Sequence Variability During Hypopharyngeal Bolus Transit

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Abstract. The pharyngeal phase of deglutition is considered to occur in a reflexive, preprogrammed fashion. Previous studies have determined a general sequence of events based on the mean timing of bolus transit and swallowing gestures. Individual variability has not been studied, however. The purpose of this study was to determine the amount of sequence variability that normally occurs during the hypopharyngeal phase of deglutition. Dynamic swallow studies from 60 normal volunteers were evaluated and event sequence variability was determined for 12 two-event sequences during swallowing of three bolus sizes. There was found to be some variability in event sequences for almost all events evaluated except for the following : (1) arytenoid cartilage elevation always began prior to opening of the upper esophageal sphincter, (2) the sphincter always opened prior to the arrival of the bolus at the sphincter, (3) larynx-to-hyoid approximation always occurred after the onset of upper esophageal sphincter opening, and (4) maximum pharyngeal constriction always occurred after maximal distension of the upper esophageal sphincter. Variability was more common during swallowing of the smallest bolus size. This information may be helpful in evaluating event coordination in patients with dysphagia.

Key words: Deglutition — Hypopharynx — Event sequence — Swallowing coordination — Deglutition disorders.

The coordination of events during swallowing is likely to have a major impact on swallowing function.

For example, if swallowing gestures occur out of sequence or without regard for the location of the bolus, poor airway protection and ineffective pharyngeal transit of the bolus may result. Previous studies have established a range of normative values for gesture timing and bolus movement relative to the onset of bolus pharyngeal transit, but the sequence of swallowing gestures demonstrated by individual subjects has not previously been evaluated [1–3]. In particular, there are no studies of the sequence of bolus gestures in which the location of the bolus is incorporated into the analysis.

The UC Davis Dysphagia Team has developed a quantitative method of swallowing evaluation using videofluoroscopy [1,4]. The timing of 14 swallowing gestures and 4 points of bolus transit are measured in each patient examined by the Team and plotted against a set of normative data developed from the evaluation of 60 normal volunteers. Both the timing and the sequence of swallowing gestures and bolus transit are graphically depicted by this method (Fig. 1). Occasionally, a patient's values fall inside the single standard deviation from the normal mean for a given parameter (see inserts in Fig. 1), but the sequence of swallowing gestures in that individual does not mirror the general sequence determined by the mean timing of gestures from the normative data. This finding causes concern that the dysphagia complaints in such a patient could be due to a disorder of gesture coordination rather than to a disorder of gesture timing. The question remains, however, as to the amount of sequence variability that is normal and whether or not certain event sequences are preserved across changes in subject and bolus characteristics.

This study proposed to evaluate variability in the sequence of specific events that occur during deglutition and establish normative data for comparison to patient data. Sequence analysis was undertaken of the dynamic swallow studies performed in

