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Respiratory-swallowing coordination in normal subjects: Lung volume at swallowing initiation

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Abstract

This study was designed to investigate the significance of bolus types and volumes, delivery methods and swallowing instructions on lung volume at swallowing initiation in normal subjects in a single experiment using a multifactorial approach. Our broad range goal was to determine optimal lung volume range associated with swallowing initiation to provide training targets for dysphagic patients with disordered respiratory-swallow coordination. Our hypothesis was that swallows would be initiated within a limited range of quiet breathing lung volumes regardless of bolus volume, consistency or task. Results confirmed this hypothesis and revealed that swallows were initiated at mean lung volume = 244 ml). Cued swallows were initiated at lower quiet breathing volumes than un-cued swallows (cued = 201 ml; un-cued = 367 ml). Water boluses were

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initiated at slightly higher quiet breathing volumes than solids. Data suggest that swallows occur within a restricted range of lung volumes with variation due to instructions, bolus type and other experimental variables.

Keywords

respiration; deglutition; lung volume; respiratory-swallow coordination

1. Introduction

Because breathing and swallowing share a common pathway, they must be precisely coordinated to protect the airway. Despite being crucial to safe and efficient swallowing, we are still lacking some fundamental information regarding normal respiratory-swallow coordination and how this requisite patterning is impacted by disease or injury. Most attention has been directed towards understanding airflow events surrounding the respiratory pause to accommodate the swallowing of liquids, and a consistent pattern has emerged of swallowing bracketed by expiratory airflow (Hiss et al., 2001; Logemann and Logemann, 1983; Martin et al., 1994a; Martin et al., 1994b; Martin-Harris, 2008; Martin-Harris et al., 2005a; Martin-Harris et al., 2003; Martin-Harris et al., 2005b; McFarland et al., 1994; Nilsson et al., 1997; Nishino et al., 1985; Nixon et al., 2008; Paydarfar et al., 1995; Perlman et al., 2005; Preiksaitis and Mills, 1996; Selley et al., 1989). Other labs have looked at the timing of the respiratory inhibition to accommodate swallowing during and after the mastication of solids and have found that swallowing occurs most frequently within the expiratory phase of the breathing cycle and at mid to low quiet breathing lung volumes (McFarland and Lund, 1995; Palmer and Hiimae, 2003; Smith et al., 1989). Taking these data together, we have argued that swallowing bracketed by expiratory flow and at mid to low quiet breathing lung volumes imparts significant mechanical and airway protective benefits centering on the key swallowing functions of laryngeal elevation and associated upper airway closure and the opening of the upper and lower esophageal sphincters (Charbonneau et al., 2005; Martin et al., 1994b; Martin-Harris et al., 2005a; Martin-Harris and McFarland, 2013; McFarland and Lund, 1995). This position is not without some controversy, however, as others have argued that swallowing requires lung volumes above the quiet breathing range (Hegland et al., 2009). We have embarked on clinical trials to optimize respiratory-swallow coordination and improve swallowing function in patients with head and neck cancer (Martin-Harris et al., 2015). These treatments are based on findings that head and neck cancer patients had inconsistent timing of swallowing within the respiratory cycle (Brodsky et al., 2010). The primary experimental objective of the current investigation was to study the potential influence of bolus types and volumes, delivery methods and swallowing instructions on the lung volume at swallowing initiation. These variables represent typical clinical manipulations either during the evaluation of and/or the intervention for swallowing disorders and thus, the potential translational impact of this work on clinical practice is direct (Chi-Fishman and Sonies, 2000; Daniels et al., 2004; Daniels and Foundas, 2001; Daniels et al., 2007; Dodds et al., 1990; Dozier et al., 2006; Lawless et al., 2003; Logemann, 1998; Logemann, 1993; Martin-Harris et al., 2008; Martin-Harris et al., 2003; Martin-Harris and Jones, 2008; Martin-Harris et al., 2000; Nagy et al.,

2013; Preiksaitis et al., 1992). Because of the lack of consensus in the literature of the ideal target volume for swallowing initiation, we focus on this important aspect of respiratory-swallow coordination in normal participants. As such, our experimental findings significantly expand current understanding as this is the first time, to our knowledge, that the impact of these experimental/clinical variables on lung volume at swallowing initiation have been explored in the same experiment and in the same experimental participants. Our working hypothesis was that despite small variations due to experimental tasks, swallows in these normal subjects would be initiated within a very limited range of quiet breathing lung volumes regardless of bolus volume, consistency, delivery method or swallowing instruction.

