Lung Volume Measured During Sequential Swallowing in Healthy Young Adults

Karen Wheeler Hegland, Jessica E. Huber, Teresa Pitts, Paul W. Davenport, and Christine M. Sapienza

Purpose: Outcomes from studying the co-ordinative relationship between respiratory and swallow subsystems are inconsistent for sequential swallows, and the lung volume at the initiation of sequential swallowing remains undefined. The first goal of this study was to quantify the lung volume at initiation of sequential swallowing ingestion cycles and to identify the respiratory pattern(s) surrounding each sequential swallowing ingestion cycle. The second goal was to compare these results with existing data for single swallows.

Method: Twenty healthy young adults served as participants, 9 males and 11 females, between 19 and 28 years of age (M = 22 years of age). Participants completed 2 trials each of 100 mL of water self-delivered by cup and by straw. Calibrated respiratory inductance plethysmography, surface electromyography, and a contact throat microphone were used to detect respiratory parameters, identify swallow-related muscle contraction, and identify swallowing sounds, respectively.

Results: Significantly higher lung volume initiation for trials delivered by straw and more variable respiratory patterns surrounding cup and straw sequential swallowing ingestion cycles existed compared with single swallows.

Conclusions: Results show that as the physiologic demands of swallowing deviate from single, small bolus swallows, the integration of the swallowing and respiratory systems change. This may reflect obligate differences in airway protection strategy and prolonged competition for respiratory resources.

Key Words: deglutition, respiration, swallow–respiratory integration, ventilation

Sequential swallowing of thin liquids requires precisely coordinated movement of multiple structures, allowing for continuous bolus flow through the oral and pharyngeal cavities without airway compromise. Under healthy conditions, humans regularly swallow liquids in a continuous manner rather than parsing into single discrete swallows. The sequential swallowing physiology has been well described in terms of swallowing event timing, the anatomic landmarks thought to be responsible for the sensory “trigger” of the pharyngeal swallow response, the structural movement(s), and the coordination of swallowing with respiration (Chi-Fishman & Sonies, 2000; Daniels et al., 2004; Daniels & Foundas, 2001; Dozier, Brodsky, Michel, Walters, & Martin-Harris, 2006; Martin, Logemann, Shaker, & Dodds, 1994). Overall, the sequential swallowing physiology has been shown to be distinct from single-swallow physiology.

One physiological difference between single discrete swallows and sequential swallowing is the movement pattern of the hyolaryngeal complex (HLC). During single swallows, the hyoid bone has a well-defined movement pattern whereby it is slightly elevated at the onset of the pharyngeal swallow, moves superiorly and anteriorly as the bolus head passes through the pharynx and into the esophagus, and then returns to a rest position, which is typically inferior to its position at the start of the pharyngeal swallow. As the hyoid moves, the larynx generally moves in concert, and at the same time, intrinsic laryngeal muscles close the glottal space and seal the laryngeal vestibule in order to prevent penetration of the bolus into the laryngeal spaces or aspiration (bolus entering the bronchi or lungs). In sequential swallow tasks, the HLC demonstrates similar anterior–superior movement; however, the pattern is more variable.

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During sequential swallowing, the HLC may remain slightly elevated between swallows in the sequence, or it may return to a more inferior position where the laryngeal vestibule opens and the epiglottis turns upright from an inverted position (Chi-Fishman & Sonies, 2000; Daniels et al., 2004; Daniels & Foundas, 2001). An additional variation of this pattern is a mixed scenario in which the HLC sometimes remains elevated and sometimes lowers within a sequence of swallows (Daniels et al., 2004; Daniels & Foundas, 2001).

A further consideration related to HLC movement during sequential swallowing is the location of the bolus at initiation of pharyngeal swallow events. Generally, during sequential swallows, the leading edge of the bolus is caudal to the ramus of the mandible at the onset of the pharyngeal portion of swallowing. Daniels and Foundas (2001) reported that 87% of sequential straw-drinking swallows were initiated when the leading edge of the bolus was at or below the level of the valleculae (inferior to the ramus of the mandible). This finding was maintained throughout the lifespan (Daniels et al., 2004), suggesting that the hypopharyngeal region is an important trigger point for pharyngeal swallowing during sequential drinking tasks. This means that bolus material nears the laryngeal aditus prior to the initiation of the pharyngeal phase of the swallow during sequential swallowing and that the HLC may be open or closed as bolus material nears the hypopharynx. Therefore, coordination of sequential swallows with the respiratory breathing pattern is particularly important for airway protection.

