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Quantitative Representation of Eustachian Tube Component Movements during Swallowing

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Abstract

Objective—Describe a method of dynamic video-endoscopy of the Eustachian tube (ET) orifice at the nasopharynx to quantitatively represent ET component movements during swallowing using a graphic function and analyze their importance to its opening mechanics.

Methods—This was a pilot study of relational event capture using a polar coordinate system applied to trans-nasal video-endoscopic recordings of the ET during 3 swallows in 5 adults. After topical anesthesia of the nose, a 45° telescope was introduced unilaterally and focused on the ipsilateral ET orifice. For each recording, consecutive still-frame images were analyzed by identifying 4 fixed-point locators; the luminal apex, lateral and medial walls and the torus. A frame-normal, horizontal line was constructed through the apex and, then, the medial angles defined at the intersection of the horizontal line and the lines from apex to each point locator were measured. The magnitudes of these angles were plotted as a function of time (i.e. successive frames) for each swallow.

Results—The resulting graphs captured the “in plane” relational movements for the locator points during a swallow. Complex interactions among the ET components were resolvable and the patterns were reproducible across swallows. Individual peculiarities observable on review of the corresponding “movies” such as double-swallows, delayed swallows and ET luminal constriction were easily identified in the graphic representation.

Conclusions—This methodology is potentially useful for summary presentations of the ET mechanics of individual patients and for quantifying differences in those mechanics between groups defined by their history of middle-ear disease.

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Keywords

Eustachian tube; video-endoscopy; mechanics; quantification

INTRODUCTION

The middle-ear (ME) functions to capture environmental sound pressures, condition those pressures as signals and present the signals as stimuli to the cochlea. Efficient functioning requires that the ME be maintained as a gas-filled cavity at near atmospheric pressure, an intrinsically unstable condition given the independent fluctuations in both the atmospheric and ME pressures [1]. The usually closed Eustachian tube (ET) represents a potential gas-phase communication between the ME and nasopharynx that, on opening, allows for the gradient-driven exchange of gas between those compartments that, in turn, resets any pre-existing ME-nasopharyngeal pressure gradient to near-zero daPa. Consequently, ET opening efficiency is inversely related to the risk for conductive hearing loss and for a ME mucosal inflammatory condition similar in presentation to otitis media with effusion [2]. For these reasons, a number of methods have been described to measure ET opening efficiency but none of these has gained wide acceptance for routine clinical assessment of disease risk in individual patients [3].

Trans-nasal video-endoscopy (TNVE) is an accepted, relatively non-invasive, clinical procedure that has a demonstrated utility for diagnosing regional pathologies, near or within the nasopharyngeal orifice of the ET [4–9]. When coupled with maneuvers typically associated with ET opening such as swallowing and yawning, TNVE also provides information regarding ET opening efficiency [10–14] as well as the mechanics that drive ET openings [15–17]. Consequently, TNVE results can be used to guide physicians in developing treatment plans for patients with ME diseases attributable to low ET opening efficiency where it is necessary, not only to identify affected cases, but also to characterize the underlying cause of the functional impairment. To date, the use of TNVE for that purpose has been limited by the primarily descriptive information extracted from the visual images for analysis and by the use of qualitative descriptors such as category assignments to characterize both ET function [10–12,15] and mechanics [16]. This introduces vagueness, subjectivity and uncertainty to the interpretation of TNVE recordings.

More recently, Poe[18] and Alper and colleagues [17] described different methods for the quantitative measurement of the acquired TNVE images but, for both, the measures were few in number and limited to selected times or events during an ET opening maneuver. In this “proof of concept” study, we describe an analytic methodology applicable to TNVE images recorded during an ET opening maneuver that yields a quantitative function relating the position of identified ET components in the 2-D image plane to time and from which the within plane movement vectors (magnitude, velocity and acceleration) of component structures and their interactions during swallowing can be easily visualized and quantified.