2. Materials and Methods

2.1 Institutional Review Board

The Medical University of South Carolina (MUSC) Institutional Review Board (IRB) for Human Research approved the study for enrollment at MUSC.

2.2 Participants

Ten male and ten female volunteers (average age = 36 years, range = 26 to 75 years) participated in this study after signing IRB approved consent. Participants were healthy volunteers with no known history of disorders of the masticatory, respiratory, or swallowing systems, medical conditions or medication use affecting swallowing or breathing, previous surgery altering airway passages, neurological disease, pulmonary disorders or smoking.

2.3 Instrumentation

Respiratory movements of the rib cage (RC) and abdomen (AB) were recorded using respiratory inductance plethysmography (RIP) (Inductotrace System, Ambulatory Monitoring, Inc.). The RC band was placed around the rib cage at midsternal level and the AB band was placed around the abdomen below the lowest rib. Nasal airflow was captured using a standard, 7-foot nasal cannula. Surface electromyograms were recorded from the submental muscles using triangular arrays of three, snap on, 10 mm surface electrodes placed 2 cm posterior to the mental symphysis with approximately 2 mm separating the electrodes. All signals were monitored online, sampled at 250 Hz and stored for later analysis using the Swallow Signals Lab™, a peripheral device of the KayPENTAX™ Digital Swallowing Workstation (DSW) (Model 7100, Lincoln Park, NJ).

2.4 Experimental Tasks

Data were collected with participants seated comfortably, facing away from recording equipment, and during a series of swallowing tasks designed to explore the effects of bolus type (liquid, pudding, solid), bolus volume (5 ml, 15 ml, uncontrolled volume), delivery method (cup, syringe, spoon) and cueing (cued, un-cued) on respiratory-swallow coordination. Prior to the swallowing tasks and for later off-line lung volume calibration, RC and AB movements were recorded as subjects (wearing nose clips) exchanged a constant volume (800 ml) of air at resting expiratory level (REL) using Respirace Spirobags (Respirace, Broomfield, CO: Embla®). After that, three trials of each bolus type, bolus volume, delivery method, and cuing (cued, un-cued) were administered. Respiratory

recordings began prior to each swallowing task, and a minimum of three respiratory cycles preceded each of the presentations. Presentation order of the individual consistencies (liquid, pudding, solid) was randomized across participants. The participant was given water from a cup following presentations of pudding and solids to facilitate comfort. Each consistency was presented through a variety of methods consistent with those reported in the current literature (Chi-Fishman and Sonies, 2000; Daniels et al., 2004; Daniels and Foundas, 2001; Daniels et al., 2007; Dodds et al., 1990; Dozier et al., 2006; Lawless et al., 2003; Logemann, 1998; Logemann, 1993; Martin-Harris et al., 2008; Martin-Harris et al., 2003; Martin-Harris and Jones, 2008; Martin-Harris et al., 2000; Nagy et al., 2013; Preiksaitis et al., 1992). Details of the swallowing tasks are presented in Table 1. A Lorna Doone Shortbread Cookie (Mondelez International, Inc) was used for the solid bolus, and a sugar-free vanilla pudding Snack Pack® (ConAgra Foods®, Inc.) was used for the pudding bolus. For the water uncontrolled volume task, a 3 oz clear drinking cup was filled three-fourths full and subjects were instructed drink the whole amount as they would normally. For the solid uncontrolled volume task, the subjects were instructed to take a normal size bite of the Lorna Doone cookie, chew as they would normally and swallow when ready. Liquid and pudding swallows were either cued or un-cued. For the un-cued presentations, the bolus was presented by the experimenter and the subject was left to swallow when they desired. For cued presentations, the experimenter presented the bolus and the subject was instructed to hold the bolus in their mouth and to swallow after prompted by the experimenter who was monitoring respiration and cued swallowing only after respiratory movements had stabilized (typically two or three respiratory cycles after bolus delivery). Subjects, either un-cued or cued, were not prompted to swallow in any particular phase of respiration.

