Temporal coordination of pharyngeal and laryngeal dynamics with breathing during swallowing: single liquid swallows

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Harris, Bonnie Martin, Martin B. Brodsky, Christina Clare Price, Yvonne Michel, and Bobby Walters. Temporal coordination of pharyngeal and laryngeal dynamics with breathing during swallowing: single liquid swallows. J Appl Physiol 94: 1735–1743, 2003. First published December 27, 2002; 10.1152/japplphysiol.00806.2002.—The critical integration of timing and patterning between respiratory and swallowing events was studied with simultaneous videofluoroscopic and respiratory recording during single liquid swallows. Respiratory phase patterns and the onsets and durations of 12 predetermined swallowing events and associated respiratory activities were studied. Results showed four highly repeatable, temporally oriented sequences (clusters) of swallowing and related respiratory events. Two respiratory phase patterns were identified without statistically significant differences in frequency of occurrence between age, gender, or race. These findings will aid in the identification of normal and abnormal patterns of breathing and swallowing in patients with dysphagia.

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The TEMPORAL COORDINATION of pharyngeal and laryngeal swallowing events with breathing is essential to the prevention of pulmonary aspiration, to adequate nutrition and hydration, and to overall human survival. However, studies are lacking that define the temporal coordination of bolus passage, pharyngeal and laryngeal events and movements, and respiration.

Normative data regarding the temporal coordination of structural movements involved in oral, pharyngeal, laryngeal, and cervical esophageal swallowing have been reported in adults from studies that used combined videoradiographic and manometric pressure recordings (1, 3, 6, 7, 11, 16, 28, 35). However, the critical integration of timing and patterning of the respiratory activity surrounding these structural swallowing movements is not known. It is well established that the larynx is tightly sealed through intrinsic and extrinsic valving during deglutition to prevent entry of food, liquid, or saliva into the respiratory tract (11, 14). Whereas the pharyngoesophageal segment (PES), the cricopharyngeal region of the cervical esophagus, is tonically contracted during breathing to prevent ingestion of air into the esophagus and stomach, it becomes compliant during the pharyngeal swallow, allowing itself to be pulled open to accommodate bolus flow (1, 3, 6, 7, 16, 35). Clearly, the discontinuation of breathing during the swallow, or swallow apnea, must occur during these swallowing events to prevent pulmonary aspiration of ingested materials. The timing and duration of respiratory cessation with laryngeal closure and PES opening during deglutition remain unknown.

Previous studies that have examined the coordination between breathing and swallowing used indirect measures because instrumentation allowing simultaneous study of breathing patterns, bolus flow, and movements of relevant structures during swallowing has not been readily available. Examples include surface electromyography or other physiological tracings (4, 5, 9, 17, 21, 25, 26, 31, 34). Although the indirect measures of swallowing are generally less invasive and permit the acquisition of greater numbers of swallowing samples, their clinical utility is suspect without simultaneous direct visual confirmation of the swallowing mechanics occurring with respiratory activity. A few studies tried to observe swallowing mechanics, either fluoroscopically or endoscopically, while making simultaneous respiratory activity measures (10, 13, 20, 22–24, 32, 33). Respiratory phase patterns surrounding the swallow and airflow patterns during the swallow were reported (10, 13, 20, 22–24, 32, 33). However, the instrumentation used in these studies was assembled in and unique to a particular laboratory, which resulted in methods that have not been applied to large numbers of subjects and blurred their clinical applicability and practicality.

\[ \text{deglutition; larynx; pharynx; respiration; dysphagia} \]
A pilot investigation demonstrated that visualization and measurement of respiratory airflow activity and videofluoroscopic swallowing signals can be synchronized and measured reliably by using commercially available equipment (15). This simplification of respiratory-swallow recording could prove clinically useful if the physiological relevance of recordings were demonstrated through establishment of normative patterns. Deviations from these normal patterns may be a sign of pathology with potential aspiration threat. Furthermore, treatment strategies on the basis of these data may be developed in an attempt to improve observed abnormal patterns and minimize the risks of aspiration, malnutrition, and dehydration. The present study is part of a larger investigation examining normal breathing and swallowing patterns across an aging continuum from young to elderly adults (19).

