Lung volume effects on pharyngeal swallowing physiology

Roxann Diez Gross,1,2 Charles W. Atwood, Jr.,3
Judith P. Grayhack,1,2 and Susan Shaiman2
1Department of Audiology and Speech Pathology and 2Pulmonary Section, Veterans Affairs Pittsburgh Healthcare System, Pittsburgh 15240; and 3Department of Communication Sciences and Disorders, School of Health and Rehabilitation Sciences, University of Pittsburgh, Pittsburgh, Pennsylvania 15260
Submitted 27 March 2003; accepted in final form 7 August 2003

Subglottic Pressure Theory for Swallowing

The rationale for this study is based on the theory that pressurized air during the swallow may play a role in the neuroregulation of swallowing function by stimulating subglottic mechanoreceptors. The subglottic pressure theory for swallowing originated from observations of altered swallowing function in tracheostomy patients in which air pressure below the true vocal folds was greatly modified, depending on the status of the tube (open or closed). The location of subglottic pressure receptors has been verified (3, 48, 49), although their function is not yet known (4, 13, 33, 42, 45, 46). Conceivably, the purpose of these receptors may be related to deglutition and not phonatory or respiratory function.

Tracheostomy Tubes and Aspiration

The placement of an indwelling, open tracheostomy tube not only functionally separates the respiratory and alimentary tracts but also eliminates the possibility of generating positive subglottic air pressure (Psub). Increased aspiration and dysphagia have been linked to the presence of an open tracheostomy tube (6–8, 28, 29). Closure of the tracheostomy tube and restoration of positive pressure can be achieved by capping or digital occlusion or by placement of a Passy-Muir speaking valve. Investigations that looked primarily at head and neck cancer patients without neurological impairment have reported that aspiration was eliminated or reduced when the tracheostomy tube was occluded during the swallow (11, 15, 43).

Additional evidence to support the importance of Psub in swallowing function has also been offered in the pediatric literature. Finder and colleagues (12) reported that dramatic reductions in aspiration of saliva were observed after the institution of constant positive airway pressure (CPAP) through the open tracheostomy tube. The authors speculated that there was a relationship between the application of CPAP and tracheostomy tube occlusion, but they did not consider that CPAP may have actually improved swallowing function by providing positive Psub during the swallow while the tube remained open.

Address for reprint requests and other correspondence: R. D. Gross, VA Pittsburgh Healthcare System, Dept. of Audiology and Speech Pathology, University Drive C 132A-U, Pittsburgh, PA 15240 (E-mail: Roxann.Gross@med.va.gov).

http://www.jap.org

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
Respiration and Deglutition

There is overwhelming evidence that points to the coupling of swallowing with the exhalation phase of respiration, but little explanation as to why this coordination exists (21, 24, 25, 38, 40). Perhaps the preferential timing of the normal swallow with the exhalation phase is a mechanism that allows for stimulation of subglottic mechanoreceptors and the generation of the Psub that seems to be missing when patients swallow with an open tracheostomy tube. Conceivably, feedback mechanisms that use afferent information from the subglottis may be more readily accessed at higher lung volumes or during exhalation when it is easiest to produce positive air pressure. Additionally, individuals who suffer from neurological injury have been shown to experience a disturbance of coordination between respiration and swallowing (9, 38). A high incidence of dysphagia and aspiration has been reported for this population as well (19, 31, 41). Possibly, a loss of optimal coupling of the onset of the swallow with higher lung volumes could result in a disruption of Psub. The disruption of requisite pressure may be key to understanding the high incidence of dysphagia and aspiration within neurologically impaired individuals and other diagnostic groups.

This experiment was designed to determine how the variation of one easily manipulated respiratory parameter, lung volume, affects specific measures of swallowing physiology in individuals without dysphagia, respiratory disease, or neurological impairment. Extremes in lung volume were used as a means to alter subglottic air pressure in individuals who do not have indwelling tracheostomy tubes.

METHODS

The protocol was approved by the Veterans Affairs Pittsburgh Healthcare System Subcommittee on Human Studies and the Institutional Review Board of the University of Pittsburgh. Informed written consent was obtained from each participant before data collection.