Coordination of swallowing with respiration has been studied for both single- and liquid sequential swallowing. The single-swallow apneic period is most likely to be followed by expiration (Martin et al., 1994; Martin-Harris, Brodsky, Price, Michel, & Walters, 2003) and is known to reset the phase of respiration in the subsequent respiratory cycle (Paydarfar, Gilbert, Poppel, & Nassab, 1995). Although the significance of expiratory airflow following a swallow is not known precisely, there are several hypotheses. It may be that expiratory airflow after a swallow is advantageous over inspiratory airflow because it would not draw material located near the laryngeal aditus toward the airway. It may be that expiratory airflow is sufficient to expel stray or residual bolus material in or around the laryngeal vestibule. McFarland, Lund, and Gagner (1994) speculated that swallows interrupting expiratory flow may facilitate laryngeal elevation, upper airway protection, and upper esophageal sphincter opening. Martin-Harris et al. (2003) suggested that the slightly adducted vocal fold posture assumed by the larynx during exhalation provides a “protective setpoint for further laryngeal closure as the swallow progresses” (p. 1740).

The pattern of respiration surrounding the sequential swallow is less consistent than that reported for single swallows (Dozier et al., 2006; Issa & Porostocky, 1994b; Martin et al., 1994). During a self-administered sequential swallowing task investigating the breathing pattern surrounding sequential swallow ingestion cycles (ICs; one or more swallows during a single-swallow-related apneic period), Dozier and colleagues (2006) found significant differences compared with single discrete swallows. In that study, sequential swallow ICs were followed by expiration in 79% of cases, in which single 5-mL boluses were followed by expiration 93% of the time. Increases in tidal volume as well as in inspiratory and expiratory times are also noted during sequential swallowing (Issa & Porostocky, 1994a, 1994b). These observations may be reflective of an overall difference in the airway protection strategy necessary for sequential swallowing as compared with single discrete swallows.

Our research group recently quantified the lung volume, in terms of percent vital capacity (%VC), at initiation of single discrete swallows (Wheeler Hegland, Huber, Pitts, & Sapienza, 2009). Healthy young adults initiated single swallows between 51%VC and 56%VC for paste (thin and thick) and thin consistencies, respectively. These lung volumes were about 20% above functional residual capacity (FRC) and slightly above those associated with the range of tidal breathing. Using relatively higher lung volumes when swallowing may be physiologically advantageous for multiple, interrelated reasons. The development of positive subglottal pressure, hypothesized as important for healthy swallowing in humans (Eibling & Gross, 1996; Gross, Steinhauser, Zajac, & Weissler, 2006), is easier at higher lung volumes due to thoracic recoil pressures. Although the precise significance of positive subglottal pressure as it relates to swallowing is not known, one hypothesis is that positive subglottal pressure developed during the swallow facilitates expiratory airflow that typically follows the swallow apneic pause (Lang, Dana, Medda, & Shaker, 2002). An alternative explanation as to the significance of positive subglottal pressure may relate to a role for subglottal mechanoreceptor stimulation with positive pressure in laryngeal adduction (Shin, Maeyama, Morikawa, & Umezaki, 1988).

An additional role for relatively higher lung volumes for swallowing (vs. tidal breathing) may relate to the initiation of an expulsive event such as an expiration reflex in the case of penetration or aspiration of bolus material into the airway. Lung inflation status at increased lung volume may inhibit inspiration in order for an expulsive event (cough or expiration reflex) to occur (Nishino & Honda, 1986) without first drawing aspirate material further into the airway. As well, the length–tension relationship of the expiratory muscles with expanded lungs (Nishino & Honda, 1986)—combined with the significant increase in expiratory pressure–generating ability with slightly increased lung volume (Otis, Proctor, & Rahn,
would theoretically enhance the strength of the expiration reflex as measured by airflow and phase duration characteristics. Although speculative in nature, these hypotheses indicate that the lung volume achieved before the onset of swallow apnea may be an important component of swallow-breathing integration and airway protective mechanisms.