This study was designed to define the temporal patterns (timing and sequencing) of 12 pharyngeal and laryngeal swallowing events with associated respiratory activity (15). The primary hypothesis was that predictable, temporally oriented sequences of respiratory, oral, pharyngeal, and laryngeal events and groupings (i.e., clusters) of these respiratory-swallowing activities are identifiable in young and middle-aged healthy adults during isolated liquid swallows. The following specific aims were addressed to test this hypothesis: 1) determine the respiratory phases associated with single liquid swallows; 2) identify differences in the respiratory phases by age, gender, and race; 3) distinguish groups of temporally related swallowing and respiratory events; 4) determine differences in temporal clusters of respiratory and swallowing events by age, gender, and race; and 5) establish the duration of apnea and differences in duration of apnea by age, gender, and race.

METHODS

Participants. Human volunteers were used for this study. The study protocol was submitted for full review and approved by the Institutional Review Board at Medical University of South Carolina. Written, informed consent was obtained from each study participant. Twenty-eight healthy adults grouped into two age categories were studied. Group 1 consisted of 14 participants (7 men, 7 women; 9 Caucasian, 5 non-Caucasian) between the ages of 21 and 40 yr [mean = 29; standard deviation (SD) = 4.7]. Volunteers in group 2 included 14 participants (7 men, 7 women; 7 Caucasian, 7 non-Caucasian) between 41 and 60 yr of age (mean = 48; SD = 5.5). Volunteers with histories significant for upper aerodigestive tract disorders or surgery, pulmonary disease, cancers of the head and neck, neurological disease, present medications with known effects on swallowing or breathing, or tobacco use during the past 10 yr were excluded from this study. No subjects were excluded who met these screening criteria.

Instrumentation. A high-resolution, dual-modality videofluoroscopic and airflow recording device was used for signal acquisition and digital storage and retrieval of respiratory and swallowing data (Digital Swallowing Workstation, model 7100, Kay Elemetrics, Lincoln Park, NJ). Nasal respiratory flow was captured by using a standard, 7-ft. nasal cannula coupled to the Workstation by using the Swallow Signals Lab hardware and software to create a digital display of the respiratory phase and apnea duration. The nasal cannula was calibrated between each subject to ensure accurate measures. Airflow direction was shown on the respiratory display with a green positive trace representing expiration and a red negative trace representing inspiration. As shown in Fig. 1, the black respiratory trace along the abscissa was defined as the apneic period (15). The sampling rate for the respiratory tracing was 250 Hz. This is an acceptable sampling rate for detecting breathing that occurs on average of 10–12 times/min in adults (30). Videofluoroscopic recordings were made with a resolution of 60 fields (30 frames) per second. The

Fig. 1. Example of simultaneous videofluoroscopy (A) and respiratory trace data (B) as seen on the Kay Digital Swallowing Workstation (model 7100, Kay Elemetrics, Lincoln Park, NJ). The green portion of the tracing represents expiration and the red portion represents inspiration. The black portion of the line along the abscissa indicates no air movement or apnea.
resolution for determining measurements with digital video recordings, therefore, is \( \approx 17 \) ms per digital field.

Simultaneous videofluoroscopy and respiratory airflow recording were conducted in a standard fluoroscopic suite. With tight coning of the X-ray beam, radiation was minimized by limiting exposure to the superior structures of the aerodigestive tract (e.g., oral cavity, pharynx, larynx, and cervical esophagus). Participants were positioned in the lateral viewing plane while standing and self-administered two trials of 5-ml liquid swallows of barium sulfate contrast solution per graded medicine cup. The liquid contrast material was the manufacturer preparation (liquid barosepsre barium sulfate suspension, catalog no. 179364, Lafayette Pharmaceuticals, Anaheim, CA) to ensure controlled viscosity between test subjects. A conservative volume was chosen to simulate a safe average bolus size typically administered to dysphagic patients during a videofluoroscopic examination. Participants were instructed to drink the liquid in their usual manner. No instructions regarding timing or manner of swallowing were given because the investigators’ aim was to analyze natural swallowing behavior. The fluoroscope was activated during the self administration of the contrast material into the oral cavity and remained activated until the bolus tail entered the esophagus through the PES. Radiation exposure times were \( \leq 1 \) min for all participants.

