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Swallowing Physiology of Sequential Straw Drinking

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Abstract. The goal of this study was to examine deglutitive physiology during sequential straw drinking in healthy young adults ($n = 15$) to learn how sequential swallowing differs from single swallows. The physiology of single swallows has been studied extensively in healthy adults and in adults with a variety of debilitating conditions, but the physiology of sequential swallows has not been studied adequately. Videofluoroscopic analysis revealed three distinct patterns of hyolaryngeal complex (HLC) movement during sequential straw swallows: opening of the laryngeal vestibule after each swallow (Type I, 53%), continued vestibule closure after each swallow (Type II, 27%), and interchangeable vestibule opening and closing during the swallow sequence (Mixed, 20%). Unlike discrete swallowing, the onset of the pharyngeal swallow occurred when the bolus was inferior to the valleculae in the majority of subjects and was significantly associated with HLC movement pattern. The leading bolus edge was inferior to the valleculae at swallow onset for Type II movement patterns. For Type I movement patterns, bolus position at swallow onset was randomly distributed between three anatomical positions: superior to the valleculae, at the level of the valleculae, and inferior to the valleculae. Preswallow pharyngeal bolus accumulation, which is common during mastication, was evident and significantly associated with the HLC pattern of opened laryngeal vestibule after each swallow. These data suggest that in healthy young adults, sequential swallows differ physiologically from discrete swallows and indicate substantial variability in deglutitive biomechanics.

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The physiology of discrete swallows has been studied extensively. In a normal discrete swallow, the bolus is propelled posteriorly in the oral cavity with a pharyngeal swallow response evoked between the faucial arches and ramus of the mandible. Hyolaryngeal excursion ensues with laryngeal valving as the bolus progresses caudally through the pharynx. The upper esophageal sphincter (UES) relaxes with subsequent tongue base and posterior pharyngeal wall contact and pharyngeal wall contraction, which allows for bolus clearance and transfer into the esophagus. Following a discrete swallow, the deglutitive system returns to rest with opening of the airway for respiration.

A critical and controversial part of deglutition has been defining the trigger point for evocation of the pharyngeal swallow, which is signaled by the onset of maximum hyolaryngeal excursion [1]. Before discrete swallows were studied in the elderly, it was posited that evocation of the pharyngeal swallow occurred when the bolus head reached the anterior faucial arches, and the pharyngeal swallow was considered "delayed" if the bolus progressed caudally before the onset of maximum hyolaryngeal excursion [2]. However, once deglutition was studied in healthy elderly adults, the trigger point for evocation of the pharyngeal swallow was extended caudally to the area where the ramus of the mandible bisects the base of the tongue [3,4]. The time period from when the bolus head passes the ramus of the mandible until the initiation of maximum hyolaryngeal excursion is generally termed "pharyngeal swallow delay time" [4] or "stage transition duration" [3]. Progression of the bolus caudal to the ramus of the mandible prior to the onset of maximum hyolaryngeal elevation has generally been considered dysfunctional and has resulted in implementation of therapeutic intervention. Perlman et al. [5] noted that in patients with dysphagia the risk of aspiration parallels pharyngeal delay time, i.e., the longer the delay in onset of the pharyngeal swallow, the greater the risk of aspiration. It has been suggested that location of the bolus at swallow onset predicts risk of aspiration [6], i.e., aspiration risk is lowest if the bolus head is superior to the ramus of the mandible at onset of the pharyngeal swallow. Risk becomes moderate if the bolus is between the ramus of the mandible and the valleculae, and aspiration risk is greatest if the bolus is inferior to the valleculae at swallow onset. However, some investigators have questioned whether inducement of the pharyngeal swallow caudal to the level of the ramus of the mandible is abnormal. A study of discrete swallows in healthy young adults found that pharyngeal swallow onset frequently occurred after the bolus head passed the anterior faucial arches [7]. The authors, however, did not identify the exact location of the bolus at swallow onset.