3. Data Analysis

3.1 Lung-Volume Calibration

The method developed by Banzett and colleagues was used to calibrate the summed RC and AB signals to provide an estimate of lung volume (Banzett et al., 1995). A standard ratio (RC to AB) of 2:1 was used to weight the signals (originally recorded at equal gain) prior to being summed. The summed signal (in voltage) was then calibrated using the known volume excursion provided by the Spirobag to provide an estimate of lung volume in ml.

3.2 Swallowing Detection

As illustrated in Fig. 1, three signals were used to detect swallowing. The primary marker was the characteristic flat line in nasal airflow corresponding with respiratory cessation to accommodate swallowing. This was corroborated by increases in submental EMG and an event marker triggered by an investigator who was observing the characteristic laryngeal elevation during swallowing. The beginning of the flat line in the nasal airflow was operationally defined as the “onset” of swallowing.

3.3 Lung volume at swallowing initiation (LVSI)

Data were first imported into an interactive software acquisition and analysis program (Acqknowledge, Biopac System, Inc.). Because swallows are normally superimposed on (and interrupt) the quiet breathing cycle, we expressed the lung volume at swallowing

initiation relative to resting expiratory level (REL) (McFarland et al., 1994). For this, we measured the difference in lung volume between the end of the expiratory phase of the third or second respiratory cycle preceding the cycle containing the swallow. These cycles were selected as reference because 1) in preliminary analyses we found that REL could increase or decrease in lung volume immediately prior to swallowing (see Fig. 1b) and thus LVSI could be either over or under-estimated, and 2) they were representative of the REL of subjects outside of the swallowing tasks. Using this approach, positive values reflect swallows above the reference REL and negative values indicate swallows initiated below the reference REL.

3.4 Statistical Analysis

With LVSI as the outcome variable, separate regression models were run to analyze bolus type, delivery method (5 ml water only), cueing (water only; all delivery methods), and volume (water from cup only). Least square means for LVSI were estimated at each level within each model and the 95% confidence intervals (CI) calculated. To account for the correlation of multiple swallows within individuals, linear mixed-effects models were fit using the restricted maximum likelihood method (REML). Averages were compared across factor levels (cueing, delivery method, volume, bolus) within each model to determine if the differences were statistically significant with level $\alpha = 0.05$. Data analysis was completed using R v3.2.3 (Team, 2015).

4. Results

As illustrated in Fig. 2, swallows could occur in successive respiratory cycles and in some participants, two or multiple swallows could occur in the same respiratory cycle. All subjects had spontaneously occurring swallows. Because respiratory movements are perturbed after swallowing (see Fig. 1), we chose to analyze lung volume at swallowing initiation during the first swallow of all three trials of each experimental task, and consistent with our previous work (Dozier et al., 2006; McFarland and Lund, 1995; McFarland et al., 1994), eliminate successive, repetitive and spontaneous swallows from further analysis. Due to technical errors, lung volume measures are missing (were not recorded) from one subject for the solid pre-measured bite task, and for one subject for the uncontrolled volume cued and un-cued tasks. Mean lung volumes relative to REL at swallowing initiation and 95% confidence intervals (CI) are summarized in Table 2 for each of the experimental tasks.

As can be seen in Table 2, swallows were initiated at mid to low quiet breathing lung volumes relative to REL. Mean lung volume averaged across all experimental tasks was 244 ml. This positions the mean LVSI measured across experimental tasks and subjects at approximately the middle of the quiet breathing lung volume range.

4.1 Cueing

Water swallows averaged across all delivery methods were initiated at lower quiet breathing lung volumes when subjects were cued (mean cued = 201 ml vs. 367 un-cued; $p < 0.001$). Representative data from Subject 1 showing the impact of cueing on 5 ml water spoon LVSI is presented in Fig. 3. The cued LVSI in this figure was 120 ml and the un-cued 480 ml.

4.2 Mode of delivery

5 ml syringe swallows were initiated at significantly lower quiet breathing lung volumes when contrasted with 5 ml spoon presentations (mean syringe = 173 ml vs. 262 ml for spoon; $p = 0.02$). Similarly, average LVSI was significantly lower in 5 ml syringe swallows compared to 5 ml cup swallows (mean cup = 299 ml; $p = 0.001$). However, there was no significant difference in average LVSI comparing 5 ml spoon to cup swallows ($p = 0.33$).