Sample

Before data collection, a power analysis based on a power of 0.70 at a 0.05 level of significance determined that 25 subjects would be required for a medium effect size. Due to anticipated data loss, 28 subjects were recruited.

Participants

The participants were 28 healthy, young volunteers recruited from the general population. The age range of the subjects was from 21 to 40 yr (mean age = 29 yr). Thirteen male subjects and 15 female subjects were enrolled. Each participant completed spirometric testing that included forced expiratory volume in 1 s-to-forced vital capacity ratio anticipated data loss, 28 subjects were recruited.

Participants

The participants were 28 healthy, young volunteers recruited from the general population. The age range of the subjects was from 21 to 40 yr (mean age = 29 yr). Thirteen male subjects and 15 female subjects were enrolled. Each participant completed spirometric testing that included forced expiratory volume in 1 s-to-forced vital capacity ratio was >70% for each participant. Subjects had no history of oropharyngeal dysphagia or complaints about oropharyngeal swallowing function. Participants recruited were free of active upper respiratory infection at the time of data collection.

Data Acquisition

Swallows were recorded by using simultaneous videofluoroscopy for timing measurements, bipolar intramuscular electromyography (EMG) of pharyngeal muscle activity, and a respiratory inductance plethysmograph (Respiritrace, Ambulatory Monitoring, Ardsley, NY) to record respiratory phases and estimated lung volumes. WinDaq waveform recording software (DATAQ Instruments, Akron, OH) was used to collect, organize, and analyze the EMG and respiratory data. The Kay swallowing workstation (Kay Elemetrics, Lincoln Park, Nj) was used to record and analyze the fluoroscopic data. All data were collected during a single session lasting ~1 h.

EMG Instrumentation

Before data collection, bilateral intramuscular EMG electrodes were placed in the lower, lateral margin of the superior pharyngeal constrictor, according to the method described by Perlman et al. (32). EMG signals were preamplified and filtered (Grass Instruments, Astro-Med, West Warwick, RI). The EMG and the output of the Respiritrace were routed through anti-aliasing filters (RC Electronics, Santa Barbara, CA). The signals were digitized with WinDaq software (DATAQ Instruments).

Respiratory Instrumentation

The Respiritrace (Respiritrace, Ambulatory Monitoring) is a respiratory inductance plethysmograph composed of two elasticized cloth bands with Teflon-insulated wire coils attached within. One band is placed around the rib cage under the arms, and the other band is placed around the waist. Each band measures the changes in the cross-sectional area of the rib cage and abdomen, allowing for the determination of changes in lung volume and monitoring of respiratory phase. Unlike other methods of measuring ventilation, the Respiritrace does not require any apparatus involving the face, making it ideal for a deglutition study.

Reliable calibration of the Respiritrace was not possible during this study because of the extremes in lung volume that were randomly required throughout each individual data collection session (26, 35). The signal from the Respiritrace was used to provide visual feedback to assist the participants in controlling their lung volumes and as visual assurance during data analysis that each participant achieved the target lung volumes in response to the verbal directions.

Videoradiographic Instrumentation

Videofluoroscopy was used to record swallowing physiology and bolus transit through the pharynx. The superior margin of the image was set consistently to contain the nasopharynx. The anterior fluoroscopic view was set to include the anterior tongue and alveolar ridges. The posterior margin of the image included the cervical bodies. Lastly, the inferior margin was set to include the upper one-third portion of the trachea. The inclusion of all of these areas ensured direct observation of entire oropharyngeal swallow. The image was magnified ×2 to increase the detail of each subject’s anatomy. The Kay swallowing workstation recorded all fluoroscopic data and audio data.