**Data analysis.** Data were recorded for single-bolus, 5-ml liquid swallows during two sequential trials for each of the 28 participants. The phase of respiration (expiration or inspiration) interrupted by the swallow and resumed during the late stage of the pharyngeal swallow was recorded to determine respiratory phase patterns. Twelve swallow events were selected for analysis based on preliminary studies showing their potential relevance to functional swallowing and breathing coordination (1, 3, 6, 7, 11, 13, 14–16, 28, 35). The measurements were made from the dual-modality digital display in milliseconds by using the digital video recorder’s slow-motion and freeze-frame capabilities. Based on a previous study (15), an acceptable error rate was established as 2 video frames or 34 ms. The onset times of the following 12 swallow events were calculated from their onset times. Therefore, difference testing of the durations, in addition to the onset event times and durations, were used to test differences between age, gender, and racial groups for onsets and durations. Independent \( t \)-tests were used to test for differences in respiratory and swallowing events were made by the PI to determine intraobserver agreement.

The onset of oral bolus transport was established as the point from which the remaining 11 events were referenced in time \( t_0 \). This event was established as \( t_0 \) because of its stability in the temporal order of events and because of its known relationship to the onset of the oral phase of swallowing activity. The lengths of time between each of these 12 swallow events were also measured and thus labeled as durations. Tables 2 and 3 provide the calculations used for the event onset times and durations.

**Statistical analysis.** Wilcoxon’s signed rank test (for related samples) was used to test for differences in respiratory phase pattern between trials for the 28 participants. Fisher’s exact tests (for independent samples) were used to test for differences in respiratory phase pattern between age, gender, and racial groups.

The distributions of onset times and durations were found to be approximately normal, i.e., unimodal with no outliers, extreme values, or marked skewness. Accordingly, means and SD were calculated for the onset times and durations. Paired \( t \)-tests were used to test for differences in event onsets and durations for each of the two trials. Independent \( t \)-tests were used to test differences between age, gender, and racial groups for onsets and durations. Durations between swallowing events were calculated from their onset times. Therefore, difference testing of the durations, in addition to the onset times, provided no new information and consequently was not conducted. Eleven independent \( t \)-tests to determine statistically significant differences in onset times were conducted for each dichotomous independent variable (age group, gender, and race). Statistical significance was set at \( \alpha = 0.05 \). With the use of the Bonferroni correction to maintain an experimentwise error rate of 0.05, \( \alpha \) was divided equally among the 11 difference tests performed, ultimately

<table>
<thead>
<tr>
<th>Table 2. Calculations for respiratory and swallowing onset times</th>
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<tr>
<td>Onset oral bolus transport ( (t_0) ) to apnea onset</td>
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<tr>
<td>Onset oral bolus transport to onset hyoid excursion</td>
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<tr>
<td>Onset oral bolus transport to onset laryngeal closure</td>
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<tr>
<td>Onset oral bolus transport to maximum laryngeal closure</td>
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<tr>
<td>Onset oral bolus transport to onset PES opening</td>
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<tr>
<td>Onset oral bolus transport to maximum hyoid excursion</td>
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<td>Onset oral bolus transport to swallow inspiration</td>
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<tr>
<td>Onset oral bolus transport to last PES opening</td>
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<tr>
<td>Onset oral bolus transport to onset laryngeal opening</td>
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<tr>
<td>Onset oral bolus transport to apnea offset</td>
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<td>Onset oral bolus transport to hyoid return to rest</td>
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<th>Table 3. Calculations for respiratory and swallowing durations</th>
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<td>Onset oral bolus transport ( (t_0) ) to apnea onset</td>
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<td>Apnea onset to onset hyoid excursion</td>
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<td>Onset hyoid excursion to onset laryngeal closure</td>
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<td>Onset laryngeal closure to maximum laryngeal closure</td>
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<td>Maximum laryngeal closure to onset PES opening</td>
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<tr>
<td>Onset PES opening to maximum hyoid excursion</td>
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<tr>
<td>Maximum hyoid excursion to swallow inspiration</td>
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<tr>
<td>Swallow inspiration to last PES opening</td>
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<td>Onset PES opening to onset laryngeal opening</td>
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<td>Last PES opening to apnea offset</td>
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<td>Apnea offset to hyoid return to rest</td>
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PES, pharyngoesophageal segment.
Table 4. Means and grand means for the onsets of 12 swallowing events