4.3 Bolus Type

Water swallows were initiated at significantly higher quiet breathing lung volumes compared to pudding swallows (mean water = 284 ml vs. 172 ml for pudding; $p < 0.001$). Average LVSI for water swallows was also significantly higher compared to solid swallows (mean solid = 121 ml; $p < 0.001$). However, there was no significant difference in average LVSI between pudding and solid swallows ($p = 0.20$).

4.4 Bolus Volume

The effects of bolus volume was investigated in cup delivery only (5 ml, 15 ml and uncontrolled volume), and no statistically significant differences among bolus volumes were observed ($p = 0.22$).

5. Discussion

The primary goal of the present investigation was to study the potential influence of different bolus types and volumes, delivery methods, and swallowing instructions on lung volume at swallowing initiation (LVSI) in healthy, normal subjects. Mean LVSI across subjects and experimental tasks ranged from 284 ml for liquids to 121 ml for solids. If we consider tidal volume is distributed between approximately 38% to 53% vital capacity (VC) (Knowles et al., 1959; Rahn et al., 1946; Whitfield et al., 1950), our data suggest that swallows are typically initiated between approximately 42% to 48% VC. Combined with previous data from our laboratories and those of others, these data support our initial working hypothesis and suggest that swallowing normally occurs within a very restricted range of mid to low expiratory *quiet breathing lung volumes* (Hiss et al., 2001; Martin et al., 1994b; Martin-Harris et al., 2005a; Martin-Harris et al., 2003; Martin-Harris et al., 2005b; McFarland and Lund, 1995; McFarland et al., 1994; Nishino et al., 1985; Preiksaitis et al., 1992; Preiksaitis and Mills, 1996; Smith et al., 1989). We have suggested previously that this range of volumes may impart significant airway and mechanical advantages for swallowing safety and efficiency (Charbonneau et al., 2005; Martin-Harris et al., 2015; McFarland et al., 1994). These advantages center on the key swallowing functions of laryngeal elevation, and associated upper airway closure, and the opening of the upper (pharyngoesophageal) and lower esophageal sphincters.

The esophagus passes through the esophageal hiatus of the crural portion of the diaphragm at or slightly above the level of the lower esophageal sphincter (LES) (Davenport and Dalziel, 1989; Kuster and Innocenti, 1997). The LES is closed at rest via tonic contraction of the intrinsic musculature and assisted by tonic activity of the crural portion of the diaphragm to prevent gastric contents from reentering the esophagus (Boyle et al., 1985; Mittal et al.,

1988). Conversely, the LES opens during swallowing to allow passage of liquids and solids bolus into the stomach via relaxation of the intrinsic muscles and inhibition of the crural portion of the diaphragm (Conklin and Christensen, 1994; Miller, 1982). The diaphragm contracts during both the inspiratory and expiratory phases of quiet breathing placing traction on the larynx, esophagus and pharynx (Agostoni and Mead, 1964; Mead and Agostoni, 1964; Trop et al., 1967). At resting expiratory level, the diaphragm has returned to its “resting”, un-contracted position and this may facilitate pharyngeal shortening, PES opening and lower esophageal bolus clearance into the stomach (Agostoni and Mead, 1964; Mead and Agostoni, 1964). Further, at end expiratory volumes, laryngeal elevators are working against the least resistance and this could facilitate laryngeal elevation necessary for airway closure. This may explain why the majority of swallows occurred within this restricted range of mid to low quiet breathing lung volumes in our normal subjects.

In contrast to the current findings, slightly higher lung volumes at swallowing initiation have been reported by Hegland and colleagues when studying the effects of different bolus characteristics (Hegland et al., 2009) and sequential liquid swallowing (Heglund et al., 2011) on LVSI. The results of Hegland et al. (2009) showed that 95% of swallows were initiated within 43% and 64% of vital capacity, with means across experimental tasks (liquid (10 and 20 ml), thin paste, and thick paste) ranging from 51% and 56% VC. Results of Hegland et al. (2011) revealed that sequential swallows by cup were initiated at significantly higher lung volumes than single swallows.