While the physiology of evocation of the pharyngeal swallow and deglutitive biomechanics have been studied extensively in the discrete swallow, research is limited in the study of consecutive swallows. In studies with mastication as the primary focus, Palmer and colleagues [8–10] identified preswallow pharyngeal bolus accumulation of triturated food prior to swallow onset. Palmer et al. [8] also evaluated liquid swallows but the study was limited to three consecutive swallows of liquid through a straw. Pharyngeal aggregation of the bolus into the pharynx was not evident with the three liquid swallows. Dua et al. [11] studied swallowing during ingestion of meal. Detailed analyses were completed during swallows of masticated material and with the saliva generated from gum chewing, but the swallows of liquids ingested during the course of the meal were not analyzed. As with Palmer et al. [8–10], Dua and colleagues identified pharyngeal dwell time prior to the onset of the pharyngeal swallow and found the epiglottic edge to be the most sensitive area for inducement of the pharyngeal swallow. Chi–Fishman and Sonies [12,13] have further challenged the concept of pharyngeal delay time for specific ingestive patterns. When comparing discrete swallows with continuous cup drinking, longer durations of stage transition have been identified with sequential swallowing [12] and extended delays in inducement of the pharyngeal swallow (mean $= 2.79 \pm 1.24$) have been described with mastication [13].

These studies suggest that discrete swallows differ from the more natural ingestive behavior of consecutive swallows and indicate that the distinction between normal and abnormal swallows may differ in discrete versus continuous swallows. When drinking, most humans typically complete consecutive swallows of varying, self-regulated amounts of liquid. As the physiology of sequential swallowing has not been clearly elucidated, particularly for straw drinking, the purpose of this study was to examine the deglutitive physiology of sequential straw drinking in healthy adults. Based on the data from the studies cited above, we posited that subjects would maintain laryngeal elevation with continual supraglottic closure during the entire swallow sequence. We predicted that the leading bolus edge for consecutive swallows would be in the proximal pharynx at swallow onset and that preswallow pharyngeal bolus accumulation would not occur.

Subjects and Methods

Fifteen healthy young males (mean age = 30 years ± 3) without history of dysphagia, neurological disease, or oropharyngeal structural damage were studied. The study protocol was approved by the Institutional Review Board at Tulane University School of Medicine and at the Veterans Affairs Medical Center in New Orleans, and written consent was obtained from each subject.

A videofluoroscopic swallowing study (VSS) was completed on all subjects as they consecutively swallowed liquid barium through a straw. Two 10-s trials, measured with a stopwatch, were completed. Subjects were instructed to initiate swallowing upon direction to start, to continually swallow at their normal pace, and to stop swallowing upon request. The examiner held the cup containing 300 mL of barium (60% w/v, diluted 2:1 water to barium) and the straw (19 cm length, 0.5 cm diameter) while subjects swallowed. VSS samples were recorded in the lateral plane using a super-VHS videocassette recorder with the radiographic focus encompassing the oral cavity (rostral to the lips) and the pharynx (caudal to the UES).

The number of swallows and the total volume ingested during each 10-s period was obtained for each subject and averaged across the two trials. Volume per swallow was calculated from the total amount swallowed during each 10-s period divided by the number of swallows. Volume per swallow was then averaged across the two trials. Patterns of movement of the hyolaryngeal complex (HLC) during the swallow sequence and bolus location at onset of the pharyngeal swallow were derived from slow motion and frame-by-frame analysis of the video recordings. HLC movement patterns were scored using a binary system of opened laryngeal vestibule with an upright epiglottis after each swallow and closed laryngeal vestibule with an inverted epiglottis after swallowing. Anterior to the valleculae, level to the valleculae, and inferior to the valleculae were the variables used to analyze bolus position at onset of the pharyngeal swallow. Initiation of maximum hyolaryngeal excursion was the biomechanical marker used to identify pharyngeal swallow onset [1].