<table>
<thead>
<tr>
<th>Event</th>
<th>OBT</th>
<th>Aon</th>
<th>HE</th>
<th>LC</th>
<th>Lcmax</th>
<th>PESo</th>
<th>HEmax</th>
<th>LO</th>
<th>SI</th>
<th>Aoff</th>
<th>PESlast</th>
<th>HRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st 5-ml Swallow</td>
<td>-700</td>
<td>327</td>
<td>393</td>
<td>591</td>
<td>611</td>
<td>668</td>
<td>1,053</td>
<td>1,092</td>
<td>1,129</td>
<td>1,181</td>
<td>1,254</td>
<td></td>
</tr>
<tr>
<td>2nd 5-ml Swallow</td>
<td>-579</td>
<td>674</td>
<td>715</td>
<td>538</td>
<td>521</td>
<td>596</td>
<td>917</td>
<td>926</td>
<td>1,121</td>
<td>1,116</td>
<td>1,192</td>
<td></td>
</tr>
<tr>
<td>Grand mean</td>
<td>-639</td>
<td>500</td>
<td>554</td>
<td>564</td>
<td>566</td>
<td>641</td>
<td>985</td>
<td>1,020</td>
<td>1,125</td>
<td>1,148</td>
<td>1,223</td>
<td></td>
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<tr>
<td>SD</td>
<td>1,540</td>
<td>945</td>
<td>961</td>
<td>320</td>
<td>313</td>
<td>299</td>
<td>220</td>
<td>318</td>
<td>351</td>
<td>351</td>
<td>281</td>
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</table>

All measurements are made in ms. First and second 5-ml swallows are based on 28 subjects, whereas the grand means and grand standard deviations (SD) are based on the average of the 2 swallows from the 28 subjects. Negative numbers indicate events occurring before oral bolus transport. OBT, onset oral bolus transport; Aon, onset apnea; HE, onset hyoid excursion; LC, onset laryngeal closure; Lcmax, onset maximum laryngeal closure; PESo, onset PES opening; HEmax, onset maximum hyoid excursion; LO, onset laryngeal opening; SI, onset "swallow inspiration"; Aoff, apnea offset; PESlast, onset last PES opening; HRR, onset hyoid return to rest.

RESULTS

Respiratory phase. Two respiratory phase patterns were identified across subjects for each 5-ml swallow. The first and predominant pattern was expiration interrupted by swallow-associated apnea followed by expiration occurring in the late stage of pharyngeal swallow activity (Ex/Ex). This pattern was observed in 79% of the swallows for trial 1 and in 82% of the swallows for trial 2. The second and less frequently observed pattern was inspiration interrupted by swallow-associated apnea followed by expiration occurring in the late stage of the pharyngeal swallow (In/Ex). This pattern characterized only 21% of the 5-ml swallows for trial 1 and 18% of the trial 2 swallows. No significant differences in the distribution of respiratory phase patterns were found between trials, age, gender, or racial groups (P > 0.05).

A negative-direction airflow phenomenon, i.e., "swallow inspiration," was observed throughout this study and occurred nearly synchronously, typically within 36 ms (SD = 226 ms; range = -1,024–1,376 ms) of the reestablishment of the airway during laryngeal descent. As the hyolaryngeal complex moved inferiorly and began to reopen, this negative airflow phenomenon was observed in 43 of the 56 (77%) swallows containing 5 ml of barium sulfate.

Onset times. No statistically significant differences (P > 0.004) were found in the mean onset times of swallowing events between the two 5-ml bolus trials. Therefore, data for onset times and durations were averaged across trials. Tables 4 and 5 display the means and SD for the onset times and durations, respectively. No significant differences in onset times were detected between age, gender, or racial groups (P > 0.004 for each comparison).

Temporal clusters. The mean onsets for swallowing and respiratory events across all subjects and both 5-ml bolus trials were calculated. Intrarater reliability on repeat analysis of 10% of these measures was 1.0. That is, repeat measures always fell within two video frames (i.e., 34 ms) of the initial measurement.

A timeline was created by using these mean onset times relative to t0 (see Fig. 2). On average, the entire respiratory swallow sequence lasted 1,862 ms (SD = 1,624 ms; range = 660–7,700 ms) with the onset of apnea typically occurring 639 ms (SD = 1,540 ms) before the onset of oral bolus transport. There was marked variability for apnea onset time as illustrated in the large range and SD. The remainder of the swallow sequence, beginning with the onset of oral bolus transport, occurred within an average of 1,223 ms (SD = 281 ms; range = 734–2,124 ms).