Even though the water (liquid) swallowing tasks in our experiment occurred at higher LVSI compared to other bolus types, they were still initiated within tidal volume range. We can only speculate about the potential reasons why swallows might have been initiated at slightly higher lung volumes in the Hegland et al. (2009) study when compared to those of the current study, but it seems likely that methodological differences in lung volume calibration and the fact that swallows were all initiated under un-cued conditions (see 5.1 Instruction) may have contributed to differences in findings. Hegland et al. (2009) speculated that swallowing above quiet breathing lung volumes might impart airway protective benefits in the event of penetration or aspiration of food or liquid during swallowing. This speculation was based in large part on the “subglottic pressure theory for swallowing” advanced by Diez-Gross and colleagues (Gross et al., 2003; Gross et al., 2012; Gross et al., 2006). Within this theory, subglottic airway pressure (the pressure beneath the adducted vocal folds due to lungs-thorax relaxation forces) is a key component of swallowing efficiency (Dettelbach et al., 1995). This theory emerged from a study of 11, tracheostomized patients consequent to surgery of the upper autodigestive tract, partial laryngectomy, neurological impairment including PD and stroke, or swallowing impairment due to cognitive difficulties or “weakness.” All had penetration/aspiration. The investigators analyzed swallowing function (from modified barium swallow study observations) of the subjects with and without a Passy-Muir Valve® and found that aspirations were eliminated or reduced when using the valve (Dettelbach et al., 1995). They subsequently argued that stretch receptors located in tracheal membranes, sensitive to subglottic air pressure, signal the appropriate moment for the respiratory pause to accommodate swallowing to the swallowing central pattern generator (Gross et al., 2003). Based on these data and those from follow-up studies, the authors argued that swallowing at total lung capacity would provide optimal subglottal

pressure (due to relaxation forces) for swallowing efficiency and productive expiratory reflex/cough. Several sources of data, however, argue against subglottal pressure as a key variable in swallowing efficiency. Airway invasion during swallowing is not typical in normal healthy adults, thus, the need for high pressures to elicit a productive cough are not necessary (Daggett et al., 2006). Further, cough and the expiratory reflex require high expiratory muscle pressures in order to generate the high flow needed to clear the airway (Korpas and Jakus, 2000; Lanini et al., 2008; Yanagihara et al., 1966). Subglottal pressure due to relaxation forces, even at very high lung volumes (well outside of the range of typical swallowing), would be insufficient for cough or the expiratory reflex (Arora and Gal, 1981; Korpas and Jakus, 2000; Lanini et al., 2008). And as reviewed above, diaphragmatic contraction necessary for high lung volumes would place considerable traction on laryngeal, pharyngeal and esophageal structures that would be counter-productive to airway safety and swallowing mechanics. In the study by Gross and colleagues (Gross et al., 2003), their subjects had difficulty swallowing at high volumes and often expired before swallowing.

5.1 Instruction

A second major finding of the current investigation was that lung volume for swallowing initiation was significantly influenced by the swallowing instruction or cueing. Although to our knowledge, the impact of instruction on LVSI has not been previously investigated, others have shown that instructional set can influence various swallowing parameters including oral transit time, pharyngeal transit time, swallowing total duration and stage transit duration (Cook et al., 1989; Daniels et al., 2007; Dodds et al., 1989). In the present investigation, LVSI was significantly lower when swallows were cued versus un-cued.. Although it seems reasonable to assume that swallowing in an un-cued context would allow subjects to adopt more natural ingestive behaviors, we believe that the introduction of the bolus and the instruction of swallowing when possible may have “forced” subjects to swallow as quickly as possible resulting in the atypical coordinative pattern of slightly higher LVSI. In contrast and for the cued presentations, waiting for the respiratory cycle to return to a steady state prior to instructing the subject to swallow created a more “natural” context for the observation of normal respiratory-swallow coordination. This finding supports the standard clinical practice of using some cued swallowing tasks during clinical and videofluoroscopic assessments of swallowing and in our respiratory-swallow training protocol (Martin-Harris et al., 2015).

5.2 Bolus Volume effects

Many authors have studied the effect of bolus volume on different parameters such as the duration of the respiratory pause to accommodate swallowing, the onset of the pause, relationship between swallow and respiratory phase and pharyngeal and esophageal sphincter pressure, duration and onset (Butler et al., 2004; Butler et al., 2009; Hiss et al., 2004; Hiss et al., 2001; Martin et al., 1994b; Martin-Harris et al., 2008; Martin-Harris et al., 2005a; Martin-Harris et al., 2003; Martin-Harris and Jones, 2008; Martin-Harris and McFarland, 2013; Martin-Harris et al., 2005b; Preiksaitis et al., 1992). Based on a review of the literature, only Hegland et al. (Hegland et al., 2009) studied the impact of bolus volume on LVSI, and found no significant differences between small (10 ml) and larger (20 ml) thin

liquid boluses both delivered by cup. Our data are consistent with this finding of no effects of liquid bolus volume on LVSI.

