ORIGINAL ARTICLE

Breathing and Swallowing Dynamics Across the Adult Lifespan

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Background: Aberrations in the physiologic components of normal oropharyngeal swallowing have been linked to aspiration events and to predisposition to aspiration pneumonia, a common, deadly disease in elderly persons. Studies have demonstrated a temporal, physiologic link between breathing and the principal physiologic swallowing components involved in airway protection during swallowing. We developed a normative model of integrated breathing and swallowing patterns using concomitant videofluoroscopic images and nasal respiratory airflow recordings.

Objectives: To establish normative temporal and respiratory-phase pattern relationships between breathing and swallowing in adult human beings across the aging continuum; to relate any alterations in these patterns to swallowing abnormality, an aspiration event during swallowing, and predisposition to aspiration pneumonia; and to develop clinically practical evaluation methods for identifying breathing and swallowing discoordination.

Setting: Fluoroscopy suite in an acute care hospital.

Participants: Eighty-two healthy adult volunteers gave informed consent. All eligible healthy volunteers were welcome and were screened for age, race, and sex for equal distribution of each.

Intervention: Respiratory-phase patterns and the onset and duration of 11 predetermined swallowing events and associated respiratory activities were studied. All participants' single-liquid barium swallow examinations were studied with simultaneous videofluoroscopy and respiratory recordings.

Main Outcome Measures: Onset of each of the 11 predetermined breathing and swallowing events was digitally recorded and analyzed. The phases of breathing before and after swallowing were identified. The presence, depth, and response to airway penetration were recorded and related to respiratory pattern.

Results: Four respiratory-phase patterns were identified that changed with advanced age. The correlation analyses of the temporal breathing and swallowing events revealed a normal pattern of 4 clearly distinguishable functional units. Differences in apnea duration and apnea offset occurred with advanced age.

Conclusion: This research provides evidence for clearly distinguishable patterns and functional groupings of breathing and swallowing events, a necessary first step toward determining whether abnormal breathing and swallowing patterns in patients with dysphagia are associated with health outcome.

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DISORDERED OROPHARYNGEAL swallowing, or dysphagia, has been implicated as a potential cause of aspiration of ingested foods and liquids, leading to pulmonary contamination, infection, and death.[1-6] The incidence of aspiration pneumonia, an infectious disease frequently associated with disordered swallowing and with high morbidity, mortality, and cost, has reached epidemic proportions in the United States.[7-9] Further, the incidence of dysphagia[10-13] and pneumonia[1,2,7,9,10,14,15] rises sharply with advanced age. As the population ages, by 2010 an estimated 16.5 million persons will require treatment of dysphagia.[16,17] The pharynx is the common conduit for gasses during breathing and for food and drink during swallowing, yet it has been only just more than a decade that researchers have truly explored the coordination of breathing and swallowing.

Breathing and swallowing are physiologically linked to ensure effortless gas exchange during oronasal breathing and to prevent aspiration during swallowing.[18-38] The contribution of discoordinated breathing and swallowing to the occurrence of aspiration pneumonia in patients with dysphagia remains unknown. This lack of information has in part been owing to limitations in technology. Emerging technology makes the synchronous recording of breathing and swallowing possible, reliable, and clinically practical, leading to the establishment of normative data regarding this patterned coordination.[19] Because alterations in pulmonary defenses[10,39,40] and changes in the speed and efficiency of swallowing[11,41-46] occur with healthy aging, this establishment of normal breathing and swallowing patterns is critical to understanding the contribution of its aberrations to aspiration and to the development of aspiration pneumonia.

The modified barium swallow (MBS) examination, a videofluoroscopic procedure for assessing oropharyngeal swallowing, is the predominant method of oropharyngeal swallowing assessment. The MBS examination is used by the swallowing examination team, typically including the attending physician; consulting specialty physician, such as an otolaryngologist, neurologist, pulmonologist, or gastroenterologist; speech-language pathologist; and radiologist.[47-51] Normative temporal swallowing measures have been established for the MBS examination in healthy young and elderly adults. These norms have been used to determine abnormal swallowing and to identify patients who are predisposed to aspiration pneumonia.[42,47-61] An aspiration event can occur at 3 points during the oropharyngeal swallow (before, during, or after), because of temporal or biomechanical disruptions to the critical and physiologically complex components involved in swallowing.[47,48,50] Evidence suggests that patients with dysphagia have a greater than 7-fold chance of acquiring aspiration pneumonia if they are found to aspirate during an MBS examination. Worse yet, in those patients who aspirate thickened liquids or semisolids, the odds of death are increased by greater than 9-fold.[62]

Results of preliminary studies, using equipment uniquely fabricated for individual clinical laboratories, indicate the existence of a potential critical temporal integration between breathing and oropharyngeal swallowing activity at videofluoroscopic examination.[36-38] In contrast with these studies, we applied new technology, using commercially available MBS equipment that permitted the synchronous recording and analysis of breathing and swallowing during videofluoroscopic imaging, to establish normative data for breathing and swallowing patterns across the aging continuum.