Results

The mean number of total swallows generated during the 10-s period was 10.33 ± 2.06 (range: 7–15) indicating that subjects swallowed about once per second. The mean total volume swallowed per 10-s trial was 115.33 ± 53.37 mL (range: 42.50–237.50 mL). The mean volume per swallow was 11.53 ± 5.9 mL (range: 3.54–26.39 mL).

Analysis of HLC movement characteristics revealed three distinct patterns during sequential straw swallows. Type I movement patterns were characterized by return of the epiglottis to upright and the opening of the laryngeal vestibule after each swallow; they were evident in 8 of the 15 subjects (53%) (Fig. 1). Type II movement patterns were characterized by continual inversion of the epiglottis and vestibule closure after each swallow; they were observed in 4 of the 15 subjects (27%) (Fig. 2). A mixed HLC movement pattern was characterized by interchangeable Type I and II patterns; it was identified in 3 of the 15 subjects (20%). A single factor analysis of variance revealed that the total volume swallowed [$F_{(2,12)} = 2.82$, $p = 0.10$], number of swallows [$F_{(2,12)} = 1.48$, $p = 0.27$], and volume per swallow [$F_{(2,12)} = 1.51$, $p = 0.26$] did not differ significantly with movement patterns of the HLC (Table 1).

The location of the leading bolus edge at onset of maximum hyolaryngeal elevation was evaluated. Ten of the 15 subjects (67%) consistently demonstrated initiation of maximum hyolaryngeal excursion when the leading bolus edge was inferior to the valleculae; only 1 of the 15 subjects (6%) demonstrated consistent evocation of the pharyngeal swallow with the leading edge of the bolus superior to the valleculae. The remaining 4 subjects demonstrated a more random bolus location pattern at onset of the pharyngeal swallow. That is, the leading edge of the bolus was not consistently located in any single anatomical area at onset of the pharyngeal swallow during the 10-s swallow sequence.

Given that on average many of the healthy adults initiated maximum hyolaryngeal movement with the leading bolus edge inferior to the valleculae, we were interested in learning whether there was a relationship between bolus location and HLC movement type. To investigate this relationship, the total number of swallows was analyzed. Analysis of all swallows across all subjects ($n = 305$ total swallows) revealed a significant association between location of leading bolus edge at onset of the pharyngeal swallow and HLC movement pattern ($\chi^2(2) = 70.83$, $p < 0.01$). A total of 184 swallows were identified as Type I, indicating that there was return of the epi-