The goal of this project was to quantify the lung volumes and respiratory phase relationships associated with liquid sequential swallows delivered by cup and by straw and to compare those data with existing data for single swallows. Lawless, Bender, Oman, and Pelletier (2003) reported significant differences in the volume of material ingested between sequential cup- and straw-drinking tasks, showing that the volume of material per sip by cup was significantly larger versus that per sip by straw. As well, Hirst, Ford, John Gibson, and Wilson (2002) reported that 78.5% of 100-mL swallows by cup were followed by expiration, versus 63.5% of the swallows by straw in healthy older people. On the basis of these data, we hypothesized that significant differences in terms of both lung volume initiation and respiratory phase surrounding the IC would exist between straw and cup swallows. Additionally, because of physiologic differences between sequential and discrete single swallows, we hypothesized that the lung volume at initiation of sequential swallowing ICs would be higher than previously reported for single swallows. Last, we hypothesized that there would be significant differences in the respiratory phase surrounding the ICs compared with single swallows.

Method

Participants

Twenty healthy young adults served as participants (nine men and 11 women) between 19 and 28 years of age. Participant information, including age, gender, and VC, appears in Table 1. A certified speech-language pathologist judged all participants as having normal oral anatomy based on an oral mechanism examination. No participant reported a history of voice or respiratory problems (including asthma), neurological disease, or head or neck surgery. All were nonsmokers for the past 5 years. The Institutional Review Board at the University of Florida approved the study (IRB# 2006-U-0013).

Equipment

The equipment setup was identical to that previously described (Wheeler Hegland et al., 2009). Briefly, respiratory inductive plethysmography (RIP) via the Respiritrace system (Ambulatory Monitoring, Inc.) transduced respiratory movements. Elastic bands were placed around the rib cage (RC) under the axilla to track RC movement and around the abdomen (AB), with the top of the band at the level of the umbilicus, below the last rib to track AB movement. The Respiritrace system was calibrated using a spirometer (ML141, ADInstruments, Inc.) coupled to a respiratory flowhead (MLT 1000, ADInstruments, Inc.). A contact microphone (Piezo-electric signal transducer, MLT1010, AdInstruments, Inc.) placed on the neck lateral to the thyroid lamina and submental surface electromyography (sEMG; Bagnoli-8 EMG System, DE-2.1 surface EMG electrode; Delsys, Inc.) were used to identify swallows. Respiratory, acoustic, and sEMG data were input to a Power lab (ML870/P), digitized, and recorded at 2 kHz to a Dell Optiplex desktop computer using Chart 5 software (ADInstruments, Inc).

Procedure

All data were collected from participants seated with their feet flat on the floor and arms resting on armrests. The volumes of the RC and the AB compartments can be summed to estimate lung volume (LV; Konno & Mead, 1967). The volumes in the RC and AB compartments are estimated on the basis of dimensional measurements provided by RIP. In general, the RC contributes relatively more than the AB to LV change, for equivalent amounts of LV change. In order to obtain accurate estimates of LV, correction factors must be computed to “weight” the relative contributions of the RC and AB to LV change. To obtain data from which correction factors

<table>
<thead>
<tr>
<th>Participant</th>
<th>Gender</th>
<th>Age (years)</th>
<th>VC (liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Female</td>
<td>21</td>
<td>2.70</td>
</tr>
<tr>
<td>2</td>
<td>Male</td>
<td>21</td>
<td>4.92</td>
</tr>
<tr>
<td>3</td>
<td>Male</td>
<td>27</td>
<td>4.96</td>
</tr>
<tr>
<td>4</td>
<td>Male</td>
<td>19</td>
<td>2.00</td>
</tr>
<tr>
<td>5</td>
<td>Female</td>
<td>24</td>
<td>3.07</td>
</tr>
<tr>
<td>6</td>
<td>Male</td>
<td>23</td>
<td>4.85</td>
</tr>
<tr>
<td>7</td>
<td>Female</td>
<td>21</td>
<td>2.71</td>
</tr>
<tr>
<td>8</td>
<td>Female</td>
<td>21</td>
<td>3.96</td>
</tr>
<tr>
<td>9</td>
<td>Female</td>
<td>20</td>
<td>2.97</td>
</tr>
<tr>
<td>10</td>
<td>Female</td>
<td>19</td>
<td>4.04</td>
</tr>
<tr>
<td>11</td>
<td>Female</td>
<td>19</td>
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</tr>
<tr>
<td>12</td>
<td>Male</td>
<td>18</td>
<td>6.09</td>
</tr>
<tr>
<td>13</td>
<td>Female</td>
<td>21</td>
<td>2.94</td>
</tr>
<tr>
<td>14</td>
<td>Male</td>
<td>20</td>
<td>3.85</td>
</tr>
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<td>27</td>
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</tr>
<tr>
<td>20</td>
<td>Male</td>
<td>27</td>
<td>5.27</td>
</tr>
</tbody>
</table>

Note. VC = vital capacity.