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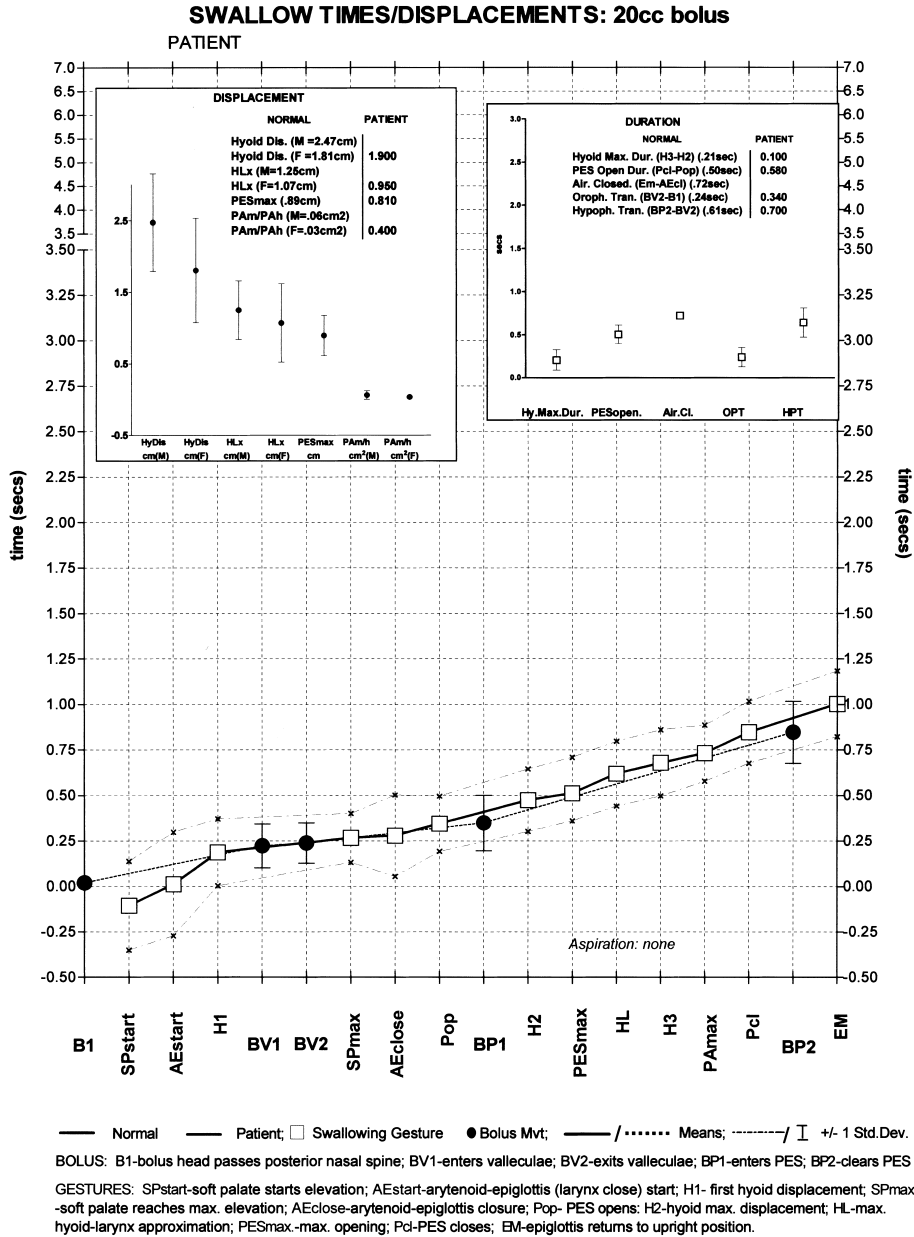
Fig. 1. Patient timing data measured from the dynamic swallow study can be plotted against the mean and standard deviation of data compiled from swallow studies performed in 60 normal adult volunteers.

our population of 60 normal controls. Included in the analysis is an evaluation of events occurring during hypopharyngeal bolus transit defined as the time between the arrival of the bolus in the vallecula and the arrival of the tail of the bolus into the esophagus.

Materials and Methods

Dynamic videofluoroscopic swallow studies were performed on 60 consecutive normal adult volunteers. The study group consisted of

30 males and 30 females with an age range of 18 to 62 years. None of the study subjects had any complaints of dysphagia or a history of central nervous system (CNS) or craniofacial abnormalities.

The radiographic studies were conducted in the Voice–Speech–Swallowing Center at UCDMC in accordance with the routine radiographic protocols approved by the institution. Equipment used included a properly collimated Phillips Radiographic/Fluoroscopic unit that provides a 63 kV, 1.2 mA type output for the full field of view mode (9 in. input phosphor diameter) (Phillips Medical Systems North America Company, Shelton, CT). Fluoroscopy studies were recorded on high-quality videotape for playback and analysis using a Sony Model 1380 Videocassette VHS Recorder/Player (Sony Corporation of Amer-