All 12 of the respiratory and swallowing events were temporally ordered, depicting four distinct groups of events, or clusters. Differences in time of >90 ms between any 2 of the 12 events marked the offset of one cluster and the beginning of the next. For example, maximum hyoid excursion occurred at an average of 643 ms and laryngeal opening took place at an average of 985 ms for each subject, a difference of 342 ms. Because the separation in time between laryngeal opening and swallow inspiration was only 35 ms on average, the next two event onsets separated in time by at least 90 ms were swallow inspiration at 1,020 ms and apnea offset at 1,125 ms, a difference of 105 ms. Therefore, the cluster defined as the events of laryn-
geal opening and swallow inspiration emerged. With the use of these criteria, the separation between events defining a cluster is almost three times greater than any measurement error occurring during analysis (i.e., 2 video fields equivalent to 34 ms), and four distinguishable clusters of swallowing and respiratory activity were identified (Figs. 3 and 4): 1) apnea onset; 2) onset hyoid, onset laryngeal closure, maximal laryngeal closure, onset PES opening, maximum hyoid excursion; 3) onset laryngeal opening, swallow inspiration; and 4) apnea offset, last PES opening, hyoid return to rest.

Apnea duration. Average apnea duration for the 5-ml cup drinking tasks was calculated at 1,764 ms.
There were no differences in the mean apnea duration by trial ($t_{(27)} = 0.445; P = 0.660$). Outliers resulted in a large SD; however, 75% of all subjects had an apneic duration of only 1 s. The average apnea duration was highly skewed and did not fit a normal distribution for this SD and mean (Fig. 5). Mann-Whitney tests did not reveal any significant differences in apnea duration by age ($U = 71.5; P = 0.227$), gender ($U = 64.5; P = 0.125$), or race ($U = 95.0; P = 0.928$).

**DISCUSSION**

The present investigation studied the respiratory patterns and temporal relationships between pharyngeal and laryngeal swallowing events and associated swallow apnea in healthy young and middle-aged adults during natural cup drinking of small volumes of liquid. Consistent with our previous experience in a pilot investigation using the same recording technology (15), an intimate relationship between the expiratory phase of respiration and pharyngeal-laryngeal swallowing dynamics was found. The majority of study participants (79% in trial 1 and 82% in trial 2) initiated swallow activity during the expiratory limb of the respiratory cycle. Swallowing was shown to be associated with complete cessation of respiration followed typically by a brief expiration. Several subjects deviated from this pattern (6 in the first trial, 5 in the second trial). They were observed to initiate swallowing activity during the inspiratory limb of respiration. The proportion of swallows initiated during inspiration throughout this study is greater than that reported in our initial work (13). A likely explanation for the variability in the phase of respiration interrupted by a swallow may be that a cup drinking task, by nature, lends itself to greater variability in habituated pattern of drinking compared with the unnatural syringe administration of liquid that was employed in our laboratory’s initial studies (12, 13). Still, commensurate with these previous findings, expiration leading to swallow apnea continues to be the preferred pattern by normal healthy volunteers in the young and middle-aged categories. The prevalence of expiration with initial swallow activity, suggesting a close relationship between the two, may be explained by the fact that exhalatory posturing of the larynx assumes a slightly adducted arytenoid-vocal fold position that affords a protective setpoint for further laryngeal closure as the swallow progresses (12).

Whereas there was a split between the expiratory and inspiratory phase of respiration as swallowing was initiated, albeit with expiration prevailing, all of the...
5-ml swallows were completed during the expiratory phase of respiration. This highly repeatable and exclusive finding was presented in our early work (13) and in studies by others using similar methodologies (4, 10, 22). The characteristic respiratory tracing depicting the majority of swallows in this study (Ex/Ex) is seen in Fig. 1. Other investigators (5) have shown greater variability in the phase of respiration associated with late swallow activity and relate the differences to the greater number of swallows sampled and larger bolus volumes studied with indirect methodologies such as electromyography. Because the present study was directed toward visualization of structural swallowing movements and known airway protection mechanisms simultaneously with respiratory activity, multiple samples were not feasible because of the radiation limitations posed by the videofluoroscopic method. Furthermore, a primary purpose of this study was directed toward the development of normative patterns of swallowing during a sequential swallowing task. Through the use of observations made simultaneously by using VFS and respiratory tracing, measurement of the onset of key swallowing components associated with swallow activity by age, gender, or race. One study (32) demonstrated an age impact on the phases of respiration associated with swallowing, but their experiments included elderly individuals over the age of 70 yr. The present study, however, included only young and middle-aged healthy adults, although it is part of a larger investigation examining respiratory and swallowing dynamics beginning with young adults and continuing across the life span into later life. It will be interesting to determine whether old age does indeed have an impact on the respiratory phases of deglutition.