Table 1. Participant information.
can be calculated, RIP signals from the RC and AB were recorded simultaneously with LV, provided by a digital spirometer (ML141, ADInstruments, Inc.) coupled to a respiratory flowhead (MLT 1000, ADInstruments, Inc.). The RC, AB, and spirometer (SP) data were collected during three calibration tasks. The calibration tasks were rest breathing (90 s of quiet breathing), a covert speech task (1.5 min reading “You buy Bobby a puppy now if he wants one” silently to themselves), and a swallowlike breathing task (90 s of trials in which participants pretended they were preparing to drink a large glass of water one time per exhalation, without actually swallowing). The covert speech and swallowing tasks were used because normal speech articulation or swallowing was not possible given that participants were breathing into the SP's mouthpiece. Published literature and our previous experience tells us that this covert task results in similar respiratory kinematics and LV changes as overt speech (Reich & McHenry, 1990) and is appropriate to the present experimental objectives. The swallowlike breathing task was also used to ensure appropriate sampling of all relevant LVs to swallowing and in order to account for potential nonlinearities in the Respitrace system at very low or high LVs.

These tasks allowed estimates to be obtained from the relationship of the RC and AB to LV at the LV ranges that were of interest in the present study. The sum of RC and AB movement was compared with the known volume obtained from the digital SP to determine correction factors for the RC and AB signals to estimate LV. The best calibration factors were determined offline using a least squares analysis (Moore–Penrose pseudoinverse function) in a custom-written MATLAB code. All data samples from the three calibration tasks were used to calculate the calibration factors. Thus, the combined RC and AB signal approached the SP signal with the least error optimized for all the contributing data points (Huber, 2007; Huber, Chandrasekaran, & Wolstencroft, 2005; Huber & Spruill, 2008). During the swallowing tasks, estimated LV at any given sample point was computed by summing RC and AB volumes after the correction factors were applied.

Participants also performed at least three trials of the VC task, with the Respitrace bands in place to estimate maximum VC for each participant (Hoit & Hixon, 1987; Hoit, Hixon, Altman, & Morgan, 1989). LV was estimated during the VC task using the correction factors. Mean VC measures across the three trials are presented in Table 1. The LV measures were converted to %VC based on this task by dividing the LV by the VC and multiplying by 100. The LV measures are expressed as %VC, where a measure of zero would correspond to residual volume.

Following calibration procedures, participants were asked to swallow 100 mL of water, twice by cup and twice using a straw (for a total of four sequential swallowing tasks each). The trial presentation order was randomized for each participant. Participants self-administered each trial, with the cup being placed in the participant's hand during the expiratory phase of a rest breath, and the cue to “swallow when you are ready” was given at end expiratory level (EEL). EEL was defined as the end of a tidal expiration and was visually determined by the experimenter from the X–Y trace of the RC and AB movement displayed on an oscilloscope. The only instructions that participants were given was to drink all water in the cup as if they were thirsty, without taking the cup or straw away from the lips or pausing during the trial. This instruction was crafted to ensure that the 100-mL bolus would be swallowed sequentially instead of broken into smaller sips of water more similar to single swallows. The participants were given no further instructions regarding the timing of the swallow and were free to initiate swallowing at any time after the cue. In order to minimize movement artifact associated with Respiband slippage, participants were instructed to keep their feet flat on the floor and restrict self-feeding arm movements to those from the armrest to the mouth and back again, with no extraneous reaching during the trial. During cup trials, participants were asked not to overextend their necks beyond what was necessary to drink all water in the cup.

**Measurements**

ICs were defined as one or more swallows included in the same swallow-related apneic period (Dozier et al., 2006). The identification of the IC onset was guided by the acoustic signal sampled from the contact throat microphone and observation of increased submental muscle activity from the sEMG recording (see Figure 1). The sEMG and acoustic data were not dependent variables; they simply served as guides in the identification of the swallows of interest, and therefore their values are not reported. In the acoustic signal, a biphasic deviation in the signal from baseline helped to differentiate the onset of oropharyngeal swallow from other submental muscle activity (e.g., activity related to oral bolus manipulation and tongue movement). Therefore, identification of IC onset was based on relative flattening of the respiratory signal along with increased amplitude in the sEMG signal, which coincided with biphasic deviation in the acoustic signal. For analysis, ICs were divided into the first IC (1 IC) and all subsequent ICs (nth IC). Breathing-related movement in the LV signal distinguished one IC from the next, where a change from apnea to inspiration/expiration demarked the ICs. The overall time analysis window included waveforms sufficient to identify the phase of respiration immediately preceding and immediately following the IC (see Figure 1). Hence, this may have included an entire respiratory cycle (inspiration and
expiration) or only inspiration or expiration, depending on the location of the IC within the respiratory cycle.