5.3 Bolus type

Another significant finding in the current investigation was that solid boluses were initiated at lower quiet breathing lung volumes when contrasted with pudding and water. Similar results were found by Hegland et al. (Hegland et al., 2009) who found differences in lung volume at swallowing initiation based on bolus type. Larger liquid (20 ml) boluses delivered by cup were initiated at significantly higher lung volume than thin paste and thick pastes delivered by spoon. Smaller liquid (10 ml) boluses were initiated at significantly higher lung volume than thick paste delivered only. The authors speculate that the differences related to bolus type or consistency are related to the higher probability of penetration with liquids versus more viscous substances and argue that higher lung volume at swallow initiation could thereby provide higher expiratory pressure in case of penetration/aspiration (Daggett et al., 2006; Hegland et al., 2009). However, imaging data do not support aspiration of liquids as a common occurrence in normal, young adults. Therefore, the explanation that high-flow expiratory pressures at the conclusion of a swallow do not appear relevant in a healthy, non-dysphagic population. Further, our previous work that combined videofluoroscopic imaging with airflow measurements demonstrated that healthy individuals typically follow the end of respiratory inhibition (pause) at or during the conclusion of swallowing liquids with a very brief low-flow expiration lending further doubt regarding the necessity of high airflow pressures during or at the conclusion of swallowing (Martin et al., 1994b; Martin-Harris et al., 2005a; Martin-Harris et al., 2003; Martin-Harris and McFarland, 2013; Martin-Harris et al., 2005b).

Although no significant effect of liquid bolus volume on LVSI was observed in our normal subjects, clinical observations of dysphagic patients, particularly those with neurologic impairment or respiratory disorders suggest that swallowing larger volumes of liquids from a cup or straw is challenging. Compared to solids or semi-solids, the velocity of bolus flow is increased, requiring a rapid neuromuscular response from pharyngeal and laryngeal mechanisms for airway closure and bolus clearance. Rapid laryngeal closure required by larger volume liquids may place a higher physiologic load on the dysphagic patient with decreased sensation and/or slowed movements of the larynx and pharynx. Perhaps the slightly increased LVSI observed in our normal subjects is compensatory in the face of this increased load. Our anecdotal clinical observations also suggest that liquids may result in the perception of air hunger, particularly in patient populations, and this may have contributed to slightly higher LVSI in liquid as contrasted to pudding and solid swallows.

5.4 Method of delivery

Another finding of the present investigation was that syringe delivered swallows were initiated at lower lung volumes as contrasted to spoon and cup presentations. Again, we can only speculate as to the influence of this experimental variable on LVSI, but one potential explanation is that the oral motor control requirements of transporting the bolus to the pharynx are greater for spoon and cup presentations when contrasted with controlled syringe administration.

6. Summary

Using these data combined with those from our own and other laboratories, and despite volume and task effects, a consistent picture begins to emerge regarding normal respiratory-swallow coordination. The data suggest that swallowing is superimposed on the ongoing quiet breathing respiratory cycle within a narrow range from mid tidal to resting expiratory lung volume levels. It seems reasonable to conclude that from a metabolic/gas exchange standpoint, this restricted range of lung volumes slightly above REL result in the minimization of perturbation to ongoing respiration while still accommodating the swallow and protecting the airway during respiratory inhibition. Else, *normal individuals would experience respiratory challenges in the context of every day eating and drinking tasks.* Clearly, this is not the case. Disruptions of respiratory-swallow coordination are common in patients with dysphagia consequent to perturbation of normal respiratory-swallow patterning following stroke and treatments for head and neck cancer (Brotsky et al., 2010; Butler et al., 2007; Leslie et al., 2002; Martin-Harris, 2008; Martin-Harris et al., 2015). This disruption in normal coordination may be compensatory to alterations in the structure and function of the swallowing mechanism and/or represent perturbations to the normally tight neural coupling between breathing and swallowing. Targeting and training appropriate respiratory-swallow patterning in dysphagic patients subsequent to treatments for head and neck cancer have already shown great promise in establishing optimal coordination and improving key components of swallowing and airway protection (Martin-Harris et al., 2015).