The unique contribution of the work in our laboratory and reported in this manuscript is the simultaneous examination of respiratory and airway protective mechanisms of the larynx, pharynx, and cervical esophagus with integrated respiratory activity with user-friendly, readily available clinical equipment. This was accomplished by recording the onsets of respiratory swallowing activity, i.e., the apneic interval, and known events that contribute to airway protection and bolus propulsion during swallowing. The initial recorded event in the temporal swallow sequence was the onset of swallow-induced apnea. In contrast to our laboratory’s earlier work using videoendoscopy, which obscured the oral dynamics of swallow (12, 13), we were able to clearly demonstrate the timing of apnea onset relative to the onset of swallow signaled by the onset of oral bolus transport on lateral VFS. Additionally, we noted that several participants initiated swallow apnea long before the onset of oral bolus transport and during the interval of loading the liquid from the cup into the oral cavity. This accounts for the longer apneic interval recorded during the natural delivery of liquid compared with syringe swallows seen in our previous studies. The average apneic period of nearly 2 s was found to be almost twice that recorded in our previous report. This variability should not be surprising given the potential for differences in habitual patterns of drinking from person to person. Despite the longer average apneic interval related to intraoral loading by some subjects, the majority of participants assumed an apneic duration of only 1 s. Consistent with other reports (5), there was no statistically significant difference in respiratory phase pattern between genders or race associated with swallowing across trials. Also, no statistically significant differences were found in the duration of apnea between the two age groups, gender, and racial groups. Some laboratories, using indirect measures of swallowing physiology and respiratory traces, have observed longer apneic durations when comparing young and middle-age subjects with elderly volunteers and gender differences with aging (5, 31). Hiss et al. (5) suggested that the longer apnea durations in elderly adults may be related to the reported slowed swallowing mechanics occurring as a natural component of healthy aging (18, 27, 29, 30, 36). Our ongoing project should be able to confirm this hypothesis as we study simultaneous swallowing mechanisms by using VFS with simultaneous respiratory tracings.

Improved technologies have permitted us the opportunity to observe two anatomically and physiologically symbiotic and remarkable events: breathing and swallowing. Through the use of observations made simultaneously by using VFS and respiratory tracing, measurement of the onset of key swallowing components known to be critical for airway protection and bolus clearance during oropharyngeal and cervical esophageal swallowing may be temporally outlined relative to respiration. Two trials, each containing 5 ml of liquid,
were studied to determine differences of durations between 12 swallowing events for age, gender, and race. Because there was concern that learning a task may have been a factor with temporal information, the impact of trial on the onset and duration measures was examined. No statistically significant differences were found in the onset times and durations of swallowing events between trials, indicating that subjects tended to repeat the order of breathing and swallowing events from trial 1 to trial 2. On the basis of this finding, the data were collapsed across trials and averaged.

Observations summarized in Table 2 and depicted in Figs. 2–4 show the leading event in the swallow as the onset oral bolus transport occurring, on average, ~600 ms after the onset of apnea. The start of movement of the oral bolus was followed by a mean of 500 ms later with the onset of hyolaryngeal excursion. Our data support the literature by suggesting that because the hyoid and larynx work as a functional unit toward laryngeal closure and PES opening during the swallow (1, 3, 6, 7, 11, 14, 16, 28, 35), laryngeal and hyoid motion were not separated. The onset of laryngeal closure occurred shortly after the initial displacement of the hyoid and averaged 54 ms. Maximal closure of the laryngeal inlet was reached within 10 ms1 of the onset of closure and nearly synchronously with the onset of PES opening. Maximal excursion of the hyolaryngeal complex was achieved within an average of 78 ms of the onset of PES opening. These temporal data are consistent with the swallowing physiology literature when considering what is known about the contribution of hyolaryngeal excursion to laryngeal closure and opening of the PES during a safe and efficient liquid swallow (1, 3, 6, 7, 11, 14, 16, 28, 35, 36).

