem associated with performing independent between-group comparisons for 14 interrelated variables, the subset of the 14 variables whose members were significant discriminators of group assignment at P ≤ .05 was first identified using a discriminant function analysis operating on the full data set, with all swallows considered to be independent observations. Then, to control for the 3 repeated swallows in each individual, a repeated-measures analysis of variance (ANOVA), with variance partitioned by group and swallow number, was performed on those variables included in the subset. All data analyses were performed using the NCSS 2007 statistical software (NCSS LLC).

Results

The mean (SD) age for the 16 group 1 participants was 35 (12) years (range, 18-54 years). Seven of the individuals were male, and 8 reported their race as being white. Three participants reported a history of allergy, and none reported a history of gastroesophageal reflux disease. Three participants had previously undergone a tonsillectomy, and 1, an adenoidectomy. None had a history of ME disease, and none had tympanostomy tubes inserted at any time. The mean (SD) age for the 17 group 2 participants was 30 (9) years (range, 20-49 years). Eight of the individuals were male, and 16 identified their race as being white. Six subjects reported a history of allergy, and 3 reported a history of gastroesophageal reflux disease. Seven participants had previously undergone a tonsillectomy, and 7, an adenoidectomy. According to self-report, ventilation tubes were inserted into the ears of group 2 participants during infancy in 4, during childhood in 10, during adolescence in 2, and during early adulthood in 1.

The interrelatedness among the analyzed variables was examined using principal component analysis operating on the full data set of all variables over all swallows. After varimax rotation, 5 primary factors were identified that together captured 84% of the total variability in these measures. The factor structure is listed in Table 1, which reports for each of the 5 factors, the component variables, their loadings, and their communalities. Five variables representing the medial rotations of the torus (ΔT2A_{HJT} and ΔT3A_{HJT}) and medial luminal wall (ΔT2A_{HLM} and ΔT3A_{HLM}) at T2 and T3 and the magnitude increase in the apex angle at T3 (ΔT3A_{AML}) loaded positively.

Figure 2. Displacement of Reference Points and Lines During a Swallow

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 eustachian tube lumen is maximally dilated. See the Figure 1 caption for an explanation of the points and lines.
Table 1. A List of the 5 Factors Identified by Principal Components Analysis and, for Each Factor, the Percent Total Variance in All Variables Explained, the Component Variables, Their Loadings, and Their Communalities

<table>
<thead>
<tr>
<th>Factor</th>
<th>% Total Variance in all Variables Explained</th>
<th>Variables</th>
<th>Loading*</th>
<th>Communalitya</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>ΔT3AHJM</td>
<td>0.52</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ΔT2AHJM</td>
<td>0.75</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ΔT3AHJL</td>
<td>0.75</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ΔT2AHJL</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ΔT3AHJL</td>
<td>0.87</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>ΔT2W</td>
<td>0.92</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ΔT3W</td>
<td>0.81</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ΔT2AHJL</td>
<td>0.70</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ΔT3AHJL</td>
<td>−0.75</td>
<td>0.57</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>ST</td>
<td>−0.96</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PT</td>
<td>−0.96</td>
<td>0.93</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>ΔT3AHJL</td>
<td>0.67</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ΔT3AHJL</td>
<td>−0.76</td>
<td>0.58</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>IT</td>
<td>−0.80</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OT</td>
<td>−0.81</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Abbreviations: IT, time interval between maximum palatal elevation and maximum eustachian tube (ET) opening; DT, opening time; PT, palatal elevation time; ST, swallow time.