METHODS

Materials

The source material for this study was the TNVE recordings for 33 otherwise healthy adult subjects with no extant ME disease who were enrolled under an IRB approved protocol designed to define the correspondence between ET opening assignments made by TNVE and by simultaneous sonotubometry [17]. Of these 33 subjects 5 subjects representing the variability of the dataset was selected for a novel advanced image analysis method. Image analysis results of the three swallows per subject was included in the current manuscript. There, consented subjects had their nasal passages topically anesthetized and decongested (1:1, 4% Lidocaine Hydrochloride, 0.05% Oxymethazoline) and surface EMG electrodes were placed on the submental skin to detect the timing of a swallowing event. Then, a 45° rigid endoscope (Hopkins, 2.7mm × 18 cm; Karl Storz Endoscopy, Germany) with attached video-camera (DigiCam 2.0, JedMed Instrument Co., St. Louis, MO) was inserted into the most patent nasal passage, advanced to the nasopharynx and focused on the ipsilateral ET orifice. A continuous video-recording (24 frames/second) of ET component structure position was made while the subject performed 3 sequential swallows and, then, the endoscope was removed. Throughout, the camera and synchronized EMG signals were split-routed to an on-line monitor for direct viewing and to the memory of a PC for storage and later analysis [17]. Five of these recordings were randomly selected for in depth, quantitative, frame-by-frame analysis.

Image Analysis

The staged analysis consisted of the: 1) selection of frame-sequences within each recording that fully captured the timing of the 3 swallows; 2) identification and marking of 4 fixed-point, structure locators on all frames contained in those frame-sequences, 3) fitting the marked points for all frames to a frame-independent, 3-D, polar coordinate system, 4) measuring the polar coordinates of each point in each frame, and 5) displaying the coordinates for all locator points as a time function.

Specifically, the complete continuous video-images for the 5 subjects were converted to QuickTime format (SmartConverter v 2.0.2, The Shedworx Team, Systemic Pty Ltd) and each swallow was identified and labeled based on the synchronized submental EMG activity (iMovie v 10.0.2; Apple Inc) and reviewed in real-time, slow motion and frame-by-frame modes. Each still frame within an EMG delimited swallow was abstracted to a sub-file by one of the investigators (SC) who then viewed each sequential still-frame in the abstracted sub-file and identified and labeled 4 consistent locator points corresponding to the superior ET lumen at the juncture of the medial and lateral laminae (Point J), the inferior torus at the midline (Point T), and the medial (Point M) and lateral (Point L) points along the ET pharyngeal orifice (See Figure 1). The locations of Point M and Point L are chosen at the level where the ET lumen is located, to reflect the changes in the orifice relevant to the ET function. Although there may be between-subject variability, due to anatomical differences, this method assures within subject consistency, required to measure the changes during the phases of swallow. For each frame, a horizontal line parallel to the superior frame-border was constructed through Point J and a Point H was located on the horizontal line at an

arbitrary medial distance from Point J, and the polar coordinates for Points T, M and L referenced to a Point J origin (i.e. $\angle HJP$, where P is the locator point; linear distance from the origin to the referenced locator point, JP) and the linear distance between Points M and L (ML , in pixels) which is referred to as lumen width, W, were measured using OsiriX v.5.8.5 software (Pixmeo, Geneva, Switzerland).

Data Analysis

It is expected that the lens-surface orientation was stable for all frames of a single recording. Under those conditions, the distance coordinate is not changed under simple “in plane” rotations and translations and, therefore, information on positional change in point location during a recording is captured fully by the changes in the point’s angle coordinate ($\angle HJP$). Therefore, the primary dataset for analysis consisted of the recording-number and, for each, the complete set of frame-numbers and corresponding angle coordinates for Points T ($\angle HJT$), M ($\angle HJM$) and L ($\angle HJL$). These data were supplemented with the data sets for 2 frame-specific measures of ET luminal width at the pharyngeal orifice, the directly measured width, W, (LM) and the apex angle defined as the angle formed by linking Points L and M through the juncture point ($\angle LJM$) and calculated as the difference between the medial angles for the lateral and medial luminal walls ($\angle HJL - \angle HJM$). Then, for each recording, frame-number was converted to time (frame-number multiplied by 1/24 seconds) and the angle coordinates for the 3 locator points (positions in the 2-D viewing plane) were plotted as a function of time to capture positional rotations for the ET component structures and the scaled apex angles and pharyngeal orifice widths were plotted as a function of time to capture the temporal pattern of ET luminal opening.

RESULTS

Unilateral ET component movements for 3 sequential swallows in 5 different subjects were recorded and analyzed as described above. The age of the 5 subjects ranged from 18 to 46 years, 3 subjects were male (2 female), 1 was Black (4 White) and none reported a positive history for otitis media. Continuous visualization of the ET component movements during the individual swallows was excellent for 13 of the 15 recorded swallows but, in 1 swallow of 2 individuals, visualization of all frames contained within the timing of the palatal cycle sequence was incomplete.