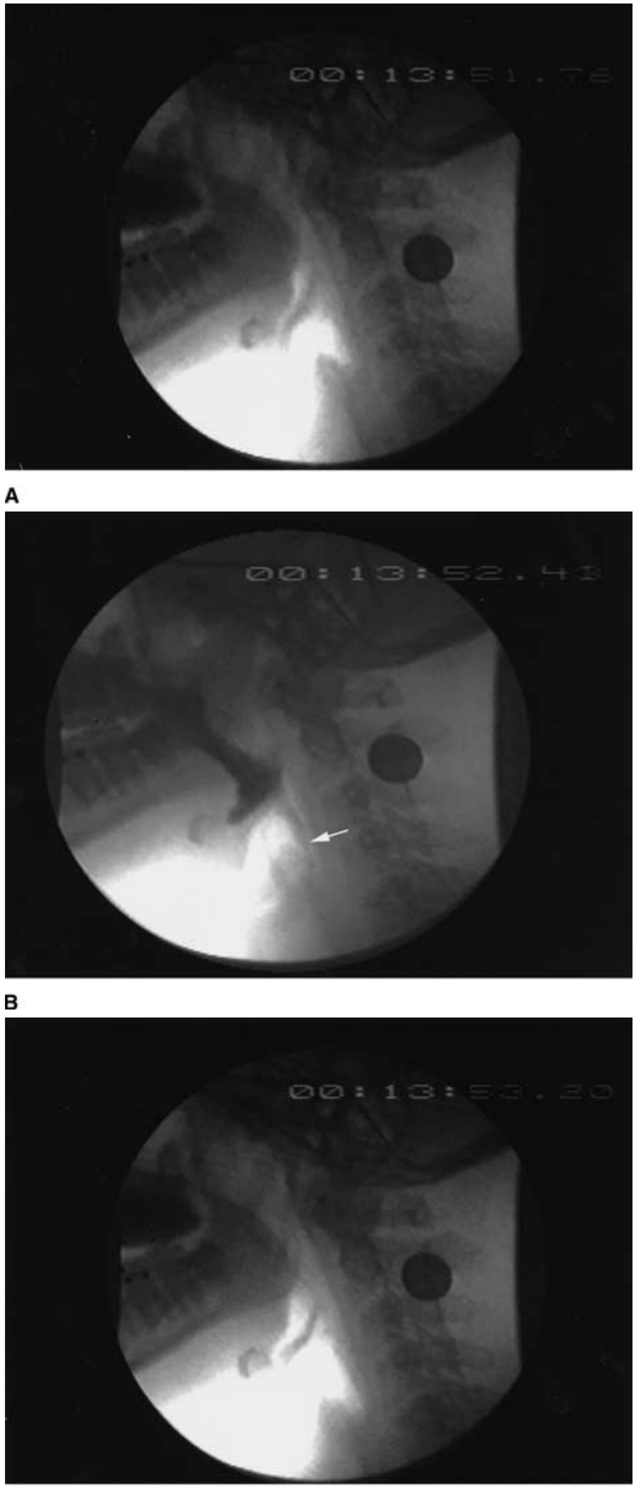
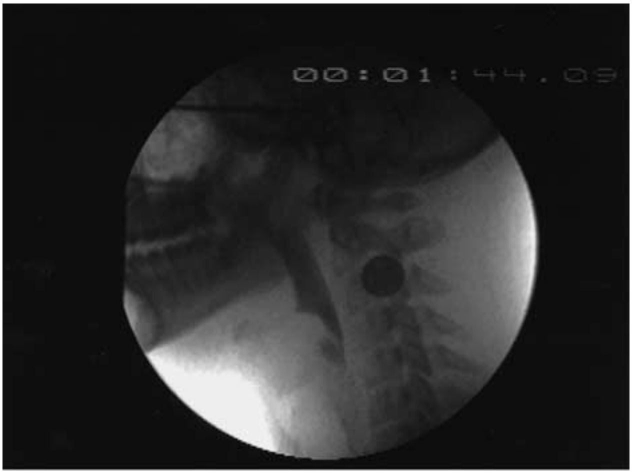
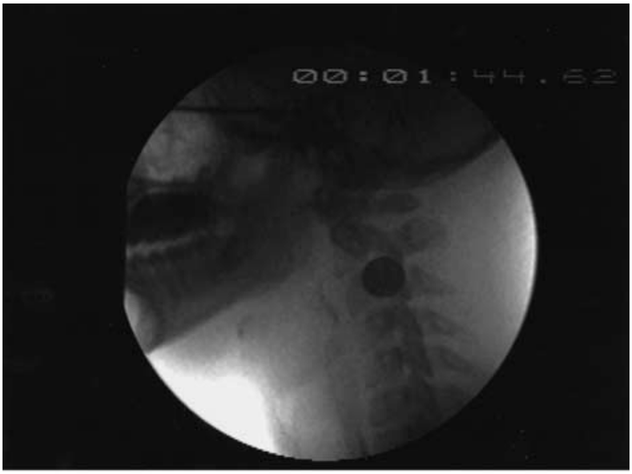


Fig. 1. Type I hyolaryngeal complex movement pattern. **A** During the 10-s swallow sequence. A bolus of barium is in the oral cavity with the epiglottis upright and the laryngeal vestibule opened. **B** Onset of the pharyngeal swallow. The leading bolus edge (arrow) is inferior to the valleculae with continued opening of the laryngeal vestibule. The contrast in the hypopharynx is less dense than in the valleculae. **C** After the swallow. The next bolus of barium is in the oral cavity with return of the epiglottis to upright and opening of the laryngeal vestibule.