METHODS

PARTICIPANTS

The study protocol was submitted for full review and was approved by the institutional review board at the Medical University of South Carolina, Charleston. Human volunteers were used for the study, and written informed consent was obtained. Medical and surgical history and medications were obtained by means of patient interview and written survey. Volunteers with a history of upper aerodigestive tract surgical procedures, including oral, nasal, pharyngeal (including uvulopalatopharyngoplasty), laryngeal, and esophageal resections, were excluded from study participation. Exclusion criteria also included a known history of swallowing disorders, dysphagia, hiatal hernia, chronic indigestion, gastroesophageal reflux disease, pulmonary disease, cancer of the head and neck, neurologic disease, current medications with known effects on swallowing or breathing, or tobacco use during the past 10 years. Patients were included if they had a history of tonsillectomy, adenoidectomy, or sinus surgery. All participants were eating solid foods and drinking liquids as part of a regular diet and had no swallowing complaints. Age, race, and sex were obtained as part of the questionnaire to discern any differences that might have occurred because of these factors.

INSTRUMENTATION

All MBS examinations were recorded on a digital, synchronous dual-modality, video recording device with high temporal resolution (Digital Swallowing Workstation Model 7200; Kay Elemetrics Corporation, Lincoln Park, NJ). The fluoroscopic unit (Philips Medical Systems, Hamburg, Germany) was equipped with a 1024-line video system. Nasal respiratory flow was captured by using a standard 7-ft nasal cannula coupled to the digital, synchronous dual-modality, video recording device with high temporal resolution using Swallow Signals Lab Model 7120 (Kay Elemetrics Corporation) hardware and software to create a digital display of the respiratory phase and the swallow apnea duration, operationally defined as the period of nasal airflow cessation. The nasal cannula was calibrated immediately prior to the study of each participant.

The sampling rate for the respiratory tracing was 250 Hz. This was considered an acceptable sampling rate for detecting breathing, which occurs on average 10 to 12 times per minute in adults. Videofluoroscopic recordings were made with a temporal resolution of 60 video fields (30 video frames) per second (16.67 ms per digital field). Testing was conducted in a standard fluoroscopy suite. Coning of the x-ray beam limited radiation exposure to the superior structures of the aerodigestive tract. The field of view was delimited by the lips anteriorly, nasal cavity superiorly, posterior pharyngeal wall posteriorly, and pharyngoesophageal segment (PES) inferiorly (eg, C5 and C6).[48,49] Participants were positioned in the lateral viewing plane while standing, and self-administered 2 trials of 5-mL liquid boluses of barium sulfate contrast solution (Liquid Barosperse Barium Sulfate Suspension, catalog No. 179364; Lafayette Pharmaceuticals, Lafayette, Ind) per graded medicine cup. This conservative volume was chosen to simulate a safe bolus dose typically administered in patients with dysphagia during a videofluoroscopic examination. Volunteers were instructed to "drink the liquid in their usual manner." No instructions (eg, changes in timing, manner of swallowing) were given, because the investigators' aim was to analyze natural liquid swallowing behavior. The fluoroscope was activated during 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 1 minute or less for all participants.

DATA ANALYSIS

The phases of respiration (inspiration, expiration), interrupted by the swallow and resumed during the late stage of the pharyngeal swallow, were recorded to determine respiratory-phase pattern. Airflow direction was shown by the polarity of the trace on the respiratory display. Expiration was represented by positive polarity and inspiration by negative polarity. A plateau in the respiratory signal along the abscissa indicated the apneic period (**Figure 1**). The onset of 11 breathing-swallowing events was selected for analysis based on preliminary studies showing their potential relevance to functional swallowing and breathing coordination.[19,20,28] These 11 events were apnea onset, oral bolus transport, laryngeal closure, hyoid excursion, PES opening, maximum laryngeal closure, maximum hyoid excursion, laryngeal opening, last PES opening, apnea offset (APOff), and hyoid return to rest, operationally defined in **Table 1**. The measurements were made from the digital display in milliseconds using the digital video recorder's slow motion and freeze-frame capabilities. An acceptable error rate was established as 2 video fields or 33.2 ms.[19] The onset time of these 11 swallowing events was recorded and analyzed for mean time of occur-

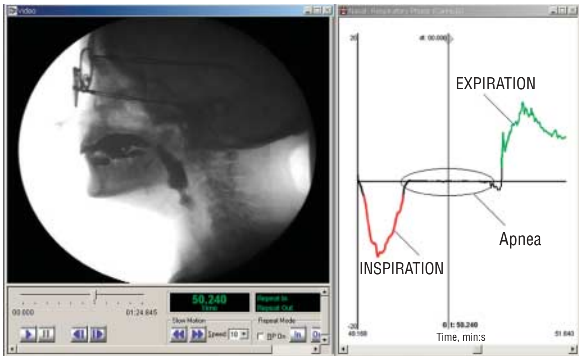

Figure 1. Detailed respiratory tracing.