Lung volume initiation (LVI) was measured at the onset of breathing cessation (apnea) associated with each IC in the sequence (see Figure 1). LVI was expressed as %VC. The LV signal was used to define the swallow-related apneic period. The period was measured from IC onset and continued as long as the LV signal was flat relative to cycles of tidal breathing (see Figure 1). Lung volume termination (LVT) was measured at the offset of swallow-related apnea. LVTs and excursions (LVI – LVT = lung volume excursion [LVE]) were checked to ensure that little to no volume was expended during the swallow, as would be expected during the apneic period. LVT and LVE were not dependent variables.

The respiratory phase (inspiratory or expiratory) that bracketed each IC was determined manually by visual inspection of the LV signal. Pre- and post-IC inspiration and expiration were identified as upward or downward movement of the respiratory signal prior to and following the apneic period, respectively (see Figure 1), and then were expressed as one of four possible respiratory patterns:

1. Ex-Ex = expiratory-apnea-expiratory
2. In-Ex = inspiratory-apnea-expiratory
3. In-In = inspiratory-apnea-inspiratory
4. Ex-In = expiratory-apnea-inspiratory.

Statistics

LVI means were computed for each participant across both delivery methods (cup or straw) across all ICs. Respiratory pattern was computed as a percentage of the
total number of ICs. Intermeasurer reliability was completed on 20% of the LVI and respiratory pattern data, including random selection of two male and two female participants; this analysis was done completely independently by a second rater. Intraclass correlation coefficients (ICCs) were used to assess intermeasurer reliability. A one-sample t test was used to test the null hypothesis that LVE = 0 (indicating lack of air expended during the apneic period). Paired-samples t tests were used to test for differences in LVI between the first IC (1 IC) and subsequent ICs (nth IC). Mann–Whitney rank sum tests were used to test for differences in respiratory pattern between the first IC and subsequent ICs. Multiple linear regression models were used to test for an effect for apneic period duration and number of swallows per IC on LVI and respiratory pattern.

A Kruskal–Wallis one-way analysis of variance on ranks was used to determine whether differences existed between the two delivery methods in terms of number of ICs and the respiratory pattern surrounding the IC. The differences for mean LVI were assessed in a three-factor multivariate analysis of variance (MANOVA), with significance set at p = .05. Delivery method (straw vs. cup) and respiratory pattern were within-subject factors in the MANOVA. Gender was a between-subject factor. The Holm–Sidak method was completed for post hoc testing. The alpha level was set at p = .05. Additionally, the Kruskal–Wallis test examined differences between LVI and respiratory pattern for the present data on sequential swallows and data previously collected from the same participants for single-water bolus swallows (Wheeler Hegland et al., 2009).

Results

Intermeasurer reliability for LVI and respiratory pattern data, assessed using ICCs, demonstrated strong positive correlations, indicating good measurement reliability (α = .819, p < .000; α = .780, p < .000). Results of the one-sample t tests indicated that LVE was not significantly different from zero, t(412) = 0.613, p = .540. There were a total of 398 ICs studied across all 20 participants. There was no difference between the first and subsequent ICs in terms of LVI, τ(396) = −.0378, p = .710, or IC respiratory pattern (Mann–Whitney U = 12085.00, p = .790). We collapsed the data for all ICs. Figure 2 depicts the distribution of ICs across trials and participants. Fifty percent of the data fell within the first three ICs. Seventeen of 20 participants contributed at least one trial that included a third IC. Only three participants (across 12 trials) completed the entire 100-mL drinking task in one IC. Apneic period duration and number of swallows per IC exhibited strong positive correlations (r = .917, p < .000). However, neither apneic duration nor number of swallows per IC was a significant predictor of LVI or respiratory pattern, F(2) = 0.451, p = .638, r² = .002; F(2) = 2.834, p = .060, r² = .009, respectively.