A



B



C

Fig. 2. Type II hyolaryngeal movement pattern. **A** During the 10-s sequence. A bolus of barium is in the oral cavity with the epiglottis maintaining its inverted position and closure of the laryngeal vestibule. **B** Onset of the pharyngeal swallow. The leading bolus edge is in the hypopharynx with continued closure of the airway entrance. **C** After the swallow. The next barium bolus is in the oral cavity with continued epiglottic inversion and closure of the laryngeal vestibule.

glottis to upright and opening of the laryngeal vestibule after each swallow. In Type I swallows, the leading edge of the bolus was randomly distributed among the three designated anatomical locations: 41/184 (22%) superior to the valleculae, 57/184 (31%) at the level of the valleculae, 86/184 (47%) inferior to the valleculae. A total of 121 swallows demonstrated a Type II pattern, indicating that there was maintenance of epiglottic inversion and laryngeal vestibule closure after each swallow during the 10-s period. For this swallowing pattern, the leading bolus edge was consistently inferior to the valleculae (113/121, 93%). Only 1/121 swallows had the leading edge superior to the valleculae and 7/121 had the leading bolus edge at the level of the valleculae (Table 2).

Another interesting observation was that in our sample of healthy young adults, preswallow pharyngeal bolus accumulation was intermittently observed during sequential straw drinking. It was identified in 8 of the 15 subjects (53%). Occurrences of bolus aggregation averaged 15% of the total swallows in 7 of the 8 subjects; however, in one subject, preswallow pharyngeal accumulation occurred in 48% of the swallows. Bolus aggregation was characterized by two or more episodes of oral filling in which the first bolus was volitionally propelled into the pharynx while the oral cavity was reloading with the second bolus. The pharyngeal swallow was subsequently evoked following the second or sometimes multiple reloading and transfer processes. Bolus aggregation was significantly

Table 1. Effect of hyolaryngeal complex (HLC) movement pattern on bolus intake[a]

HLC pattern	Total volume swallowed (mL)	Number of swallows	Voume per swallow (mL)
Type I	91.56 ± 30.35	9.56 ± 1.76	9.70 ± 2.99
Type II	124.37 ± 57.02	11.63 ± 2.69	11.55 ± 7.12
Mixed	166.67 ± 73.92	10.67 ± 1.44	16.41 ± 9.36

[a]Values are means ± SD.

Table 2. Relationship of location of leading bolus edge at swallow onset and hyolaryngeal complex (HLC) movement pattern

	Bolus location[a]		
HLC pattern	Superior	Valleculae	Inferior
Type I	22%	31%	47%
Type II	1%	6%	93%

[a]Superior-rostral to the valleculae; valleculae-at the level of the valleculae; inferior-caudal to the valleculae.

associated with the Type I HLC movement pattern ($\chi^2(1) = 13.73$, $p < 0.01$). Aspiration, defined as entry of barium inferior to the level of the true vocal folds, was not observed on any swallow in the sample of healthy young adults.

Discussion

In this investigation we sought to delineate specific parameters of deglutition with continuous straw swallowing. The purpose of this study stems from the fact that most normative data are derived from the study of discrete swallowing, and it may be that continuous swallows differ from discrete swallows. In turn, normative data on discrete swallows have been used to explain biomechanical and physiological features of deglutition during typical food and liquid consumption. The results of this study, however, suggest that in healthy young adults sequential swallowing differs physiologically from swallowing of isolated boluses.