Data Acquisition Protocol

Considering that Psub during the swallow cannot be measured noninvasively in nontracheostomized participants, the polarity of Psub was inferred by having participants swallow at total lung capacity (TLC), which is consistent with the end of maximal inhalation and before the onset of exhalation (highest positive Psub), at resting expiratory level or func-
tional residual capacity (FRC), where recoil forces are inactive or less active (~34% vital capacity equating to a lower or midrange Psus), and at residual volume (RV), which is the end of forced exhalation and before the onset of inhalation (~0% vital capacity and lowest Psus or negative). Participants were observed swallowing three separate, standardized 5-ml pudding-consistency barium boluses under video-fluoroscopy, with simultaneous recordings of pharyngeal EMG and Respitrace output at each of the three targeted lung volumes. The pudding boluses were taken from a mixture of 30 ml of Intropaste barium sulfate paste (Lafayette Pharmaceuticals, Lafayette, IN) and 60 ml of pudding (Hunts snack pack, Hunt-Wesson, Fullerton, CA). The resulting mixture had a viscosity of ~5,800 cp. The viscosity of the pudding and barium mixture was measured by using a Brookfield DV-I + Viscometer at ambient temperature (spindle no. 4 at 20 rpm). A syringe was used to measure the 5-ml bolus onto the spoon. In all cases, the pudding bolus was placed in the subject's mouth with a teaspoon. The three conditions were randomized within and between subjects to avoid order effects and/or habituation to any of the lung conditions. Three swallows at each lung volume were recorded for a total of nine swallows per subject.

**EMG Data Analysis**

Out of 252 total swallows recorded, 48 were removed from final analysis because they did not occur at the targeted lung volume. The complete data sets of two subjects were removed entirely because of poor respiratory data. Respiratory data were judged as inadequate for analysis when the deflection of the signal was not large enough to allow for confident determination that the target lung volumes had been obtained. The inadequate signal was most likely the result of too loosely placed bands. Although every attempt was made to place and maintain two electrodes in each subject, only one channel of EMG could be analyzed per subject. Out of 204 remaining swallows, 49 swallows could not be analyzed because of electrode dislodgement. Electrode dislodgement was most likely attributable to the combined motion of swallowing and the high viscosity of the bolus. Furthermore, after review of the videofluoroscopic tapes, six more swallows were removed because it was discovered that the subject had split the bolus in two rather than swallow the entire bolus in one swallow. Therefore, a total of 149 swallows (or 14 subjects with complete data sets) were entered into the final EMG analysis.

**Physiological Measurements Taken From EMG**

WinDaq interactive software (DATAQ Instruments) was used to analyze the duration and amplitude of the superior pharyngeal constrictor EMG signal during the swallow. The signal was rectified, digitized, and integrated over time. For each swallow, the duration of the signal was determined by selecting the onset and offset of the rectified signal. Once the signal duration was established, the signal amplitude was determined by calculating the mean rectified and integrated EMG over a fixed interval of 800 ms (23). The value 800 ms was selected before data analysis because this is the mean swallow duration reported by Perlman et al. (32). The average of the three swallows per condition was used for final analysis.

**Fluoroscopy Data Analysis**

Out of 204 swallows, 179 individual swallows (22 subjects with complete data sets) were used for the final fluoroscopic analysis. A total of 25 swallows were removed from the fluoroscopic analysis because the bolus was split into two swallows, the fluoroscope was turned on late, the contrast of the X-ray was too dark to see pertinent anatomy, or the subject moved during the swallow. Swallows of poor EMG quality, but occurring at the target lung volume, were not excluded from the fluoroscopic analysis.

**Physiological Measurements Taken From Videofluoroscopy**

**Bolus transit time.** The starting point for bolus transit time (BTT) was taken from the first videofluoroscopic frame, where the head of the primary bolus reaches the lower margin of the mandible. The primary bolus was defined as the portion of the bolus being actively propelled by the tongue. The end point was taken when the superior margin of the cricopharyngeal sphincter was observed to close behind the tail of the primary bolus. BTT was measured three times for each swallow, and the average value was used for analysis.

**Pharyngeal activity duration.** Pharyngeal activity duration (PAD) is a measurement that was established for the purpose of distinguishing the pharyngeal motor response time from BTT. PAD also distinguishes between hyoid motion onset associated with the phase transition time period (between the oral and pharyngeal phases) and the anterior hyoid thrust that is associated primarily with the onset of the pharyngeal swallow.

The starting point was the first frame in which the onset of hyoid motion associated with the pharyngeal swallow was observed. The ending point was taken as the first frame in which air was again observed in any portion of the pharynx. PAD was also measured three times for each swallow, and the average value was used for analysis.