Table 2 shows the descriptive statistics, including average number of ICs, number of swallows per IC, mean, and standard error for LVI according to delivery method (cup or straw). There was no significant effect of delivery type on respiratory pattern, H(1) = 1.263, p = .261, or on the number of ICs, H(1) = 0.327, p = .567. Fourteen of 20 participants exhibited all four possible respiratory patterns during trials. The remaining six demonstrated at least two of the four patterns during trials.

Results of the MANOVA indicated no significant effect for gender on LVI, F(1, 69) = 2.424, p = .125. We found a significant effect for delivery method, F(1, 397) = 42.379, p < .001, and respiratory pattern, F(3, 397) = 5.940, p < .001, but no interaction between delivery method and respiratory pattern, F(3, 397) = 1.697, p = .17. LVI was found to be higher for cup than for straw delivery methods (see Table 2 and Figure 3). Table 3 shows the

Table 2. Descriptive data for cup and straw sequential swallow tasks.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cup</th>
<th>Straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average number of ICs</td>
<td>5.55</td>
<td>4.98</td>
</tr>
<tr>
<td>Average swallows/IC</td>
<td>1.70</td>
<td>1.35</td>
</tr>
<tr>
<td>LVI (% VC) (SD)</td>
<td>62.9% (10.61)</td>
<td>55.6% (10.74)</td>
</tr>
<tr>
<td>Pattern (% total ICs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ex-Ex</td>
<td>33.0%</td>
<td>29.2%</td>
</tr>
<tr>
<td>In-Ex</td>
<td>13.2%</td>
<td>16.7%</td>
</tr>
<tr>
<td>In-In</td>
<td>17.0%</td>
<td>20.4%</td>
</tr>
<tr>
<td>Ex-In</td>
<td>37.0%</td>
<td>33.8%</td>
</tr>
<tr>
<td>Follow with expiration</td>
<td>46.2%</td>
<td>45.9%</td>
</tr>
<tr>
<td>Preceded with expiration</td>
<td>70.0%</td>
<td>63.0%</td>
</tr>
</tbody>
</table>

Note. IC = ingestion cycle; LVI = lung volume initiation; Ex = expiratory; In = inspiratory.

Figure 2. Graph depicting the distribution of total number of ICs across sequential swallow trials and participants. All trials had at least one IC, and 50% of the data falls within the first three ICs. Only 12 of 398 trials consisted of only one IC.
results of post hoc testing for respiratory pattern. Independent of delivery method, swallows that were followed by expiration (In-Ex and Ex-Ex) were associated with higher LVI versus those followed with inspiration (In-In and Ex-In; see Table 3 and Figure 3).

We found significant differences between sequential swallows and previously reported data on single swallows of thin liquid (10 mL water, and 20 mL water delivered by cup), $H(2) = 45.675, p < .001$. Post hoc testing indicated that sequential swallows by cup were initiated at higher LVI versus single thin swallows; however, we found no difference between LVI for sequential swallows delivered by straw and single-water swallows (see Table 4 and Figure 4).

**Discussion**

Sequential swallows were initiated at LVs higher than those that are typically associated with tidal breathing and showed variability with regard to the respiratory phase that preceded and followed each IC. Sequential swallows delivered by cup were initiated at significantly higher LVs than those delivered by straw. Furthermore, the respiratory phase that bracketed each IC had a significant effect on the LVI for that cycle. These effects were not due to differences in number of ICs, apneic period duration, or number of swallows within an IC. These findings were different than those for single discrete swallows of thin liquid in that (a) sequential swallows delivered by cup were associated with significantly higher LVIs, (b) the respiratory phase pattern surrounding single swallows was most often Ex-Ex, and (c) the respiratory phase surrounding the single swallows did not have a significant effect on LV. These findings add to an existing body of knowledge, both empirical and anecdotal, that the physiologic mechanism(s) by which swallows are integrated into the ventilatory breathing pattern is influenced by the type (both volume and delivery method) of bolus being swallowed.