* Loading indicates the correlation between the variable and the factor, varies from −1 (negative correlation) through 0 (no correlation) to +1 (positive correlation). Communalities are the proportion of the variation of a variable that is accounted for by the factor, similar to the R2 value. A list of the variables associated with each of the 5 identified factors and the degree of relationship between variable and factor expressed as a “loading,” essentially the correlation coefficient between the variable and the factor, and a “communality,” which is a measure of the fractional variance in the variable explained by the factor (range 0 to 1).

b Variables representing the change in the internal angle (apex angle) formed at the junction of the medial and lateral lamina at the ET orifice at T2 (ΔT2AHJM) and T3 (ΔT3AHJM). T2 is the time of maximum soft palate elevation and medial lamina rotation, and T3, the time when the ET lumen is maximally dilated.

c Variables representing the change in angle coordinates for the 3 points as positive and, at each time, ordered such that the medial rotation of the torus was greater than that for the medial luminal wall that, in turn, was greater than the lateral luminal wall. Of the 14 variables, 3 (ΔT2AHJL, ΔT2W, and OT) were significant discriminators of group membership at P ≤ .05. These variables represent the medial rotation of the torus tubarius, the relative increase in luminal width at T2 and the opening time. Combined, these 3 variables had a sensitivity of 73% and a specificity of 71% with respect to assigning individual swallows to group 2 participants. Repeated-measures ANOVA confirmed the between-group significance of the differences in ΔT2W and ΔT2AHJL (P = .02 and .04, respectively), but not that for OT (P = .17). None of these variables had a significant effect of swallow number (P > .30 for all).

Discussion

Transnasal videodendoscopy of the ET system, a relatively non-invasive procedure, is available to most practicing otolaryngologists for diagnosing those static nasopharyngeal and periluminal pathologic conditions5-10 as well as certain abnormal ET mechanical interactions during swallowing (and other maneuvers)11-15-17 that could be the cause of an otherwise diagnosed low ET opening efficiency. Consequently, the method holds promise to identify the targeted intervention(s) most likely to improve low ET functional efficiency in individual patients. To realize that goal, it is first necessary to identify those pathologic conditions and/or abnormal mechanical interactions that are specific and sensitive predictors of low ET functional efficiency in individual patients. While many discrete pathological expressions can be reasonably assigned to “tentative” predictor class membership, as yet there is insufficient knowledge regarding the variability in “normal” ET mechanics to assign an observed mechanical pattern to a nonnormal, dysfunctional state. In most previous reports, ET component movements during swallowing and/or other maneuvers were described qualitatively, the descriptions were grouped into pat-
tterns sharing common features, and the patterns were assigned to ordinal classes presumptively ranked with respect to the type and relative level of “abnormality.” Such qualitative analyses are inherently subjective and do not capture the interpreter and intraclass and interclass variability required to make the unambiguous and exclusive functional class assignments useful in identifying “causal” associations.

More recently, Poe and colleagues measured the relative magnitudes of 3 selected ET component movements at their maximum change during a swallow (torus rotation, lateral wall displacement, and palatal elevation) and recorded interevent times (cycle time and valve opening time) for swallows captured by videofluoroscopy in 3 groups of individuals: no ME disease, chronic OM with effusion (COME), and no ME disease but patentulous ETs. To control for the interassessor variability in image magnification and orientation resulting from the difficulty of imposing standardized lens-surface relationships across evaluations, they referenced all linear measures to torus length. Pairwise comparisons (control-COME and control-patulous ET) of the average values for these quantitative variables were made using simple parametric statistics, which documented significantly lesser lateral displacement of the lateral ET wall during swallowing in both the COME and patentulous groups and a longer cycle time in the patentulous group compared with the control group. Their study demonstrates the feasibility of applying quantitative analytic methods to these types of dynamic video image data and, perhaps, the utility of that analytic format for identifying between-group differences in component translations during swallowing. However, the few variables measured in their study do not capture fully ET component movements and their interactions during swallowing, which could bias and/or mislead interpretations as to what constitutes “normal” and “abnormal” ET mechanics.