Table 1. Operational Definitions for Bolus Flow Measures and Physiologic Components of Swallowing

Component	Operational Definition
Oral bolus transport	Posterior movement of bolus tail via superoposterior tongue movement (defined at time 0 [t_0], from which all other measures were calculated)
Apnea onset	Plateau in respiratory trace along abscissa
Bolus position at posterior angle of ramus of mandible	Bolus head arrival at posterior angle of ramus of mandible
Hyoid excursion	Superior and anterior movement of hyoid bone
Laryngeal closure	Forward displacement of arytenoid cartilages to epiglottic petiole
Maximum laryngeal closure	Maximum contact of arytenoid cartilages to epiglottic petiole
Pharyngoesophageal segment opening	Forward displacement of cricoid cartilage from posterior pharyngeal wall
Maximum hyoid excursion	Highest and most forward movement of hyoid bone
Last pharyngoesophageal segment opening	Last point in time when pharyngoesophageal segment is open
First laryngeal opening	Separation of arytenoid cartilages from epiglottic petiole
Apnea offset	Departure from plateau in respiratory trace along abscissa in positive or negative direction
Hyoid return to rest	Point at which hyoid has moved (from its most superior and anterior position) to stable, relaxed position

rence and resulting temporal order. The first video frame for each swallow event was operationally defined as its onset. The onset of oral bolus transport was established as the point from which the remaining 10 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 its known relationship to the onset of the oral swallowing.[18,19] The presence of airway penetration (ie, entry of contrast material into the laryngeal vestibule) and aspiration (entry of contrast material below the level of the true vocal folds) were also recorded for each swallow, using the standardized penetration-aspiration scale (PA scale).[47,48,60,61] The PA scale is an 8-point multidimensional indicator of airway invasion that describes whether the airway is invaded; if so, to what level relative to the vocal folds; the participant's response to the airway invasion; and whether the invasive material is ejected from the airway (**Table 2**).

Table 2. Scoring system for Penetration-Aspiration Scale

Category	Score	Description
Penetration		
	1	Contrast does not enter airway
	2	Contrast enters airway, remains above vocal folds, no residue
	3	Contrast remains above vocal folds, visible residue remains
	4	Contrast contacts vocal folds, no residue
	5	Contrast contacts vocal folds, visible residue remains
Aspiration		
	6	Contrast passes through glottis, no subglottic residue visible
	7	Contrast passes through glottis, visible subglottic residue despite patient response
	8	Contrast passes through glottis, visible subglottic residue, no patient response

STATISTICAL ANALYSES

The sign test was used to test for a trial effect on respiratory-phase pattern. Differences in the temporal measures between trials were examined with matched *t* tests adjusted for multiple comparisons. The Fisher exact test was used to test for differences in respiratory phase by sex and racial groups. Independent sample *t* tests were used to determine whether respiratory phase varied by mean age. The Fisher exact test was used to test for differences in PA scale scores between respiratory-phase patterns. Differences in apnea duration among sex and racial groups were analyzed with the Mann-Whitney test, because of the presence of outliers in the apnea duration measure. Regression analysis was used to estimate the variance in apnea duration explained by age. Correlation coefficients were calculated to determine the relationships between the 11 temporal measures and to define the functional units that composed the oropharyngeal liquid swallows.

RESULTS

DEMOGRAPHICS

The final analyses included 76 subjects. Volunteers were instructed to avoid extraneous head and body movement (with the exception of habitual tilting of the head backward when loading the mouth from the cup) and to drink the liquid in their usual manner. Volunteers who were unable to accurately follow test instructions (n=2) and those with temporal measures that indicated extreme outliers (n=4) were excluded from the analyses. These exclusions were individually investigated. The 2 subjects who did not follow the instructions moved their head and body position with each swallow and limited the visual field for accurate analysis. Four subjects initiated apnea onset or apnea offset more than 3 SDs above the mean value for the entire sample, indicating that these represented atypical subjects. These subjects who held their breath longer were possibly swallowing atypically