Figure 2 shows the two measures of ET pharyngeal orifice opening, apex angle and lumen width (a) and the measured angle coordinate for the 3 locator points (Points T, M and L) in the 2-D plane of view (b) for all frames contained within the EMG-identified swallow periods as functions of time (sec) from recording onset for subject #15022. There, the 5 plotted lines represent the signal magnitude-time function for each variable recorded at a density of 24 measurements/second. The functions for all 5 variables are characterized by a low magnitude, high frequency “jitter” reflecting the random, inter-frame variability in position identification, a more pronounced, large magnitude, low frequency oscillation representing the “true” change in 2-D position effected by swallowing, and a variable-magnitude, random-direction shift in the basal values for the sequential swallows most probably representing slight shifts in the lens-surface orientation during the between-

swallow time intervals. Note that, for all 3 swallows, the pattern of change over time in the functions for the apex angle and pharyngeal orifice width are nearly identical in both relative signal magnitude and signal duration. This duplicate information was expected from a consideration of the represented geometry and characterized all swallows analyzed in this report. Consequently, to avoid redundancy, only the pattern of change in the apex angle is shown in the figures that follow.

An examination of the palatal movements during the time periods identified by EMG activity as “swallowing” showed that interval to contain fully the period of palatal motion, but the onset of the EMG activity preceded palatal motion possibly reflecting preparatory muscle activity and terminated well after completion of the palate motion cycle. Therefore, a better appreciation of the temporal inter-relationships for the 4 signal magnitude-time functions is gained by rescaling the signal magnitudes as directional changes relative to their respective value recorded at a reference time ($t=0$). There, time=0 was assigned to the frame recorded immediately before the onset of palate elevation as identified on review of the slow-motion video recording. The baseline-referenced, magnitude-time functions for subject #15022 are displayed in Figure 3 for the apex angle and angle coordinates of the 3 locator points. There, the function for the apex angle measures the “in plane” increases and decreases in lumen opening during the swallow and for the positional variables captures the degree of “in plane” medial (negative change) and lateral (positive change) rotations of the respective structure relative to the luminal apex.

In this example, all 3 swallows were characterized by a relatively large magnitude, coupled medial rotation of the ET cartilage and medial wall of the pharyngeal orifice. At or near the time of maximum rotation, there was a pronounced lateral displacement/rotation of the lateral luminal wall, followed by a movement of all structures in the direction of their pre-swallow locations. Of note, in these graphs (and in those for the other subjects), the angle positions of the locator points at termination of palatal movement were not identical to their respective positions measured before the onset of palatal movement. The explanation for these shifts is not known, but they most probably represent measurement artifacts since the swallow cycle was completed prior to the time of measurement.

This temporal pattern of components movements is expected from both the known relative timings of the tensor (mTVP) and levator (mLVP) veli palatini muscle activities during a swallow and from past descriptions of “normal” ET component movements during a swallow [17, 19], and is fully consistent with the motions noted on review of the respective slow motion video. Similar patterns of “in plane” structure rotation/translation characterized the graphic functions for the 3 swallows of the TNVE recordings for subjects #15026 and #15027. In contrast, on review of the slow motion recordings and as captured using the above outlined methods, the patterns of ET component movements during swallowing were quite different for subjects #15028 and #15023.

For subject #15028, review of the TNVE slow motion recording noted a complex, multiphase pattern of palatal motion for all 3 swallows that was described by the observer as “long double-swallows” consisting of repeated cycles of palatal elevation and depression. Figure 4 shows the graphic representation of ET component movements captured by the

above-described methods. There, for each swallow, the apex angle (and pharyngeal orifice width) versus time function showed a cyclic pattern of dilation and constriction, which was driven by a series of repeated lateral and medial rotations of the medial and lateral lumen walls. While clearly atypical, the significance of this anomalous behavior with respect to impacting ET opening efficiency is not known. For subject #15023, review of the TNVE slow motion recording noted what was described by the observer as an “abnormal constriction (versus dilation) of the ET lumen during the swallows”. Figure 5 shows the graphic representation of those observations as developed using the presented methodology. There, all 3 swallows were characterized by an initial constriction of the ET lumen as evidenced by a decrease in the apex angle followed by a rapid luminal dilation that was maintained after the palatal cycle was completed. Driving this behavior was an early medial rotation of the lateral ET luminal wall that closely tracked the ET cartilage/medial wall rotations, followed by a rapid lateral displacement of the lateral wall without a subsequent medial displacement to restore the pre-swallow position. Again, a functional interpretation of this behavior cannot be advanced based on these data alone.