The average bolus volume during sequential straw drinking was variable but averaged 12 mL per swallow with an average of one swallow per second. Based on a single ingestion from a cup, the average volume per swallow was determined as 21 mL [14], which is significantly higher than the volume we identified for continuous straw swallowing. This difference may be related to the method of ingestion—cup vs. straw—as well as to the nature of the ingestion—continuous vs. discrete. However, we noted a wide range of average volumes, 4–26 mL per swallow in our cohort, suggesting that other factors may influence average bolus volume. While we did not measure subject weight and height, these factors may impact average bolus volume. It may be that body size is directly related to volume swallowed, with larger subjects swallowing greater volumes than smaller subjects. Future studies may want to investigate the effect of height and weight on volume intake. If a relationship does indeed exist, individualizing maximum volumes administered during dynamic examination may facilitate clinical accuracy. Anderhill et al. [14] also reported differences based on gender related to volume ingested, with males averaging volumes of 25 mL and females averaging 20 mL per single swallow. Our sample was limited to healthy young males, but future studies may want to examine gender differences in sequential swallowing.

Three distinct patterns of hyolaryngeal movement during sequential straw swallowing were identified, indicating substantial variability in deglutitive biomechanics: (1) opening of the laryngeal vestibule after each swallow (Type I), (2) maintenance of laryngeal vestibule closure after each swallow (Type II), and (3) variable opening and closing of the laryngeal vestibule during the swallow sequence (mixed type). These findings are provocative in that they indicate a greater degree in biomechanical variability than previously suggested. These data differ from previous research which identified prolongation of laryngeal excursion to be a primary biomechanical component during sequential straw drinking [15]. Although variability was evident in our study, consistent prolongation of HLC excursion was noted in 4 of the 15 subjects (27%). However, the majority of our subjects (8 of 15, 53%) demonstrated a pattern of lowering of the HLC complex with laryngeal vestibule opening after each swallow during the 10-s sequence. Martin et al. [15] identified prolongation of laryngeal elevation with extended duration of apnea in most subjects during consecutive straw drinking; however, respiration during the sequence was identified in some subjects. Duration of apnea was strongly associated with duration of laryngeal excursion. While we did not measure respiratory events, results suggest that apnea was maintained through the 10-s sequence in that the number of swallows, the volume swallowed, and the volume per swallow were similar among groups. No interruptions in intake and transfer of the liquid were observed for any subject. Further research elucidating the effects of HLC movement patterns on respiration during sequential swallowing is warranted.

During consecutive straw drinking, the leading edge of the bolus was generally in the distal pharynx at onset of maximum hyolaryngeal excursion; these results differ from our *a priori* hypothesis in which we indicated that the bolus would be in the proximal pharynx at swallow onset. While research of discrete swallows has revealed that the pharyngeal swallow is typically evoked between the anterior faucial arches and the ramus of the mandible, studies of mastication as well as consecutive cup drinking have indicated that inducement of the pharyngeal swallow may be caudal to the ramus of the mandible. Dua et al. [11] noted the leading edge of the bolus to be in the pharynx at swallow onset in 60% of the liquid swallows generated from gum chewing and 76% of the triturated swallows. Moreover, over half of these boluses for each consistency dwelled in the valleculae prior to onset of the pharyngeal swallow, with only a small percentage (liquid 11%, solid 2%) located in the pyriform sinuses at swallow onset. Dwell time proved to be significantly shorter when the bolus contacted the epiglottic edge compared with the valleculae and pyriform sinuses. Palmer and colleagues [8–10] have noted similar results during mastication in which parts of the bolus were in the proximal pharynx at onset of the pharyngeal swallow. In support of the above studies, we found the leading edge of the bolus to be caudal to the ramus of the mandible in the majority of sequential straw swallows. Regardless of HLC movement pattern, the majority of swallows (86%) were elicited when the leading bolus edge was inferior to the mandibular angle. Moreover, our results extend these findings to suggest that the hypopharynx may be a crucial trigger point in elicitation of the pharyngeal swallow in sequential straw drinking. Between-subject analysis revealed that the majority of the cohort consistently demonstrated evocation of the pharyngeal swallow when the leading bolus edge was inferior to the valleculae, and analysis of individual swallows further confirmed these findings. Research in experimental animals has identified numerous pharyngeal and laryngeal fluid receptor sites for evocation of the pharyngeal swallow [16,17]. When bypassing the oral stage of swallowing and slowly infusing liquids directly into the valleculae of humans, Pouderoux et al. [1] identified no occurrence of the pharyngeal swallow when the bolus was contained in the valleculae. The pharyngeal swallow was induced only when the bolus reached the pyriform sinuses. As the oral stage was bypassed, the authors hypothesized that the hypopharynx was a prime stimulus location for elicitation of protective swallows. Our data expand these results and suggest that the hypopharynx may be a prime stimulus location for the evocation of sequential alimentary swallows. Furthermore, these data further support the notion that multiple receptor sites within the oropharynx must be stimulated in order to achieve the threshold necessary to evoke a pharyngeal swallow [for review, see 18].