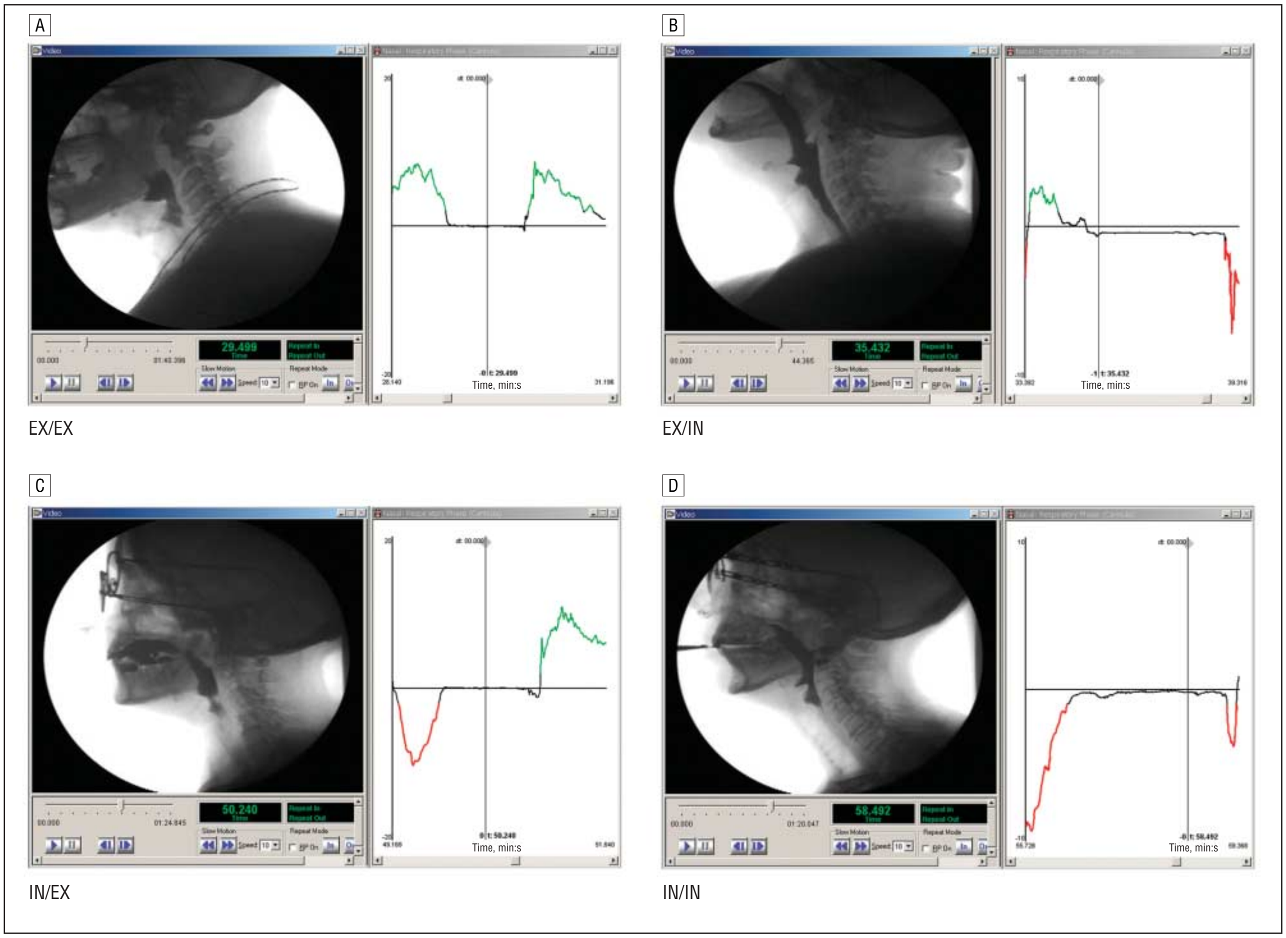

Figure 2. Four respiratory-phase patterns during swallowing. EX/EX indicates expiration/expiration (A); EX/IN, expiration/inspiration (B); IN/EX, inspiration/expiration (C); and IN/IN, inspiration/inspiration (D).

under the laboratory conditions. In this sample size, these extreme outliers inflated the estimates of central tendency and variance that would have biased the results.

RESPIRATORY PHASE

Four respiratory-phase patterns were identified (**Figure 2**): expiration/expiration (EX/EX), expiration/inspiration (EX/IN), inspiration/expiration (IN/EX), and inspiration/inspiration (IN/IN). Most participants (trial 1, 71%; trial 2, 75%) produced the EX/EX pattern, followed by IN/EX as the second, but much less frequent, pattern (trial 1, 22%; trial 2, 18%). The EX/IN pattern was produced by 4 participants (5%) in trial 1 and 3 participants (4%) in trial 2. The least frequent pattern was IN/IN, produced by only 1 participant (1%) in the first trial and 2 participants (3%) in the second trial. The cells were collapsed for the age, sex, and race analyses to either the predominant EX/EX pattern or a new category created as "Not EX/EX," because of the infrequent respiratory patterns. With these new categories of respiratory pattern, no significant differences in respiratory-phase pattern by trial were identified ($P = .69$). Further, significant differences were not found in respiratory pattern by sex (trial 1, $P = .57$; trial 2, $P = .14$) or racial group (trial 1, $P = .23$; trial 2, $P = .21$). Given the potential for loss of information by the use of 4 age groupings, each participant's real age replaced the divisions. A significant difference (trial 1, $P = .04$; trial 2, $P = .04$) was found in mean age between respiratory phases. The mean (SD) age for the EX/EX pattern was 56 (23) years and the mean age for the nonpredominant patterns IN/IN and EX/IN was 68 (21) years. The PA scale scores were collapsed into 2 categories based on severity (1-2, normal; 3-8, disordered). Most subjects had a score of either 1 (contrast did not enter the airway) or 2 (contrast entered the airway above the vocal folds, with no residue). No differences in PA scale scores between the respiratory patterns were detected in either trial (trial 1, $P = .65$; trial 2, $P = .25$).

APNEA DURATION

Apnea duration ranged from 0.50 to 10.02 seconds. Outliers were present in the 2 oldest age groups, with extreme outliers at 7.83, 8.45, and 10.02 seconds. The median apnea duration for both trials was 1.00 second. No significant differences ($P > .05$) in apnea duration were found for sex or race.