**Aspiration-penetration severity level.** Assignment of the aspiration-penetration score (34) was made after three observations of each swallow.

**RESULTS**

To determine redundancy of the dependent variables, correlations between the dependent measures were calculated by using the one-tailed Pearson correlation with a significance level set at 0.01. EMG duration showed a significant correlation of 0.68 and 0.76 for BTT and PAD at TLC (P = 0.007 and 0.00138, respectively). The correlation coefficient of 0.767 met the predetermined criterion of ≥0.80 for removal; however, this finding occurred in only one combination at one level of the independent variable. Therefore, none of the variables was removed from the final analysis.

**Penetration and Aspiration Scores**

No aspiration or penetration was observed on any swallow for any lung volume. All swallows were rated 1 (no aspiration or penetration within the laryngeal vestibule).

**Statistical Analyses**

The means, SDs, and SEs are displayed for each dependent variable in Table 1. Normality testing (Kolmogorov-Smirnov) showed that EMG amplitude, EMG duration, and BTTs were normally distributed. A single-factor repeated-measures analysis of variance was performed for each measure, utilizing respiratory vol-
Table 1. Mean, SD, SE, and number of subjects for the three lung conditions (TLC, FRC, RV)

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>SE</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EMG amplitude, mV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLC</td>
<td>5.37 (4.36)</td>
<td>1.17</td>
<td>14</td>
</tr>
<tr>
<td>FRC</td>
<td>5.50 (4.03)</td>
<td>1.08</td>
<td>14</td>
</tr>
<tr>
<td>RV</td>
<td>5.11 (4.00)</td>
<td>1.07</td>
<td>14</td>
</tr>
<tr>
<td><strong>EMG duration, ms</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLC</td>
<td>952.00 (188.00)</td>
<td>31.50</td>
<td>14</td>
</tr>
<tr>
<td>FRC</td>
<td>902.00 (166.00)</td>
<td>44.50</td>
<td>14</td>
</tr>
<tr>
<td>RV</td>
<td>1,000.00 (126.00)</td>
<td>33.70</td>
<td>14</td>
</tr>
<tr>
<td><strong>Bolus transit time, ms</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLC</td>
<td>521.00 (81.40)</td>
<td>17.40</td>
<td>22</td>
</tr>
<tr>
<td>FRC</td>
<td>527.20 (55.70)</td>
<td>11.90</td>
<td>22</td>
</tr>
<tr>
<td>RV</td>
<td>520.00 (72.40)</td>
<td>15.40</td>
<td>22</td>
</tr>
<tr>
<td><strong>Pharyngeal activity duration, ms</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLC</td>
<td>690.00 (112.00)</td>
<td>24.00</td>
<td>22</td>
</tr>
<tr>
<td>FRC</td>
<td>694.00 (122.00)</td>
<td>26.00</td>
<td>22</td>
</tr>
<tr>
<td>RV</td>
<td>719.50 (105.00)</td>
<td>22.30</td>
<td>22</td>
</tr>
</tbody>
</table>

n, No. of subjects; EMG, electromyography; TLC, total lung capacity; FRC, functional residual capacity; RV, residual volume.

Table 2. Repeated-measures ANOVA

<table>
<thead>
<tr>
<th>Variable</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>f</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp EMG</td>
<td>0.0005</td>
<td>2</td>
<td>0.0003</td>
<td>0.171</td>
<td>0.844</td>
</tr>
<tr>
<td>Duration EMG</td>
<td>67.4</td>
<td>2</td>
<td>33.7</td>
<td>2.60</td>
<td>0.094</td>
</tr>
<tr>
<td>BTT</td>
<td>778.5</td>
<td>2</td>
<td>389.3</td>
<td>0.328</td>
<td>0.722</td>
</tr>
</tbody>
</table>

BTT, bolus transit time; SS, sum of squares; df, degrees of freedom; MS, mean squares.