Herein, an alternative quantitative methodology was used to explore the mechanics of ET component movements during swallowing as well as to define possible differences in ET mechanics between groups of individuals with different levels of ET opening efficiency as previously reported. A total of 33 transnasal videoendoscopic recordings of ET component movements during 3 sequential swallows—16 from adults with no history of ME disease and 17 from adults with past tympanostomy tube insertion(s)—were analyzed. For each recording, the timing to selected events during each swallow were recorded. Then, an externally referenced, time-independent, polar coordinate system was used to localize points defining the projected positions of the torus and the medial and lateral luminal walls on 2-dimensional, still-frame images before the onset of swallowing, at the time of maximum palatal elevation, and at the time of maximum ET luminal opening. Relative “in-plane” medial-lateral component displacements and absolute “in-plane” component rotations about a fixed apex point (referenced to the preswallow state) were calculated as simple differences in the polar coordinates for each point between the defined times and baseline.

To address the first aforementioned goal, principal component analysis was used to explore the interrelatedness among the quantitative variables for 4 event and interevent times and, at 2 times during a swallow, the relative “projected” change in 1 linear and angular measure of the luminal dilation and the absolute rotation of the points locating the torus and medial and lateral luminal walls. That analysis documented full independence of the time and spatial variables (no factor structure included variables in both classes). For the former, the time to maximum palatal elevation was the major determinant of swallow time (factor 3) but was not a predictor of luminal opening time. Luminal opening time, in turn, was primarily determined by the time between maximum palatal elevation and the maximum luminal opening (IT) (factor 5). For spatial variables, that analysis documented a high level of redundancy in the information captured by the angular and linear measures of luminal dilation (factor 2) and in the rotational variables at the 2 time points (factor 1). The analysis also showed a coupled medial rotation of the torus-medial luminal wall that partly drives luminal dilation (factor 1) and a negative effect of me-

### Table 2. Means and Standard Deviations of the 4 Time Variables, the Linear Variable, and the 8 Angular Variables for Groups 1 (Control) and 2 (History of Ventilation Tube Insertion), and the F and P Values Assigned by the Discriminant Function Analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group 1</th>
<th>Group 2</th>
<th>F Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔT2W</td>
<td>0.34 (0.47)</td>
<td>-0.02 (0.49)</td>
<td>12.96</td>
<td>.001</td>
</tr>
<tr>
<td>ΔT2W</td>
<td>0.45 (0.38)</td>
<td>0.14 (0.46)</td>
<td>0.84</td>
<td>.36</td>
</tr>
<tr>
<td>ΔT3W</td>
<td>13.76 (12.48)</td>
<td>4.49 (18.48)</td>
<td>0.01</td>
<td>.93</td>
</tr>
<tr>
<td>ΔT3AMJL,°</td>
<td>12.20 (9.98)</td>
<td>9.26 (10.44)</td>
<td>1.47</td>
<td>.23</td>
</tr>
<tr>
<td>ΔT3AHJM,°</td>
<td>36.05 (12.96)</td>
<td>27.72 (9.45)</td>
<td>9.89</td>
<td>.002</td>
</tr>
<tr>
<td>ΔT3AHJL,°</td>
<td>27.12 (15.96)</td>
<td>18.13 (11.55)</td>
<td>0.44</td>
<td>.51</td>
</tr>
<tr>
<td>ΔT3AHJT,°</td>
<td>16.35 (8.82)</td>
<td>12.37 (8.54)</td>
<td>0.08</td>
<td>.77</td>
</tr>
<tr>
<td>ΔT3AHJL,°</td>
<td>11.46 (11.28)</td>
<td>7.97 (8.38)</td>
<td>0.51</td>
<td>.48</td>
</tr>
<tr>
<td>ΔT3AMJL,°</td>
<td>2.59 (12.15)</td>
<td>7.88 (19.01)</td>
<td>0.01</td>
<td>.93</td>
</tr>
<tr>
<td>ΔT3AMJL,°</td>
<td>-0.74 (9.45)</td>
<td>-1.28 (7.31)</td>
<td>0.32</td>
<td>.58</td>
</tr>
</tbody>
</table>

Abbreviations: IT, time interval between maximum palatal elevation and maximum eustachian tube opening; OT, opening time; PT, palatal elevation time; ST, swallow time.

a See Table 1 footnotes for an explanation of the variables.

b Percent change from baseline.
dial rotation of the lateral luminal wall on the magnitude of luminal dilation (factors 2 and 4).