TEMPORAL COORDINATION OF APNEA AND SWALLOWING PHYSIOLOGY

The correlation analyses showed a well-timed coordination between groups of respiratory and physiologic swallowing events (functional units), with 1 exception, apnea

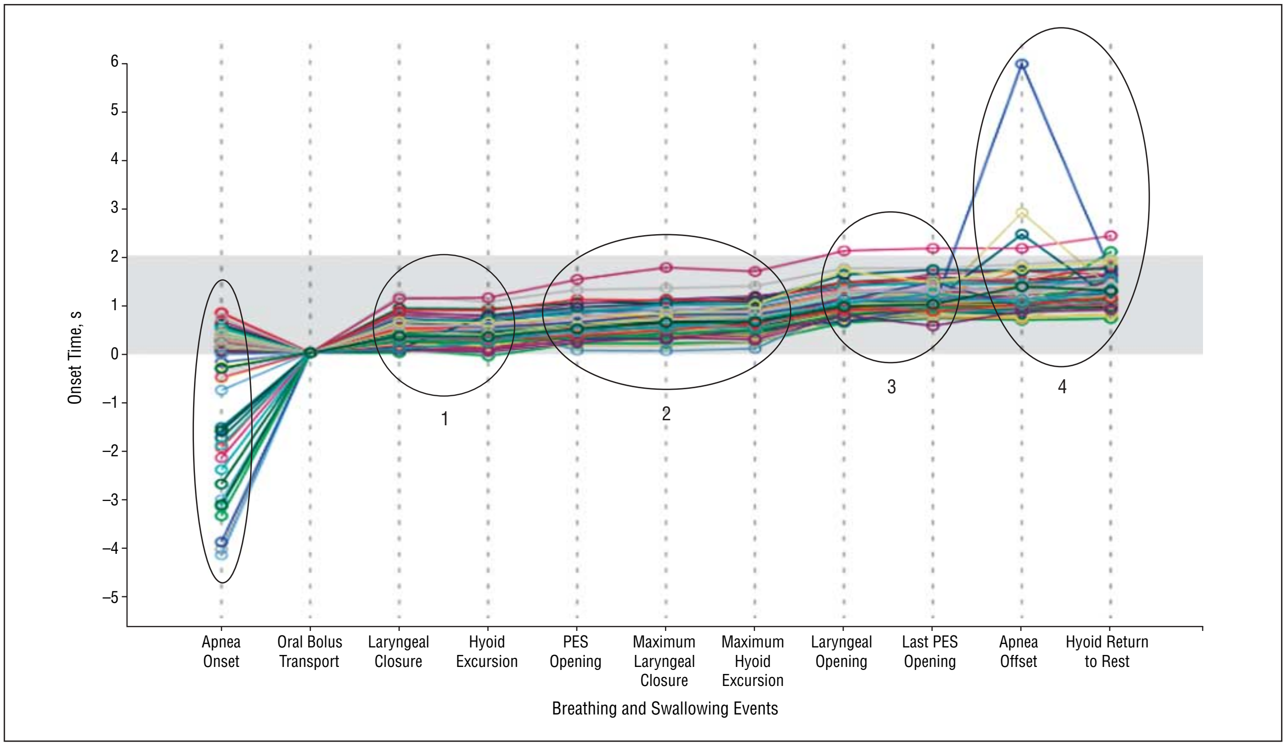

Figure 3. Subjects' onset of temporal respiratory and physiologic swallowing events and related functional units. PES indicates pharyngoesophageal segment.

onset. **Figure 3** shows each temporal data point for all measurements for all subjects. The scatter plots in **Figure 4** illustrate the correlation on which the functional units were based. The swallow and respiratory events, with the exception of apnea onset, typically occurred within 2 seconds. Apnea duration was highly variable, and often began before the onset of swallow (ie, t_0). Most subjects assumed apnea during loading of the liquid material into their mouth. The onset of laryngeal closure and onset of hyoid excursion were strongly correlated (trial 1, $r = 0.66$; trial 2, $r = 0.85$), and formed the first functional unit in the swallow. These closely correlated events always occurred prior to the event that signaled the next functional unit, onset of PES opening. Pharyngoesophageal segment opening showed a strong positive correlation with maximum laryngeal closure (trial 1, $r = 0.80$; trial 2, $r = 0.89$) and maximum hyoid excursion (trial 1, $r = 0.96$; trial 2, $r = 0.92$). These 3 events were grouped based on their strong positive correlations; they all occurred prior to the event that signaled the third function unit, onset of laryngeal opening. Onset of laryngeal opening was highly correlated with last PES closure (trial 1, $r = 0.94$; trial 2, $r = 0.85$). Apnea offset and hyoid return to rest showed a high positive correlation (trial 1, $r = 0.75$; trial 2, $r = 0.71$), with APOff typically occurring before hyoid return to rest. In several subjects, however, the hyoid returned to its rest position before breathing resumed (ie, APOff).

One-way analysis of variance revealed that the time of APOff was significantly later ($P < .01$) in the oldest age group (≥81 years), with a mean (SD) of 1.69 (1.14) seconds compared with a mean of 1.04 (0.24) seconds in the youngest age group (21-40 years). Regression analysis revealed that real age explained 18% ($r = 0.43$) of the variation in APOff time ($P < .001$). Apnea offset accounted for 66% ($\rho = 0.81$; $P < .001$) of the variation in total swallow duration. There was also a tendency for total swallow duration to increase with age. Age accounted for 18% ($\rho = 0.43$; $P < .001$) of the variation in total swallow duration.