Table 1. Definitions and abbreviations

B1	the first movement of the most anterior part of the bolus from a stable or "hold" position that passes the posterior nasal spine; all further timing measures are made relative to B1
BV	the arrival of the head of the bolus in the vallecula
BP1	the head of the bolus arrives at the upper esophageal sphincter
BP2	tail of the bolus leaves the upper esophageal sphincter
PCl	the moment the upper esophageal sphincter closes and the bolus has fully entered the esophagus
AE-start	onset of aryepiglottic fold elevation
AE-close	aryepiglottic fold elevation to the point of supraglottic closure
H1	first superior–anterior movement of the hyoid
H2	the point at which the hyoid reaches its maximum displacement
Pop	onset of upper esophageal sphincter (PES) opening
PESmax time	time at which the upper esophageal sphincter has reached its widest opening
HL	maximum larynx to hyoid approximation
PAmax time	maximum pharyngeal constriction

ica, New York, NY). A graphic time display provided by an RCA character generator (RCA, Indianapolis, IN) and JVC AC adapter Model C412 (JVC, Wayne, NJ) was included on the videotape so that timing information at 0.01-s intervals was recorded. The swallow studies were recorded at 30 frames per second. Measures were made during the swallowing of a 1-, a 3-, and a 20-cc liquid bolus (Liquid Barosperse Barium Sulfate Suspension, catalog No. 179312, Lafayette Pharmaceuticals, Inc., Anaheim, CA). Swallowed material was presented to the subject by cup.

The studies from each subject were analyzed without information about the identity of the subject by the primary author. The videotaped images were captured on a Cardio-Loop (Eigen, Inc., Grass Valley, CA) which allowed for image enhancement and manipulation when needed. Timing measures were reported in seconds. A list of timing measurement definitions and corresponding abreviations provided in Table 1.

The onset of bolus pharyngeal transit (**B1**) is defined as the first movement of the head of the bolus from a stable or "hold" position that passes the posterior nasal spine and results in all or part of the bolus entering the oropharynx. The posterior nasal spine is located at the end of the hard palate and is a good landmark for the anterior border of the oropharynx. The timing of all subsequent swallowing events is determined relative to the onset of bolus pharyngeal transit.

The completion of bolus pharyngeal transit (**BP2**) is defined as the moment the tail of the bolus leaves the upper esophageal sphincter and the bolus has fully entered the esophagus. This time corresponds to closure of the upper esophageal sphincter (**Pcl**). Bolus pharyngeal transit time can be divided into an oro- and a hypopharyngeal phase by the arrival of the bolus in the vallecula (**BV**). If the bolus bypasses the vallecula, the time when the bolus passes the level of the base of the vallecula is designated as the onset of hypopharyngeal transit. The events included in this study were limited to those that occurred during hypopharyngeal transit.

The hyoid bone moves during a swallow as a result of suprahyoid muscle contraction [2,3,5]. The first superior–anterior movement of the hyoid that results in a swallow is designated as **H1**. **H2** is defined as the time when the hyoid reached its maximum displacement during the swallow.

The outlines of the epiglottis and the arytenoid cartilages are visible against the relative hypodensity of the pharynx in the lateral projection on the X-ray. As a result, it is possible to identify movement of these structures, in particular, when the most superior part of the arytenoid cartilages begins to elevate and again when it

makes contact with the down-folding epiglottis [6]. The onset of arytenoid cartilage elevation relative to the start of the swallow (**AE-start**) and the point of vertical supraglottic closure (when the most superior part of the arytenoid cartilages makes contact with the down-folding epiglottis, designated as **AE-close**) were therefore measured.

The onset of upper esophageal sphincter (UES) opening relative to the onset of bolus pharyngeal transit was measured. **Pop** designates the time when the UES opens. This time is identified as the moment the narrowest part of the upper esophagus between C4 and C6 opens. We use this definition of the location of the UES because we feel that the narrowest point of opening is the most functionally significant. It is also very reliably identified on a dynamic swallow study as opposed to a measurement made from the often poorly defined top of the air column in the trachea. The arrival of the head of the bolus at the UES is designated as **BP1**. **PESmax time** reflects the time at which the UES has reached its widest opening (in lateral view).

While the UES is open, larynx-to-hyoid approximation occurs, presumably as a result of thyrohyoid muscle activity. This event brings the larynx further anterior and under the tongue base. The timing of this event is designated as **HL**.

As the bolus is propelled into the upper esophagus, the pharynx is typically completely obliterated by the tongue pushing against the contracting posterior pharyngeal wall. This gesture is crucial to a successful swallow and the timing of it is designated as **Pamax time**. Incomplete contact between the contracting pharynx and tongue base results in pharyngeal residue after the swallow that may be aspirated [7].