When combined with the recorded mean values for the variables, those observations can be formulated as a testable hypothesis of ET opening mechanics during swallowing. First, contraction of the levator veli palatini muscle (mLVP) visualized as soft palate elevation causes a variable duration, tightly coupled medial rotation of the torus-medial tubal wall that, in turn, causes by “drag” a much lesser magnitude medial rotation of the lateral luminal wall. At this time, the magnitude of luminal dilation, but not a full luminal opening capable of ME pressure regulation, depends on the opposing effects of the relative magnitudes of medial rotation of the medial and lateral luminal walls. Thus, this phase of lumen dilation is primarily a consequence of the medial rotation of the torus-medial wall complex effected by mLVP contraction but maximized as a function of the resistance of the lateral wall to coupled medial rotation perhaps mediated by tissue stiffness properties and/or baseline tensor veli palatine muscle (mTVP) tonus. Second, at or immediately after maximum soft palate elevation and at the time that the mLVP begins to relax as visualized by the onset of a decrease in soft palate elevation, mTVP contraction causes lateral displacement (or rotation) of the lateral luminal wall to approximate its preswallow position. In this phase, full luminal opening capable of ME pressure regulation is favored by large medial rotation of the medial wall effected by mLVP activity coupled with large lateral displacements (rotations) of the lateral wall effected by mTVP contraction. The temporal resolution afforded by the few analyzed within-swallow images is not sufficient to characterize the mechanics underlying closure of the ET lumen, which is expectedly effected by similar, but reverse, interactive movements of the medial and lateral luminal walls on relaxation of both the mLVP and mTVP. This mechanistic hypothesis for ET luminal opening needs to be tested in future studies using similar analytic methods but with protocol modifications to include additional structural landmarks, a much higher temporal density of analyzed time frames, and a direct measure of the presence or absence of gradient-driven gas flow through the ET for each swallow.

To address our second goal, the complete set of variables was compared for differences between groups of individuals assigned based on the presence or absence of past tympanotomy tube insertion(s). Previous studies that used manometric tests of the effectiveness of ET opening in ME pressure regulation in adults with no current ME disease but with and without a history of ventilation tube insertion(s) for OM reported lower trans-ET gas conductance with swallowing for the former when compared with the latter, indicative of a poorer ET opening efficiency in the group with a positive disease history. Participants enrolled in this study had ET function evaluated by sonotubometry with the results showing a significant between-group difference in certain sonotubometric signal parameters interpretable as less-efficient ET openings in the group with a disease history (group 2). We hypothesized that this between-group difference in ET opening efficiency is reflected in group-level differences in ET mechanics as quantified by our methodology. There, the identification of a subset of the analyzed variables that included significant predictors of group assignment was done using a discriminant function analysis operating on all swallows. That statistical method has the advantages of screening large number of potentially interrelated (highly correlated) variables in one operation and then identifying the best, if any, significant predictor of subgroup assignment for each group of correlated variables. The analysis identified 3 variables—medial rotation of the torus at T2, change in ET luminal width at T2, and ET opening time—that were significantly different between the subgroups. When combined, that minimal variable set correctly assigned individual swallows to group 2 at a sensitivity of 73% and specificity of 71%. This accuracy level supports the continued refinement of these analytic methods for purposes of defining specific sets of mechanical variables, with each set associated with a different “type” of impairment in ET functional efficiency. In a second analysis, the members of the identified subset were tested for between-group significance using a repeated-measures ANOVA. That analysis identified significant between-group differences in the medial rotation of the torus at T2 (greater for group 1) and the change in ET luminal width at T2 (greater for group 1), but not in the opening time, a discrepancy possibly attributable to the lower group sample sizes (individuals vs swallows) for that test. A consideration of ET mechanics suggests that the 2 displacement events are causally related such that the lesser increase in luminal width is a direct consequence of the lesser medial rotation of the torus in persons with a positive OM history. Because the magnitude of torus-medial wall rotation during swallowing was the only primary mechanistic variable identified in this study as being different between the 2 groups, it is tempting to suggest that a low magnitude maximum torus rotation is causally responsible for the lower ET opening efficiency previously reported for that group of individuals.