Sequential swallows delivered by straw were initiated at lower LVs than those delivered by cup. The total

**Table 3.** Results of post hoc testing for differences in lung volume initiation between the four respiratory patterns.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Mean difference</th>
<th>( t )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex-Ex/In-Ex</td>
<td>-1.575</td>
<td>0.949</td>
<td>.343</td>
</tr>
<tr>
<td>Ex-Ex/In-In</td>
<td>4.275</td>
<td>2.756</td>
<td>.006</td>
</tr>
<tr>
<td>Ex-Ex/Ex-In</td>
<td>3.540</td>
<td>2.782</td>
<td>.006</td>
</tr>
<tr>
<td>In-Ex/In-In</td>
<td>5.850</td>
<td>3.193</td>
<td>.002</td>
</tr>
<tr>
<td>In-Ex/Ex-In</td>
<td>5.114</td>
<td>3.144</td>
<td>.002</td>
</tr>
<tr>
<td>In-In/Ex-In</td>
<td>-0.735</td>
<td>0.490</td>
<td>.625</td>
</tr>
</tbody>
</table>

**Note.** Bolded \( p \) values indicate significant differences.

**Table 4.** Results of post hoc testing for differences in lung volume initiation between 100-mL cup and straw tasks and single swallow tasks.

<table>
<thead>
<tr>
<th>Task</th>
<th>Difference ranks</th>
<th>( Q )</th>
<th>( p &lt; .05 )</th>
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<tbody>
<tr>
<td>Sequential straw/single swallow</td>
<td>40.081</td>
<td>2.268</td>
<td>no</td>
</tr>
<tr>
<td>Sequential cup/single swallow</td>
<td>112.25</td>
<td>6.157</td>
<td>yes</td>
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</tbody>
</table>
number of ICs for the straw task was not different than those for the cup tasks. Additionally, no differences were found in the phase of respiration surrounding each IC for straw and cup swallows. There are a few plausible explanations for this difference. First, it may simply be that the act of drawing material in via a straw requires reallocation of lung inflation forces such that the total volume of air in the lungs decreases. In addition, researchers have shown that the volume of material ingested per sip when material is delivered by cup is significantly larger versus when material is delivered by straw (Lawless et al., 2003). As previously shown (Wheeler Hegland et al., 2009), single swallows of large thin boluses (20-mL water) are initiated at significantly higher IVs than thicker consistencies (peanut butter and pudding boluses); however, the LVI associated with smaller thin boluses (10 mL) is not significantly different than thicker consistencies. Thus, it is possible that this difference may be due to larger bolus size for straw versus cup and not necessarily the delivery method itself.

Single-swallow apneic periods are most commonly preceded and followed by expiration, a finding hypothesized to be protective in nature, as expiratory airflow would direct stray bolus material away from the airway (Lang et al., 2002; Martin-Harris et al., 2005). Interestingly, the non–Ex-Ex patterns occurred more commonly for sequential swallow ICs (for both cup and straw delivery methods) than has been observed for single swallows. These differences were observed in both the first and nth ICs (see Figure 5). This finding is in agreement with Martin and colleagues (1994), who used similar respiratory recording methods during sequential swallowing of 100 mL of water delivered by straw. The distribution of respiratory patterns found in that study indicated the Ex-Ex occurred less often (only 46% of the time), and the nondominant Ex-In pattern occurred more often (38% of the time) during the 100-mL task compared with single-swallow tasks (Martin et al., 1994). Results of the present study are demonstrably similar, with Ex-Ex occurring for only 31% of ICs and Ex-In occurring for 35% of ICs. It is plausible that the increased variability in respiratory pattern is related to the overall time requirements for the sequential swallowing task. Study participants took upwards of 10 s to complete the entire 100-mL task. This is in contrast to single swallows, which are typically completed in 1 s or less (Vaiman, Eviatar, &

Figure 5. A raw data waveform illustrating the variability for the respiratory pattern surrounding ingestion cycles (ICs) during a sequential swallow delivered by straw. Each vertical line marks the onset of an IC. Specifically, the first solid line from the left marks the onset of an IC preceded by inspiration and followed by expiration (In-Ex); the next solid line marks an IC preceded by expiration and followed by inspiration (Ex-In). The vertical lines were added for illustration purposes only and were not present during data analysis.
Segal, 2004). During the sequential task, most participants breathed between ICs, perhaps to avoid building up carbon dioxide. In fact, just three participants (in 12 trials) completed the entire 100-mL task in 1 IC (see Figure 2).