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Highlights

- Lung volume at swallowing initiation in normal subjects is described
- Swallowing is superimposed on the quiet breathing respiratory cycle.
- Swallowing occurs from mid tidal to resting expiratory lung volume levels.
- Effects of bolus type, task and instructions were observed.
- Swallowing at mid to low lung volumes is advantageous for airway protection.

Fig. 1.

a. Illustrating recorded signals and determination of swallowing onset. From top to bottom: Nasal Airflow, Respiratory movements of the rib cage (RC) and abdomen (AB), the lung volume estimate, and submental surface EMG (sEMG). Shown are the flatline in nasal airflow and the beginning of the respiratory pause to accommodate swallowing which was used to determine the “onset” of swallowing. Also indicated is resting expiratory level (REL) at the end of the expiratory phase of the third cycle prior to the respiratory cycle containing the swallow.

b. Shown is an enlargement of the box in Figure 1A indicating resting expiratory level (REL) at the end of the expiratory phase of the third cycle prior to the respiratory cycle containing the swallow and the method for determining lung volume at swallowing initiation (LVSI).

Fig. 2.

Illustrating sequential swallowing. From top to bottom: Nasal airflow, lung volume estimate from the summed and calibrated movements of the rib cage and abdomen, and submental surface EMG (sEMG) from participant 1 during the swallowing of 5mL pudding spoon uncued. The vertical arrows indicate the beginning the swallow related to the task and a sequential swallow.

Fig. 3.

Illustrating cued versus un-cued swallowing. Lung volume estimated from the summed and calibrated movements of the rib cage and abdomen recorded from participant 1 during the swallowing of 5ml of water from a spoon and under the two experimental conditions of “un-cued” and “cued.” The vertical line indicates the beginning of the flat line in the nasal airflow signal (not shown) used to mark swallowing.

Table 1

Swallowing tasks.

Bolus Consistency	Volume/Bolus Size	Method of Delivery	Cueing
Water	5 ml	Syringe by the examiner	Un-cued
	5 ml	Syringe by the examiner	Cued
	5 ml	Teaspoon by the examiner	Un-cued
	5 ml	Teaspoon by the examiner	Cued
	5 ml	30 ml medicine cup, self-administered	Un-cued
	5 ml	30 ml medicine cup, self-administered	Cued
	15 ml	3 oz clear drinking cup, self-administered	Un-cued
	15 ml	3 oz clear drinking cup, self-administered	Cued
	Uncontrolled volume	3 oz clear drinking cup, self-administered	Un-cued
	Uncontrolled volume	3 oz clear drinking cup, self-administered	Cued
Pudding	5 ml	Teaspoon, self-administered	Un-cued
	5 ml	Teaspoon, self-administered	Cued
Solid	Lorna Doone Shortbread Cookie, uncontrolled bite	Self-administered	Un-cued
	½ Lorna Doone Shortbread Cookie	Self-administered	Un-cued

Table 2
Lung volume at swallowing initiation

Task	Lung volume (ml) at swallowing initiation relative to REL		
	N*	Mean	95% Confidence Interval
5 ml water syringe un-cued	60	212	147 – 277
5 ml water syringe cued	60	134	69 – 199
5 ml water spoon un-cued	60	377	283 – 471
5 ml water spoon cued	60	147	53 – 241
5 ml water cup un-cued	60	378	265 – 492
5 ml water cup cued	60	219	105 – 333
15 ml water cup un-cued	60	457	343 – 571
15 ml water cup cued	60	283	169 – 397
Uncontrolled volume cup un-cued	57	408	309 – 507
Uncontrolled volume cup cued	57	219	120 – 318
5 ml pudding spoon un-cued	60	188	119 – 256
5 ml pudding spoon cued	60	157	88 – 225
Solid uncontrolled bite	60	115	70 – 160
Solid premeasured bite	57	127	82 – 173
Water, all delivery methods			
Un-Cued	297	367	294 – 440
Cued	297	201	128 – 275
Water, cued or un-cued			
5mL Syringe	120	173	122 – 223
5mL Spoon	120	262	187 – 338
5mL Cup	120	299	207 – 390
15mL Cup	120	370	278 – 462
Uncontrolled Volume Cup	114	313	234 – 392
Bolus			
Solid	117	121	86 – 156
Pudding	120	172	118 – 227
Water	594	284	219 – 349

* Number of total swallows from 20 participants