If shown to be valid in future studies, these mechanistic observations may explain, in part, the high prevalence ofOME attributable to low ET opening efficiency in the cleft palate population and in populations characterized by velopharyngeal insufficiency. Because these conditions are associated with anatomically based abnormalities in mLVP function, the magnitude of mLVP attributed medial rotation of the torus during swallowing would be diminished as was previously reported in a videendoscopic study of ET movements during swallowing in cleft palate patients. In turn, the deficient torus rotation would limit the maximum ET luminal dilation (with or without complete luminal opening) during mTVP contraction. Past studies present data both supporting and refuting this mechanism with, for example, Hassan and colleagues reporting that palatoplasty that includes intravelar veloplasty promotes OME resolution in cleft palate children but Finkelstein and colleagues reporting that functional mLVP anomalies do not correlate with OM risk. Resolution of this discrepancy has important implications to the choice of interventions for reducing OME risk in patients with velopharyngeal insufficiency but requires concurrent assessments of ET component movements using quantitative analysis of videendoscopic recordings and of ET openings capable of ME pressure regulation during swallowing in patients with velopharyngeal insufficiency. This is a goal of our continuing studies.
As a side note, the data structure for this study allowed us to evaluate the possibility of mechanical fatigue with repeated swallowing. This would be detected as a significant difference among swallows in the magnitudes for some or all variables. In a supplemental analysis (data not shown), the effect of swallow order (S1, S2, S3) on the magnitude of each variable was evaluated for significance using a repeated-measures ANOVA with variance partitioned by swallow and person. Because this was an exploratory analysis, the standard cutoff for significance (P ≤ .05) was not adjusted for multiple comparisons. The difference among swallows was significant for only 2 variables, the time to maximum palatal elevation (P = .03; post hoc testing, S1 < S2 = S3) and the change in the apex angle at T3 (P = .01; post hoc testing, S1 = S2 < S3). The increased time to maximum palatal elevation for later swallows may represent the need for an increased “saliva gathering” time in preparation for those swallows but does not influence ET mechanics. More interesting is the greater T3 apex angle at the last swallow, which could reflect a longer delay in luminal closing with implications regarding the hysteresis of the luminal opening-closing cycle. However, these positive and negative observations regarding mechanical fatigue remain tentative and need to be tested as formal hypotheses in future studies.

Conclusions

This report presents an analytic method for abstracting quantitative information from transnasal videooendoscopic recordings of ET component movements during swallowing and translating that information into a description of the mechanics of planar ET component movements during swallowing. The informational value of those descriptions is supported by the identification of differences in component mechanics between groups with different expected levels of ET opening efficiency based on sonotubometric testing. However, this exploratory study was designed as a “proof of concept” and was not intended to provide a clinically useful methodology to study the effects of mechanical interactions on ET function. For example, prior to any general application of this or a related methodology, the interrecorder and intrarecorder reproducibility in localization of the points used here or suggested by future work to identify component structures needs to be defined. Also, because all analyzed spacial variables define vectors of change in a 2-dimensional projection of a 3-dimensional space, consideration needs to be given to standardizing the lens to surface distance and orientation in an effort to minimize the relational angles between the viewing plane and the plane(s) of structural movement(s) and thereby maximize the quality and quantity of the captured information. Finally, it is important to concurrently assess the extent of active ET openings (by manometric testing and ET component translations and rotations by videooendoscopy. Past studies used simultaneous or consecutive (this study) sonotubometric testing to define active opening function or for group assignment, but sonotubometry only yields a signal whose characteristics are probabilistically and not definitively related to a true opening. With changes made to satisfy these considerations, this interwoven methodology holds promise to identify the underlying mechanical causes for different classes ET opening dysfunctions (when applicable) and thereby provide guidance with respect to the diagnosis and management associated pathologic conditions.

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REFERENCES