Interobserver reliability among four judges was established on measures made from 15 of the normal swallow studies and was found to be greater than 90% for each measurement parameter reported, except for larynx-to-hyoid approximation (HL) which had a 75% interobserver reliability.

The sequence of various sets of two swallowing events, including bolus transit events and swallowing gestures, was determined by comparing the relative timing of these events during the swallow. In other words, it was determined in what order the two events occurred in each individual swallow study. For example, did event A occur prior to event B, or vice versa? The frequency of each of the two possible sequences was then calculated for the study population of normal subjects by bolus size category. In some individuals, certain measurements could not be made secondary to movement artifact on the swallow study. The number of individ-

Table 2. AE-close before H2

	1 cc	3 cc	20 cc
Ratio	50/59	51/58	54/54
Percent	**85%**	**88%**	**100%**
H2 (mean ± SD)	0.58 ± 0.3	0.51 ± 0.25	0.49 ± 0.22
AE-close (mean ± SD)	0.52 ± 6.27	0.41 ± 0.24	0.27 ± 0.21

Table 3. H2 after Pop

	1 cc	3 cc	20 cc
Ratio	30/59	42/60	58/60
Percent	51%	70%	97%
Simultaneous	0	0	2
Pop (mean ± SD)	0.56 ± 0.30	0.41 ± 0.17	0.32 ± 0.13
H2 (mean ± SD)	0.58 ± 0.3	0.51 ± 0.25	0.49 ± 0.22

Table 4. AE-start before Pop

	1 cc	3 cc	20 cc
Ratio	59/59	58/58	54/54
Percent	100%	100%	100%
AE-start (mean ± SD)	0.26 ± 0.29	0.11 ± 0.20	−0.01 ± 0.26
Pop (mean ± SD)	0.56 ± 0.30	0.41 ± 0.17	0.32 ± 0.13

Table 5. AE-close before Pop

	1 cc	3 cc	20 cc
Ratio	46/59	51/58	41/49
Percent	78%	88%	84%
Pop (mean ± SD)	0.56 ± 0.03	0.41 ± 0.17	0.32 ± 0.13
AE-close (mean ± SD)	0.52 ± 0.27	0.41 ± 0.24	0.27 ± 0.21

uals included in each analysis is reported with the analysis data. Differences in the amount of variability for a given two-event sequence between bolus categories was compared using a chi-squared analysis. To account for multiple chi-squared tests, the alpha was adjusted to 0.007 (0.05/7).

Results

The results of the analysis are reported in general sequence order. Events that occur in proximity to one another were compared with one another. The analysis began with the first events to occur after the bolus had arrived in the vallecula, that is, the closure of supraglottic structures and maximal hyoid bone elevation.

The superior portion of the arytenoid cartilages had usually made contact with the down-folding epiglottis by the time the hyoid reached maximum elevation (**AE-close** usually occurred prior to **H2**; see Table 2). Reversal of that timing relationship was occasionally observed with the smaller bolus sizes but was not seen in the larger bolus category. (**H2 before AE-close**: 1 cc = 15%, 3 cc = 12%, 20 cc = 0%) However, differences in the amount of sequence variability across bolus sizes was not significant with stringent adjustment of alpha ($p = 0.0143$). Vertical closure of the laryngeal vestibule was previously found to occur earlier relative to the onset of the pharyngeal phase of the swallow with increases in bolus volume while the timing of maximal hyoid bone elevation is not as sensitive to changes in bolus size [1]. That is not to say that hyoid bone movement did not respond to changes in bolus volume. On the contrary, we know from previous studies that the hyoid bone moves farther with larger bolus volumes [8].

The onset of UES opening also occurred most commonly prior to the time when the hyoid bone reached maximum elevation (**Pop** usually occurs before **H2**; see Table 3). In other words, the hyoid had reached maximum elevation *after* the onset of UES opening. However, with the smaller bolus sizes, that timing relationship is reversed 49% of the time (**Pop**

after H2: 1 cc = 49%, 3 cc = 30%, 20 cc = 3%; **Simultaneous Pop and H2**: 20 cc only = 3%). Again, the percentage of sequence variability between Pop and H2 was significantly related to the bolus size category ($p < 0.0001$).