DISCUSSION

TNVE of the ET at its nasopharyngeal orifice is a relatively non-invasive procedure available to most practicing otolaryngologists. Past studies show that static TNVE is capable of diagnosing extant nasopharyngeal and periluminal pathologies that can adversely affect ET function [4–9], while more recent work suggests that dynamic TNVE can identify abnormal ET opening mechanics [12, 15–18]. Consequently, TNVE may represent a relatively low cost, simple clinic procedure to diagnose both the presence of ET dysfunction and the possible cause of an identified dysfunction in individual patients, information particularly relevant to patient management decisions.

To that end, it is necessary to characterize the mechanical interactions among ET component structures that define “normal” function and to identify the classes of those interactions considered to be pathological. Most past studies presented dynamic TNVE results as lengthy descriptions of typical cases [4, 10, 12, 15] or assigned those descriptions to one of a number of functional “classes” [16]. Such qualitative analyses are subjective and potentially biased by sufficiently large inter-interpretor and intra- and inter-class variabilities to preclude unambiguous and exclusive assignments of individual cases to meaningful functional categories. Recognizing these deficiencies, a few investigators attempted to quantify selected changes in ET component relationships during swallowing, but these analyses were preliminary and were limited in measures and assessment times-points [17, 18].

Anatomically, the ET, a usually closed biological tube extending from the ME to the nasopharynx, consists of a mucosa-lined lumen bounded superiorly and medially by a mucosa-covered cartilage and inferiorly and laterally by a veiled membrane. Two muscles functionally relate to the ET, the mTVP and the mLVP. The former takes origin from the lateral membranous wall of the ET, descends inferio-laterally to round the hamulus and inserts into the palatine aponeurosis. Effective contraction of the mTVP during swallowing or other activities displaces the lateral wall of the ET inferio-laterally to fully open the tubal lumen. While the mLVP does not have direct tubal attachments, that tubular muscle lies in

intimate contact with the membranous floor of the tube from its origin at the petrous temporal bone to its insertion into the soft palate. Anteriorly the mLVP bundle lies medial to the ET cartilage in coronal cross-section such that mLVP activity during speech and swallowing exerts a superior-medial force on that cartilage which usually causes a superior-medial rotation of the cartilage and medial luminal wall relative to the lumen apex. Thus, efficient luminal opening during swallowing is effected by the mLVP imposed medial rotation of the cartilaginous wall coupled with the later mTVP imposed lateral displacement of the lateral wall [19]. Past studies suggest that ET opening efficiency is determined not only by the effective application of these forces by the two muscles, but also by the relative timing of those force applications [17, 20].

The ET component structures acted on by the mTVP and mLVP during a swallow, the medial and lateral walls of the ET lumen and the ET cartilage, and their positional translations/rotations during a swallow (and other maneuvers) are identifiable on the 2-D, paracoronal projections of the nasopharyngeal ET orifice captured by TNVE. Past studies have described these movements and their apparent contribution to ET opening [12, 16, 17]. Here, in a proof-of-concept analysis, we attempted to quantify and summarize the ET component movements and their interactions during a swallow by plotting component location within the viewing plane as a function of time. Specifically, stable and repeatable structure landmarks were identified on each frame of a TNVE recorded swallow and then mapped onto a fixed, 2-D, polar coordinate system within the plane of view. When graphed as a function of frame-number (time), the temporal dynamics of landmark rotations about the luminal apex (measured as the angle coordinate) and spatial translations (measured as the distance coordinate) during a swallow as projected onto that plane were quantitatively captured. The typical function for a swallow showed an early and prolonged medial rotation of the ET torus and medial wall attributable to mLVP activity, and, at near maximum rotation, a lesser magnitude, lateral translation of the lateral ET wall attributable to mTVP activity, followed by counter-rotations/translations attributable to cessation of muscle activity partly restoring the pre-swallow positions. Importantly, variations among individuals in this typical pattern that were consistent for all swallows were observed, as for example, by the graph presented for subject #15028 (Figure 4) showing a complex, multi-phase constriction/opening/constriction of the ET pharyngeal orifice during a swallow and by that for subject #15023 (Figure 5) showing an abnormal, medially (as opposed to laterally) directed lateral wall translation and a consequent constriction of the ET pharyngeal orifice during all 3 swallows. As opposed to the variability of ET component movements between subjects, there is striking similarity between swallows of the same subject.