Location of the leading bolus edge at swallow onset appears to be strongly related to hyolaryngeal movement pattern. When the supraglottic region remained closed with continuation of epiglottic inversion after each swallow during the sequence, the leading edge of the bolus was in the hypopharynx in over 90% of the swallows upon initiation of maximum hyolaryngeal excursion. Even though the bolus was in the distal pharynx, risk of aspiration appeared to be small as the airway entrance was closed; indeed, no subjects demonstrating this HLC movement pattern aspirated. Receptor field variability was observed in the swallows where the laryngeal region opened and the epiglottis returned to upright after each swallow during the 10-s sequence. In these swallows, the bolus was randomly located in the pharynx at swallow onset. Based on conventional clinical wisdom and previous hypothesis [6], it would seem that risk of aspiration would be increased when the bolus dwelled in the hypopharynx while the entrance to the airway was opened. However, this was not the case in our study in which aspiration was also not evident for the Type I swallows. It must be emphasized that the cohort consisted of healthy young adult men with presumably intact sensory and motor pathways for deglutition. Nevertheless, HLC movement pattern and leading bolus edge at swallow onset may have an impact on deglutitive safety with aging or disease and warrants further study.

An unexpected finding was the presence of preswallow pharyngeal accumulation of the bolus during sequential straw drinking. Furthermore, this bolus aggregation was significantly related to swallows in which laryngeal vestibule closure was not maintained after each swallow. This is not unlike stage II transport observed with mastication in which subjects transferred the triturated bolus into the pharynx while continuing to chew the remainder of the bolus with subsequent elicitation of the pharyngeal swallow [8–10]. However, unlike mastication in which pharyngeal aggregation occurs during oral processing of the solid bolus, there was no oral processing and segmentation of the liquid bolus. Furthermore, the liquid bolus generally aggregated in the pyriform sinuses, not in the valleculae. Similar to stage II transport, preswallow pharyngeal accumulation was achieved by volitional lingual propulsion of the bolus into the pharynx and not by premature pharyngeal spillage or sucking of the bolus directly into the pharynx. Following propulsion of the liquid into the pharynx, the oral chamber resumed a filling mode with subsequent triggering of the pharyngeal swallow. In general, only one bolus aggregated in the hypopharynx prior to swallow onset; however, in one subject, four episodes of oral filling and emptying occurred prior to onset of the pharyngeal swallow.

These data indicate considerable flexibility in the oropharyngeal swallowing mechanism. Results indicate that concepts of "normal" deglutitive physiology need to be broadened, particularly with respect to ingestive pattern. This is crucial in order to prevent misclassification of normal swallowing physiology as pathological and initiation of inappropriate therapeutic or dietary management.

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