COMMENT

The primary objectives of this study were to establish normative respiratory-phase patterns and the temporal coordination of physiologic events related to breathing and swallowing in adult human beings. This study represents a series of clinical investigations distinguishing normal from abnormal breathing and swallowing coordination, ultimately leading to the determination of the relationship between aberrant patterns and an aspiration event or chronic aspiration of ingested foods and liquids in various patient populations.

The EX/EX respiratory pattern was clearly the predominant phase pattern produced by healthy individuals in this cohort during the 5-mL cup drinking task. Differences in the predominant pattern were not found between sex and racial groups. This finding supports our preliminary work and the pilot work[18,19,27] of others who used small numbers of subjects or indirect recording methods,[25-38] and fits with the theory that exhalation is in some way the preferred respiratory phase that brackets oropharyngeal swallowing activity in adults. Though vocal fold motion could not be viewed from the lateral videoradiographs in this study, the expiratory phase of breathing is associated with a paramedian vocal fold position during the early and late stages of the pharyngeal swallow.[27,63] This suggests that the paramedian position of the true vocal folds may somehow facilitate the airway

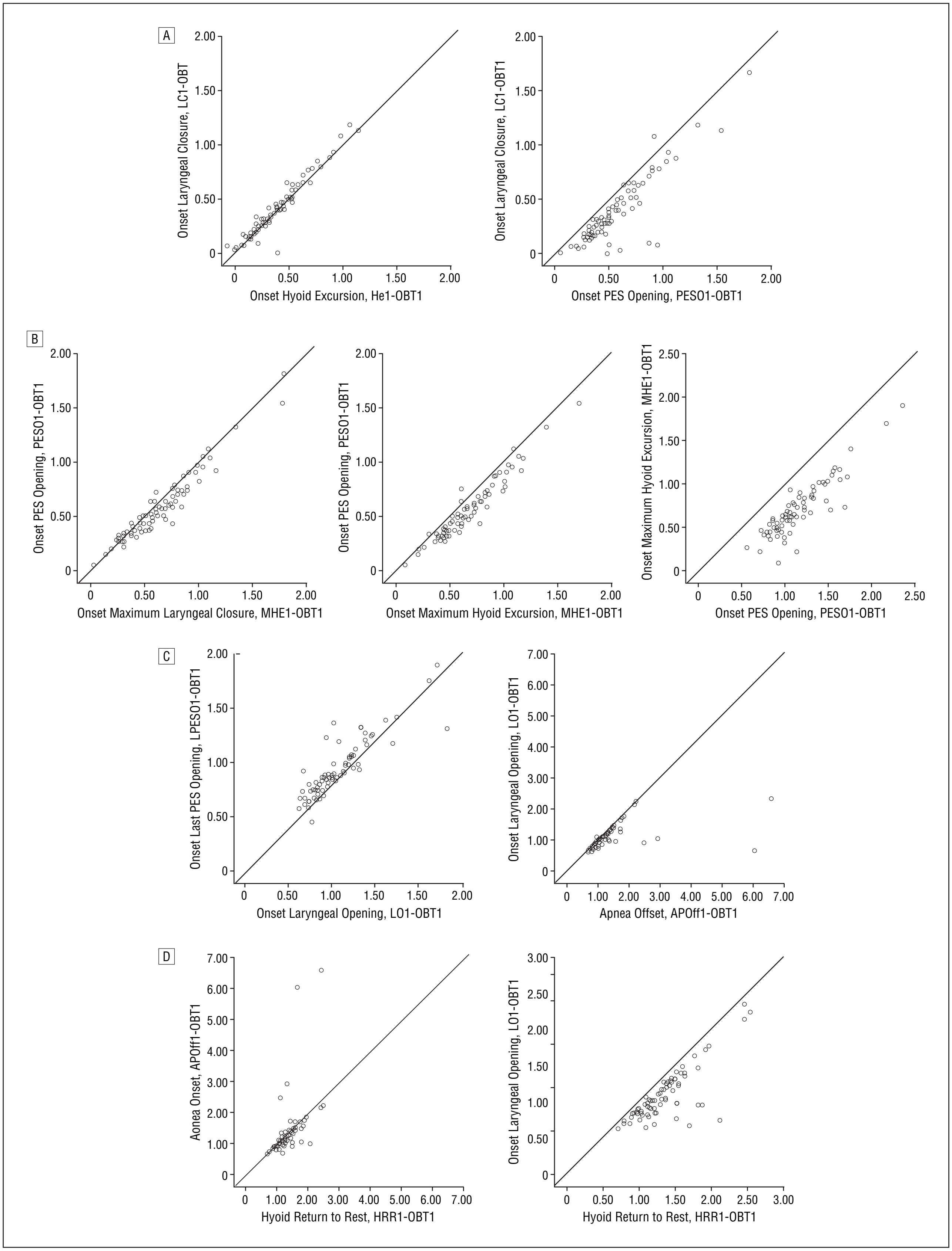

Figure 4. Functional units of temporal respiratory and physiologic swallowing events. APOff indicates apnea offset; APOn, apnea onset; HE, hyoid excursion; HRR, hyoid return to rest; LC, laryngeal closure; LO, laryngeal opening; LPESO, last pharyngoesophageal segment (PES) opening; MHE, maximum HE; MLC, maximum LC; OBT, oral bolus transport; PESO, PES opening; 1, first trial; and 2, second trial. A, Temporal event correlations underlying functional unit 1 (LC–PESO). B, Temporal event correlations underlying functional unit 2 (MHE–LPES). C, Temporal event correlations underlying functional unit 3 (LO–APOff). D, Temporal event correlations underlying functional unit 4 (LO–HRR).