These simple graphs effectively summarized the swallow associated structural movements visually appreciated on review of the corresponding “movie” sequences and allow for quantification of component movement vectors (magnitude, direction, rate of change) as well as the mechanical interactions among the components [17]. Importantly, the functions can be parameterized using simple mathematical operators to yield quantitative measures of event and inter-event timing (by subtraction in the time domain), maximum change in component structure location (by subtraction in the spatial domain), the direction and magnitudes of change vectors such as the velocity and acceleration of structure motion (by calculation of the slope of the function at each time) and signal-envelope “shape” descriptors

such as the area under the curve (AUC) and the physical moments for the AUC such as “center of mass” (by integration). The small number of analyzed swallows and the large between-subject variability in this pilot study, a consequence of intentionally choosing a qualitatively variable sample precludes establishing population level quantitative representations of the dynamic image variables that could be summarized in tables. Larger samples will be needed to assign and test validity of the shape descriptors.

These examples document both atypical ET component movements during swallowing that may or may not have functional implications. Functional assignments for the various patterns require simultaneous recording of a functional parameter such as the ME-nasopharyngeal pressure gradient which is known to change if and only if a pressure-regulating complete luminal opening had occurred during the swallow. The observation of different patterns of ET component movements during swallowing with possible functional consequences emphasizes the potential power of combinational testing that couples simultaneous TNVE and tests that capture pressure-regulating openings for diagnosing the presence/absence of ET dysfunction and the cause of the dysfunction.

These results demonstrate the feasibility of using this analytic methodology to quantify and summarize the “in plane” ET component movements that occur during a swallow with clear applications in both the clinical and research settings. Regarding the former, summary reports for clinical TNVE examinations could be standardized to include a graph displaying the temporal dynamics of ET component movements, a short listing of any quantitative deviations from an “accepted-normal” reference in the onset time, rate of change (velocity, acceleration) and magnitude for each component movement and their interactions, and a brief interpretation of the functional consequences, if any, of the noted deviations. Standardized data for all such examinations could be entered into a de-identified reference library available to all for use in refining diagnoses and treatment plans. For individual patients, such reports would permit the diagnosis “by rule” of the presence/absence of abnormal ET function, the assignment of a probable cause to any diagnosed dysfunction, and a recommendation as to “best” treatment. For research, a standardized analytic methodology would allow a quantitative description of the dynamics of ET component movements as an interactive mechanism and the formal testing of hypotheses using parametric statistical procedures. For example, the time-axis for the graph could be synchronized to that for the simultaneously recorded: video-signals to test hypotheses regarding the interpretation of abnormal structural interactions; the EMG activities of the mTVP and mLVP to test hypotheses regarding the driving forces underlying structural movements, and sonotubometry, ME pressure or trans-ET gas flow signals to test hypotheses regarding the correspondence between component configuration at a specified time during a swallow and a fully functional, pressure-regulating, ET opening, among others.

However, before adopting this methodology for those purposes, additional work needs to be done on standardizing the dynamic TNVE image acquisition protocol and on more fully developing the image processing methodology. While the current methodology adequately captures the relational dynamics of ET component locators during swallowing as visualized on a TNVE recording, the derived mathematical information is applicable only to cases with the same 2-D projection plane of the 3-D system being imaged as defined by lens-surface

orientation. There, the image-lens distance determines component structure magnification in the 2-D projection (reflected in the measured linear but not angular variables) while the orientation of the 2-D image plane relative to the main plane of “true” motion determines the observable structures and the degree of skew introduced into the angular measures by “out of plane” rotations/translations. Ideally, lens-surface distance and orientation would be standardized for all examinations to maximize the generalizability of the mathematical descriptions of component dynamics. Also, the current process of assigning structure locators is effort intensive and time consuming and does not necessarily include all structure movements of interest. To address this, we are exploring the possibility of integrating shape analysis programs into the process with the goals of identifying physically meaningful, stable locators (e.g. center of mass and other physical moments, the tangent to curved surfaces) and partly automating the process.