As both the onset of arytenoid cartilage elevation (AE-start) and the onset of UES opening (Pop) generally occurred prior to maximum hyoid elevation (H2), we looked at the relationship of these two events to each other. The onset of arytenoid cartilage elevation always occurred prior to the onset of UES opening (Table 4). **Pop always occurred after AE-start**, irrespective of the size of the bolus swallowed. Usually, the arytenoid cartilages had also completed closure against the epiglottis prior to the onset UES opening (**Pop** occurs after **AE-close**; see Table 5). In about 17% of cases overall, the UES began to open before the supraglottic structures were completely closed (**Pop before AE-close**: 1 cc = 22%, 3 cc = 12%, 20 cc = 16%). Variability of the timing relationship did not differ significantly with changes in the bolus size category ($p = 0.3524$).

Although less common, the UES was found to open (Pop) before the arytenoid cartilages achieved

Table 6. Pop before or with BP1

	1 cc	3 cc	20 cc
Ratio	59/59	60/60	60/60
Percent	100%	100%	100%
Pop (mean ± SD)	0.56 ± 0.30	0.41 ± 0.17	0.32 ± 0.13
BP1 (mean ± SD)	0.59 ± 0.29	0.46 ± 0.23	0.34 ± 0.14

Table 7. AE-close before BP1

	1 cc	3 cc	20 cc
Ratio	55/59	52/58	43/50
Percent	93%	90%	86%
AE-close (mean ± SD)	0.52 ± 0.27	0.41 ± 0.24	0.27 ± 0.21
BP1 (mean ± SD)	0.59 ± 0.29	0.46 ± 0.23	0.34 ± 0.14

Table 8. AE-close before HL

	1 cc	3 cc	20 cc
Ratio	56/57	54/56	48/48
Percent	98%	96%	100%
AE-close (mean ± SD)	0.52 ± 0.27	0.41 ± 0.24	0.27 ± 0.21
HL (mean ± SD)	0.72 ± 0.29	0.65 ± 0.23	0.61 ± 0.16
HL-AE-close (mean ± SD)	0.20 ± 0.09	0.24 ± 0.13	0.33 ± 0.23

Table 9. HL before Pop

	1 cc	3 cc	20 cc
Ratio	57/57	57/57	58/58
Percent	100%	100%	100%
Pop (mean ± SD)	0.56 ± 0.30	0.41 ± 0.17	0.32 ± 0.13
HL (mean ± SD)	0.72 ± 0.29	0.65 ± 0.23	0.61 ± 0.16

complete closure against the epiglottis (AE-close) in some cases. The location of the bolus in the pharynx at that time and the proximity of the bolus to the supraglottic structures during these events was of interest in terms of airway protection. The analysis of bolus arrival at the UES sphincter (BP1) relative to the timing of sphincter opening (Pop) and the timing of supraglottic closure (AE-close) was done. The bolus did not arrive at the UES and sit there waiting for the UES to open. **BP1 never occurred prior to Pop**. The UES was already open when the bolus arrived or opened simultaneously with bolus arrival (Table 6). This timing relationship did not change with changes in bolus size.

Such was not the case with vertical supraglottic closure, however. Usually, but not always, the arytenoid cartilages had closed against the epiglottis (AE-close) before the bolus arrived at the sphincter (BP1), but in every bolus category there were some instances where the bolus arrived at the sphincter prior to complete closure of the supraglottic structures. (**BP1 before AE-close**: l cc = 7%, 3 cc = 12%, 20 cc = 14%; see Table 7) Bolus arrival at the sphincter before complete supraglottic closure was not significantly different with changes in bolus size category.

After closure of the supraglottic structures, the laryngeal skeleton was seen to elevate and approximate the hyoid bone (HL). This gesture pulled the larynx under the tongue and further protected the airway. Our analysis found that only rarely did **HL** occur before **AE-close**, irrespective of bolus size category (p = 0.3994). The supraglottic structures were closed before the larynx approximated the hyoid in by far the majority of cases. The time between these events became even greater with a larger bolus where the supraglottic structures closed earlier (**HL before AE-close**: 1 cc = 2%, 3 cc = 4%, 20 cc = 0; see Table 8).