closure that ensues at the level of the laryngeal valves during the pharyngeal swallow. The paramedian posturing of the true vocal folds appears to place the airway in a protective position compared with the abducted vocal fold posturing characteristic of inhalation before or after swallowing.[27,63] Inhalation with an abducted vocal fold position may facilitate entry of portions of the ingested material or saliva into the laryngeal inlet prior to or during the late stages of the pharyngeal swallow. This would be of particular concern in patients with impaired pulmonary defenses, such as suppressed cough or decrease in upper airway sensation.

A shortcoming of the present study is that there is no experimental comparison with the normal sample. Studies are under way to investigate the patterns of breathing and swallowing coordination and the associations of aberrant patterns to aspiration events and aspiration pneumonia in patient populations with known dysphagia, such as those with stroke, progressive neuromuscular disorders, chronic pulmonary disease, or head and neck cancer. Even though most participants in this study did not demonstrate laryngeal penetration or aspiration, findings of current studies in our laboratory indicate disordered breathing and swallowing coordination and a temporal pattern in patients with dysphagia who are receiving treatment of head and neck cancer. The nondominant IN/IN pattern became the dominant pattern, with associated high incidences of aspiration during the MBS examination.[64]

A higher occurrence of inhalation bracketing the swallow was observed in the current study in individuals older than 65 years. Though the healthy individual who demonstrated the nondominant phase pattern did not aspirate during the liquid swallow, the altered age-related pattern may predispose to more severe dysphagia and aspiration in patients with age-related diseases such as stroke or progressive neurologic conditions. We are uncertain of the effect that departures from normal respiratory-phase patterns has on the health outcomes in patients with dysphagia. Given the predictions regarding the increases in age-related diseases known to be related to dysphagia and pneumonia, longitudinal studies are demanded to determine the relationship between abnormal swallowing physiology and respiratory-swallowing discoordination, and morbid health outcomes that threaten the growing frail elderly population, such as malnutrition, aspiration pneumonia, and death.

The onset of swallow apnea, unlike the phase pattern, was highly variable in healthy participants, regardless of age. Many individuals initiated breath holding prior to contact of the cup to the lips or during loading of the liquid into the oral cavity. The variability of apnea onset in young and old healthy subjects may indicate that the time of breath holding initiation prior to swallowing may be a learned trait or habituated response to drinking that is unique to the individual. This finding demonstrates the lack of clinical usefulness in attempting to apply norms to the onset of apnea when a normal pattern does not exist. In contrast to the apnea onset event, the offset of apnea was relatively stable in the young individuals, but occurred significantly later in the oldest cohort (≥81 years). The functional significance of the prolonged apnea offset is uncertain, but may be related to an overall increase in total swallow duration that has been shown in healthy aging adults without dysphagia.[11,41-46]

Our study demonstrated that a brief exhalation typically occurs during descent of the hyoid bone and larynx, with concurrent reestablishment of an open (ie, laryngeal opening) airway. Whereas apnea onset must occur before the onset of the pharyngeal swallow (eg, onset of hyoid excursion and pharyngeal bolus passage to prevent aspiration), breathing during the exhalation phase often resumes prior to completion of the pharyngeal swallow in healthy adults. This finding supports earlier studies indicating that expiratory-related airflow may serve to expel misdirected liquid or particles of food that may enter the upper airway during swallowing.[18,19,25,37]

Disruption in temporal coordination of the critical physiologic components of swallowing, such as superior and anterior movement of the hyoid bone and larynx with consequent closure of the laryngeal vestibule, has been associated with aspiration during the MBS examination.[48-50] This study systematically observed the temporal coordination of the physiologic swallowing events coordinated with the obligatory apneic pause during swallowing. Five groupings of events were found and easily identified from the digitized swallowing recordings (Figure 3). These groupings are based on the high temporal correlation of 1 event with the others constituting a group, and are described as functional units because of their apparent interdependent action in the biomechanics of normal swallowing. The onset of apnea stood alone because of its early, variable, onset time and low correlation with the other respiratory and swallowing events. Thus, the onset of oral bolus transport was defined as t_0 and signaled the onset of swallowing activity. The onset of laryngeal closure and superoinferior hyoid movement are early physiologic events during the pharyngeal swallow.[42,47-49,55,65] It follows that these 2 events were highly correlated and composed the first functional unit. The onset of PES opening, maximal closure of the laryngeal vestibule, and maximal hyoid displacement compose the height of pharyngeal swallowing activity, and formed the second functional unit. These 3 events have a key role in airway protection and bolus propulsion through the pharynx and into the cervical esophagus.[47-59,65] Closure of the PES and reestablishment of an open airway (ie, laryngeal opening) were closely linked, and formed the third functional unit. The resumption of respiration (ie, APOff) and the return of the hyoid to its resting position were closely related in time. These 2 events formed the fourth and final functional unit that described the oropharyngeal swallow. The functional units, based on the intercorrelations of temporal events during liquid swallowing, formed a functional physiologic videoradiographic and animated model of the normal breathing and swallowing process (**Figure 5**). These normal models will be used for comparative use and development of disordered models in patients with disturbed breathing and swallowing coordination.