Recent developments in the management of ET dysfunction, specifically the introduction and recent FDA approval of ET balloon dilation have in fact accentuated the role and importance of TNVE. Limitations to use ET function testing as the criteria for balloon dilation as well as renewed focus on the inflammatory and functional changes around the NP ET orifice have elevated TNVE criteria as an indication for balloon dilation of the ET. Static and dynamic evaluation of the ET orifice and video recording of this imaging for documentation and comparative purposes is necessary and useful. Thus, TNVE should become routine component of the assessment in any center that plans to treat ET dysfunction. While simple and standardized methods of image analysis will be necessary for the otolaryngologists that assess and manage ET dysfunction, efforts such the one presented here aimed at developing more refined methods for assessing the physiology and pathophysiology of ET should continue. Advancements the safer radiologic imaging methods with better time and spatial resolution will allow correlations with the dynamic changes documented in TNVE.

In summary, this report presents an analytic methodology to quantify and summarize the visual information available from TNVE recordings of planar ET component movements during swallowing (and other maneuvers). For all labeled ET components, the method effectively captures “in plane” movement onset, velocity, acceleration and magnitude during a swallow or other maneuver as well as the mechanics of inter-component structural interactions. With broad application, the methodology allows for a rigorous, relatively unambiguous, and standardized definition of “normal” and “abnormal” ET opening mechanics based on TNVE recordings. The latter has direct clinical application to individual patients with respect to diagnosing the presence/absence of ET dysfunction and assigning the cause of the dysfunction. However, additional work is needed on standardizing image acquisition and processing before the power of this methodology can be fully exploited.

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Figure 1.

Static image of the ET and related structures at its nasopharyngeal orifice as visualized in one frame of a dynamic TNVE recording. In the analysis, fixed locator points were assigned to sequential frames at the midline of the inferior border of the torus tubarius (T), the medial (M) and lateral (L) walls of the ET lumen and the superior juncture of those walls (J). A horizontal line through the juncture point (J) was constructed parallel to the upper frame border and a reference point, H, was located on that line at an arbitrary distance medial to the juncture point. Measured for analysis were the medial angles from Point H through Point J to Points T ($\angle HJT$), M ($\angle HJM$) and L ($\angle HJL$), and the linear distance between Points M and L ($\overline{ML}$, W, in pixels). Additionally, the apex angle of the ET lumen, $\angle MJL$, was calculated as the difference between the measured angles $\angle HJL$ and $\angle HJM$.

FIGURE 2 b

Figure 2.

Graphs displaying the 2 measures of ET pharyngeal opening, width (W) and apex angle (<MJL) (a), and the angle coordinates for the 2-D position of Points T (<HJT), M (<HJM) and L (<HJL) as functions of time (b) from onset of increased EMG activity for subject # 15022. Measurements were made at a sample density of 24 measurements/second for the 3 time periods identified as swallows by an elevated submental EMG signal. Note that the signals for the 2 measures of luminal opening are nearly identical in scaled magnitude and duration, thus providing redundant information.

Figure 3.

A graph relating the apex angle and the 3 angle coordinates to time for the data shown in Figure 2 after normalization to a baseline measured on the image frame immediately preceding the first frame evidencing soft palate elevation, i.e. the pre-swallow resting state. Times are referenced to a baseline value of “0” and extend for the full period of palatal movement. Signal magnitudes at each time represent the absolute magnitudes at that time minus the respective magnitudes at time 0. Note that the pattern of change in the apex angle is the resultant difference between the changes in the positions of the lateral and medial walls of the ET pharyngeal orifice.

Figure 4.

A normalized graph relating the 3 angle coordinates and the apex angle to time for the 3 swallows of subject #15028. Note the multi-phase signal oscillations, which were synchronized to, repeated palatal elevation/descent cycles within each swallow as visualized on the slow-motion video recording.

Figure 5.

A normalized graph relating the 3 angle coordinates and the apex angle to time for the 3 swallows of subject #15023. Note that the apex angle first decreases (constriction of the pharyngeal orifice) and then increases (dilation of the pharyngeal orifice) for all 3 swallows, which is synchronous with the early biphasic medial and lateral displacements of the lateral luminal wall.