Both larynx-to-hyoid approximation (HL) and the onset of UES opening (Pop) generally occurred after closure of the arytenoid cartilages against the epiglottis (AE-close). The proximity of the timing of these events leads one to wonder if they are physiologically related. In other words, does the elevation of the larynx towards the hyoid initiate opening of the UES? The analysis of larynx-to-hyoid elevation versus the onset of UES opening revealed that **HL always occurred after Pop** (Table 9). The UES was already open when the larynx approximated the hyoid bone, making it unlikely that larynx-to-hyoid approximation resulted in opening of the sphincter. Because larynx-to-hyoid approximation occurs after the sphincter starts to open, it is possible that it is related to maximum opening of the UES. Our analysis, however, revealed that usually **PESmax time** occurs prior to **HL** (Table 10). There is variability in this relative timing relationship, which is reversed in some cases, especially with a smaller bolus size (**HL prior to PESmax time**: 1 cc = 26%, 3 cc = 21%, 20 cc = 10%). Differences in variability between bolus size categories were not significant (p = 0.0854). A direct relationship of HL with PESmax time could not be established by this method of analysis.

There are likely multiple factors that lead to maximum distension of the UES including intrabolus

Table 10. PESmax time before HL

	1 cc	3 cc	20 cc
Ratio	42/57	45/57	52/58
Percent	74%	79%	90%
PESmax time (mean ± SD)	0.68 ± 0.30	0.55 ± 0.18	0.55 ± 0.18
HL (mean ± SD)	0.72 ± 0.29	0.65 ± 0.23	0.61 ± 0.16

Table 11. H2 before PESmax time

	1 cc	3 cc	20 cc
Ratio	55/59	53/59	41/60
Percent	93%	90%	68%
H2 (mean ± SD)	0.58 ± 0.3	0.51 ± 0.25	0.49 ± 0.22
PESmax time (mean ± SD)	0.68 ± 0.30	0.55 ± 0.18	0.55 ± 0.18

Table 12. Pop vs. PESmax time vs PAmax time

	1 cc	3 cc	20 cc
Pop (mean ± SD)	0.56 ± 0.30	0.41 ± 0.17	0.32 ± 0.13
PESmax time (mean ± SD)	0.68 ± 0.30	0.55 ± 0.18	0.55 ± 0.18
PAmax time (mean ± SD)	0.79 ± 0.29	0.71 ± 0.18	0.72 ± 0.14

Table 13. PAmax time prior to HL

	1 cc	3 cc	20 cc
Ratio	48/57	49/57	51/58
Percent	84%	86%	88%
HL (mean ± SD)	0.72 ± 0.29	0.65 ± 0.23	0.61 ± 0.16
PAmax time (mean ± SD)	0.79 ± 0.29	0.71 ± 0.18	0.72 ± 0.14

pressures. Adequate hyoid bone elevation has been shown to be needed for UES opening [7]. We found that the hyoid usually reached maximal elevation (H2) prior to maximal distension of the UES (PES-max time) (Table 11). Like the majority of hypopharyngeal events, there was variability in that relationship. However, unlike the majority of the timing relationships evaluated, greater variability was found during swallowing of a larger bolus size ($p = 0.0003$) (**PESmax time prior to H2**: 1 cc = 7%, 3 cc = 10%, 20 cc = 32%).

Another contributor to maximum distension of the UES may be the timing of maximum constriction of the pharynx, driving the bolus from the pharynx into the esophagus. The comparison of the relative timing of these events revealed that **PAmax time always occurred after PESmax time** (Table 12). Based on this finding, it follows that the timing of UES opening (Pop) also always occurred prior to maximum pharyngeal constriction (PAmax time).

Both maximum pharyngeal constriction (PA-max time) and larynx-to-hyoid approximation (HL) were found to occur after maximum distension of the UES (PESmax time). The analysis of the relationship of these two events to each other revealed that usually **HL** happens before **PAmax time** (Table 13). A reversal of that timing relationship occurred on about 14% of cases, and the amount of variability did not change with changes in bolus size ($p = 0.9078$) (**PAmax time prior HL**: 1 cc = 16%, 3 cc = 14%, 20 cc = 12%).