A pilot investigation demonstrated that visualization and measurement of respiratory activity could be indirectly measured from nasal airflow recordings with the method used in the current experiment.[18,19,27] The nasal airflow signal correlates well with recordings of rib cage and abdominal wall displacement during breathing[18,27] and has become the recommended technique for track-

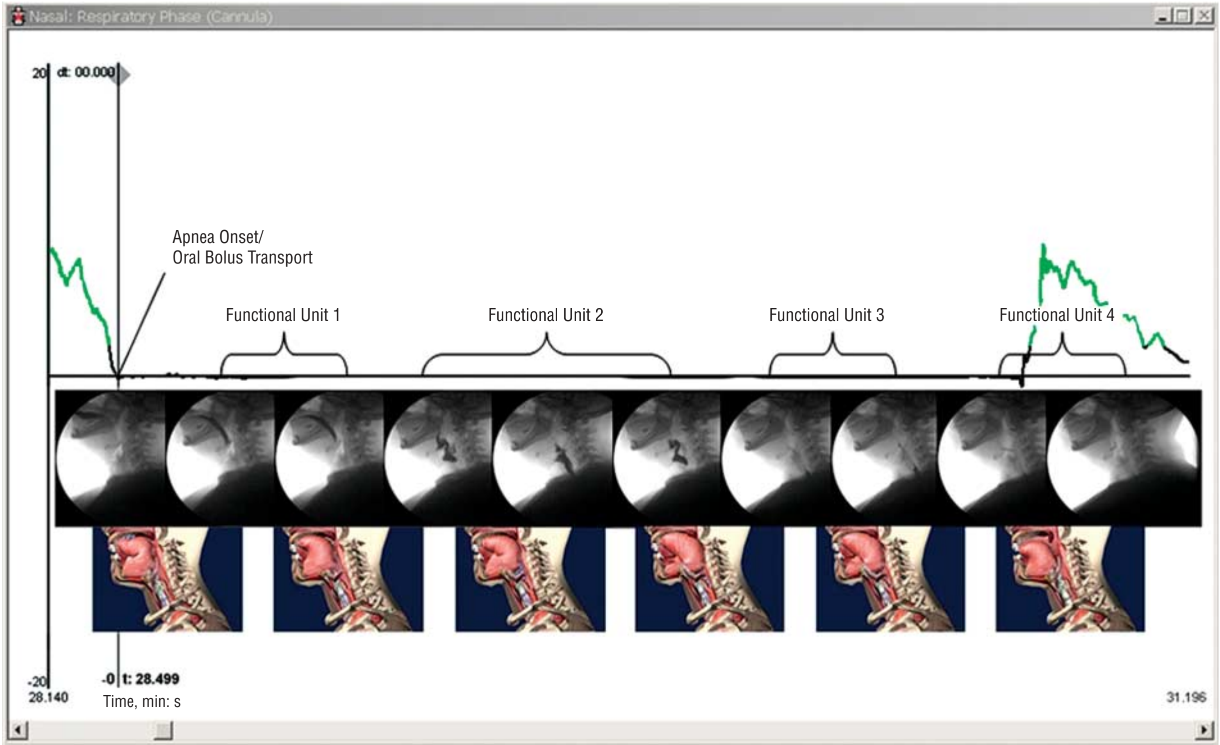

Figure 5. Model of coordination of breathing and swallowing.

ing respiratory-related airflow during swallowing.[66] Further, we found that respiratory activity and videofluoroscopic swallowing signals can be synchronized and measured reliably using commercially available equipment during liquid swallowing.[19] The results of the current study point to the ease and accuracy of using a combined nasal airflow and swallowing recording system that accommodates most fluoroscopy units and suites. The addition of the respiratory swallow analysis would not extend radiation exposure beyond the limits of a typical MBS examination, because the analysis is conducted offline and often after the recording unit is removed from the fluoroscopy suite. The functional units were easily identified during the current study by viewing the combined respiratory and MBS recordings in slow motion and frame-by-frame mode. Departure from these predicted functional units of physiologic events might signal breathing and swallowing abnormalities, offering an even higher clinical yield for routine MBS examinations.[67]

Early detection of swallowing impairment, including breathing and swallowing discoordination that contributes to aspiration in the MBS examination, may lead to prevention of pneumonia or to a cost-effective, expedited swallowing diagnosis and treatment plan. The establishment of a direct link between these abnormal breathing and swallowing patterns with aspiration pneumonia will be a challenge, given the multifaceted nature of aspiration pneumonia, and will require carefully controlled longitudinal investigations of the relationship between breathing and swallowing abnormalities and the occurrence of aspiration pneumonia in like patient populations. The findings of the current study represent an initial step toward this far-reaching objective that has high clinical relevance in our aging population.

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