Examination of the data illustrated in Fig. 2 reveals that swallow apnea is maintained during this sequence, not permitting the exchange of respiratory airflow into or from the closed laryngeal compartment. Bolus passage continued through the pharynx after maximal displacement of the hyolaryngeal complex during the average 242-ms period before the onset of reestablishing laryngeal opening. Just after the onset of laryngeal opening during the later stages of pharyngeal swallowing, a brief “inspiratory spike” was seen in the respiratory trace (Fig. 2). This inspiratory spike has been described in observations by others (4, 10, 12, 13). This highly replicable finding was observed in our study by using videendoscopy (12, 13); however, its relationship to swallowing dynamics was obscured because of the white-out artifact of the endoscopic technique that occurs at the height of the swallow and during early laryngeal descent. A slight negative pressure repeatedly was been shown to be associated with maximal hyolaryngeal excursion and PES opening (3, 6, 7, 16, 35), but the time interval between these events and this inspiratory spike (shown in Fig. 1; a mean duration of over 400 ms) far exceeds any hint at a functional relationship. Paydarfar et al. (22) also noted this inspiratory spike phenomenon and provided insight into its physiological association. They appropriately described this event as a “brief . . . interval of ‘inspiratory’ airflow at the end of the zero flow interval, corresponding to a small lung volume” (p. 281). These investigators also utilized simultaneous VFS with respiratory recording; however, the instrumentation was unique to their particular laboratory. They also included simultaneous manometric pharyngeal recordings. Using their technology, they observed that the inward inspiratory spike was a nonrespiratory phenomenon and occurred because of a momentary reversal of positive pharyngeal pressure to a slight negative pressure with the offset of pharyngeal contraction (13). Although the functional significance of this airflow event remains unknown, it does appear to be an inherent component of single bolus liquid swallows. There may also be a contribution of pressure changes within the larynx with the reopening of this tightly sealed chamber on the basis of the near synchrony, i.e., two video frames, of the negative spike and initial opening of the larynx as seen in our study.

Consistent with our previous finding using endoscopy was that apnea offset occurred in the later stages of pharyngeal swallowing as opposed to occurring as a postswallow phenomenon. The resumption of respiration occurred an average of 86 ms earlier than final descent of the hyolaryngeal complex. That is, most participants produced a short expiration as the larynx was descending and reopening. The airway protective significance of this integration of expiration may be that the positive exhalatory pressure facilitates expulsion of any potentially misdirected liquid from the laryngeal vestibule into the pharynx for safe swallowing (12, 13, 21). Apnea offset with the resumption of expiration occurred nearly coincidently with final collapse of the PES, i.e., last PES opening. The last event observed in the oropharyngeal/cervical esophageal swallow for this study was the return of the hyoid to its resting position, inherently signaling that the participant had completed the ingestion task.

The outcomes presented in this study are particularly relevant for not only how clinicians regard variability in their understanding of swallowing in the nonimpaired general population across the life span, but also how this affects their clinical judgment when confronted with a patient who has a swallowing disorder. Demonstrated here, and previously (8, 30, 36), is the temporal variability of the onset of swallowing events. Consistent with these studies, our findings also show considerable variance in onset times for each of the respiratory-related and swallowing events. However, the clustering of events did not differ across subjects. The temporal clusters in this study defined themselves by grouping the swallowing events together such that the time between any two events with an average of >90 ms (>5 video fields) created an onset and an offset to the cluster. Because the accuracy of recording these data points has been found to be two

1 Although resolution of video fields is 17 ms, the 10 ms here is the result of averaging timings across subjects for each of the events and then computing the duration between the onset of laryngeal closure and maximum laryngeal closure.
video fields between trained observers (15), documentation of clustering of events may represent a more realistic and functionally meaningful alternative in clinical practice. We may find that the predictable clustering of respiratory-swallowing events seen in young and middle-aged adults will differ from those observed in older adults based on known changes that occur in swallowing with healthy aging (8, 18, 27, 29, 30, 36). Different clusters of respiratory and swallow activity may be classified as typical in old and very old subjects in attempts to distinguish swallowing disorders from normal age-related changes. We believe that this dual-modality recording of respiratory and swallowing dynamics will prove clinically feasible and useful in the detection of abnormal breathing and swallowing patterns that may lead to potential airway threat, significant nutritional compromise, and pulmonary morbidity.

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REFERENCES