In summary, certain bolus and gesture timing relationships were found to exist during hypopharyngeal bolus transit that did not vary between subjects or across bolus categories. The onset of arytenoid cartilage elevation (AE-start) always occurred prior to opening of the UES (Pop). The sphincter always opened prior to the arrival of the bolus at the sphincter (BP1). Larynx-to-hyoid approximation (HL) always occurred after the onset of UES opening. Maximum pharyngeal constriction (PAmax time) always occurred after maximal distension of the UES (PESmax time). Some variability in the relative timing of all other event sets analyzed by this study was found.

Given the above findings, the most common sequence of events should have been: **AEclose/Pop/BP1/H2/ PESmax time/HL/PAmax time**. When we evaluated individual swallowing sequences, we found 7 individuals who demonstrated the sequence when swallowing a 1-cc bolus, 25 individuals who demonstrated that sequence during a 3-cc bolus swallow, and 23 individuals who demonstrated the sequence during a 20-cc bolus swallow. A total of 45/180 (25%) swallows contained that sequence.

Discussion

This study revealed substantial variability in the sequence of events during hypopharyngeal bolus transit. The amount of variability in general was found to be greater during smaller-bolus-size swallows. In only two instances was sequencing variability found to be greater during the larger-bolus swallows. Vertical supraglottic closure (AE-close) typically occurred prior to the arrival of the bolus at the UES (BP1) but a reversal of that sequence occurred more frequently

in the largest-bolus category. Maximal UES distension (PESmax time) typically occurred prior to maximum elevation of the hyoid bone (H2) but reversal of that sequence occurred more commonly during the swallow of the large-bolus size. These findings may be the result of faster pharyngeal transit of the bolus during swallowing of a larger-bolus size and the arrival of the bolus at certain locations in the pharynx before gestures could catch up [1]. Generally, it appeared that faster transit of the bolus, such as occurs during a larger-bolus swallow, results in less opportunity for variation and a more "reflexive" pattern of swallow event sequencing.

There are currently two theories relating to how the central nervous system controls the sequence of events during the pharyngeal phase of swallowing [9,10]. The reflex chain theory holds that each motion of the pattern stimulates peripheral receptors whose afferent impulses trigger the next motion. In other words, each gesture in the swallowing sequence triggers the onset of the next gesture. The central pattern generator theory holds that a central neural circuit exists in the brainstem that is capable of generating the pattern of muscular activation without sensory feedback. The central pattern generator responds to some sensory input to "finely tune" the pattern but otherwise can function without sensory feedback. Both of these theories are based on the notion that the pharyngeal phase of deglutition is primarily "reflexive" in nature and occurs as the result of a predictable sequence of neuromuscular activity. There is evidence from human and animal studies to support both theories [9–12]. However, with the advent of sophisticated brain imaging techniques it has become increasingly clear that deglutition is an extremely complex activity that generally involves input from several higher CNS structures as well as sensory feedback [13]. As a result, it is likely that the sequence of events during the pharyngeal phase of swallowing varies in response to multiple sensory and higher CNS stimuli.

The findings of this study support the possibility of multiple sources of input into swallow sequence control based on the amount of variability identified in normal individuals. Variability around certain events was found to be the norm. Unfortunately, the evaluation of event coordination in individual patients becomes difficult in this situation because any sequence of these events falls within a normal range. Certain other event sequences were preserved across individuals and bolus size categories, however. These few event sequences can be employed in the analysis of patient swallowing coordination and, if found to be reversed in patients, the event sequences will confirm a diagnosis of poor swallowing coordination.

In addition to providing information about normal variability in swallow sequencing, this study provided information about general swallowing physiology. By evaluating the relationship of swallowing events to one another and to bolus transit, this study supports the concept that the onset of arytenoid cartilage elevation and closure against the epiglottis appears to occur by a mechanism that is independent of hyoid elevation and larynx-to-hyoid approximation. The timing of vertical supraglottic closure was more responsive to changes in bolus size than any of the other swallowing gestures.

Further study of event coordination is warranted. Intrasubject variability should be analyzed and will provide information about changes in swallow sequences in the same subject at the same sitting and at different times. Perhaps with further study, the ability to identify subtle swallowing coordination abnormalities in individual patients will emerge.

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