The respiratory pattern surrounding ICs also had a significant effect on the LVI—another difference from single swallows, where no effect was found for respiratory pattern on LVI (Wheeler Hegland et al., 2009). ICs that were followed by expiration (i.e., Ex-Ex and In-Ex) were initiated at higher LVs than those followed by inspiration. It is interesting to note that of all 398 ICs examined across all participants, only three (all from the same participant) were found to occur at LVs below 30%VC (26.8%VC, 27.3%VC, and 28.2%VC). There were only 18 ICs (4.5% of the data) that occurred below 40%VC. Of the ICs with LVIs occurring below 40%VC, 72% were followed with inspiration. The physiologic efficiency of using the natural recoil forces of the lungs—thorax unit—combined with the goal of maintaining ventilatory status throughout the sequential swallowing task—may help explain both the LVI relationship to respiratory pattern as well as increased variability in respiratory pattern surrounding each IC.

Dozier et al. (2006)—who investigated respiratory phase, among other variables, for sequential swallowing—used a 50-mL thin barium mixture and found the majority (78%) of first ICs were followed with exhalation. Forty percent and 38.6% fell into In-Ex and Ex-Ex patterns, respectively. Only 5.7% exhibited the Ex-In pattern that was found to be more prevalent for the 100-mL water swallowing both in the present study and in the Martin et al. (1994) study. The recording methods used were different in the 2006 study, as nasal airflow was used to track respiratory phase. This might account for the distinction. Nasal manometry is influenced by air movement through the nasal and pharyngeal cavities that can be induced via velopharyngeal movement, making it potentially misleading for measurement of sequential swallowing that can have several closings/openings of the velopharyngeal port during sequential swallowing (Daniels et al., 2004). However, RIP—the method used in the present study—is sensitive to shape change or body movement and, even when carefully calibrated, does not directly measure airflow. Therefore, identifying the inspiratory or expiratory phases, which are by definition descriptions of airflow, is done indirectly based on the assumption that positive or negative deflections in the respiratory signal are actually reflective of inspiration or expiration, respectively. Matsuo, Hiitemae, Gonzalez-Fernandez, and Palmer (2008) used both nasal airflow and RIP in their study of respiration during feeding on solid foods. When directly comparing the two signals, they concluded that the nasal airflow signal was less accurate because it overestimated a plateau phase following expiration, rather than continued active expiration, due to (a) lack of measurement of oral airflow and (b) detection of air moving between the nasal and pharyngeal cavities. Certainly a face mask pneumotachograph would be the most accurate way to measure airflow; however, studying “natural” swallowing with such equipment obstructing the oral cavity would not be reasonable. Therefore, although RIP is not designed to measure airflow directly, it is presently a good option for measuring swallow-related respiratory parameters in a more natural manner.

Other possibilities that may account for differences in respiratory phase measures include swallowing plain water versus liquid barium or differences in instructions (“swallow like you are thirsty” in the present study vs. swallow in your “usual manner” in the Dozier et al., 2006, study). This cannot be discerned for certain based on the results of these studies, although it certainly may be a conceivable explanation. One last contributing difference between the studies may be the age range for the Dozier et al. (2006) study, which included persons between 23 and 91 years of age compared with the present study age group of only 19–28 years of age.

Hiss, Strauss, Treole, Stuart, and Boutilier (2003) along with Charbonneau, Lund, and McFarland (2005) have demonstrated persistence of swallowing apnea and single-swallow respiratory phase relationships following total laryngectomy, suggesting it is not online feedback from the larynx that is singularly responsible for swallowing—respiratory coordination. Modifications in the swallow—respiratory relationship occur with changes in bolus parameters, including bolus size, delivery method, and consistency, suggesting that multiple upper airway afferents contribute to the successful integration of swallowing into the ventilatory pattern. Pulmonary feedback may also play an important role in integrating the two systems. It is likely that multiple sensors, including those from the upper airway and pulmonary stretch receptors, provide input that is communicated between the swallowing and respiratory central pattern generators.

The results of the present study add to the knowledge base regarding swallow—respiratory integration, showing that as the physiologic demands of the task deviate from single, small bolus swallows, the integration of the two systems changes in terms of the amount of air available in the lungs as the swallow is initiated (for trials delivered by straw) and in terms of the respiratory phase surrounding the swallow. It may be that as the respiratory system is faced with prolonged competition for resources, the system must respond in order to maintain ventilatory status. Challenging the system with larger volumes of liquid to swallow would be noteworthy, as it would lend insight as to how the respiratory system responds to greater and more prolonged competition for resources. Measures not only of LV and respiratory phase but also of perceived breathlessness and exertion
over the course of 300-mL or 400-mL swallows, or even during an entire meal, would provide information regarding how a more complex swallowing task impacts the integration of the two systems.

References


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