Table 3. Student-Newman-Keuls

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Difference in Ranks</th>
<th>q</th>
<th>P &lt; 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAD-RV vs. PAD-FRC</td>
<td>16.000</td>
<td>3.411</td>
<td>Yes</td>
</tr>
<tr>
<td>PAD-RV vs. PAD-TLC</td>
<td>14.000</td>
<td>4.221</td>
<td>Yes</td>
</tr>
<tr>
<td>PAD-TLC vs. PAD-FRC</td>
<td>2.000</td>
<td>0.603</td>
<td>No</td>
</tr>
</tbody>
</table>

PAD, pharyngeal activity duration.

Motivated by the notion that the anatomic overlap of the respiratory and alimentary tracts along with the intermingling of brain stem neurons involved in respiratory and swallowing enable processing of sensory information across systems, we hypothesized that alterations in the respiratory system could elicit physiological changes in pharyngeal swallowing function. This hypothesis was based on the subglottic pressure theory and the findings of several experiments in which aspiration was reduced or eliminated in subjects with indwelling tracheostomy tubes when the tube was closed, allowing for the buildup of Psub during the swallow (11, 27, 43). Consistent with the theory that Psub may be integral to efficient swallowing, statistical analysis of the data revealed a significantly longer duration of PAD for swallows that occurred in the low subglottic pressure condition (RV) compared with swallows that occurred at higher lung volumes (TLC and FRC). Convergent validity is provided in previous work by Logemann et al. (22) and Gross et al. (16) in which longer contraction times of pharyngeal swallowing musculature were measured when tracheostomy tubes were open (zero Psub) compared with closed tubes in which Psub during the swallow could be generated.

Gross et al. (16) found that, in tracheostomy subjects, PAD duration could increase as much as 314 ms when the tube was opened and subglottic air pressure was zero. They postulated that a feed-forward system may detect the loss of Psub and that the timing difference was long enough to allow for cortical processing. In this experiment, the largest timing difference in PAD was 32 ms and occurred between TLC and RV at 32 ms. This small durational difference also rules out
the possibility of a closed-loop feedback controller and lends support for feed-forward (predictive) modulation (1, 14, 36). How subglottic mechanoreceptors may control and alter swallowing function in a closed system (no indwelling tracheostomy tube) where Psub is a function of lung volume, as well as the significance of the durational differences measured in this experiment, can be further discussed and interpreted via the theoretical framework of motor control.

Motor Planning Theory

Open-loop theory, developed as a linear paradigm to understand ballistic movement (2,5), eventually escorted in the search for neural substrates such as the central pattern generator (CPG) (14). This paradigm states that information processing or preplanning (top down) occurs before the movement is executed. Schmidt (36) altered the model such that the stored “program” was general rather than specific. A general motor program would, therefore, permit adjustments to be incorporated into the preplanning stage (prescriptive approach) as a means of improving or ensuring accuracy of the movement. Feed-forward controllers operate most precisely in a context in which “experience-based” motions are executed. Significant positive correlations between EMG duration, BTT, and PAD were present only for swallows occurring at TLC. If TLC most closely approximates the initiation of the most efficient motor program, then these correlations may be indicative of the condition that is closest to the swallowing program (i.e., the lungs are filled and Psub is likely to be sufficiently positive).

PAD of swallows occurring at FRC were not significantly different from TLC, perhaps because the potential to generate positive pressure was still present. PAD-FRC was significantly shorter than PAD-RV, with a median difference of 17 ms. Interesting, these midlung range swallows were nearly one-half the time duration difference between TLC and RV (Fig. 1). The meaning of this relationship, if any, is unclear; however, it may further suggest the possibility of a linear relationship (consistent with the predictive model) between lung volume and PAD should a range of lung volumes be studied in the future. Conceivably, a target lung volume range for optimal swallowing function may exist.

Perhaps the status of the respiratory system at the time when swallow elicitation was required to occur within this protocol (especially at RV) presented a potential “disturbance.” When a disturbance is detected, neural swallowing components may calculate the effects that the disturbance was likely to have on the swallow and respond by enabling functions required to counteract these effects (18). Again, it is possible that the condition of the respiratory system before the swallow resulted in an altered or “corrected” durational parameter descending from the suprabulbar structures and onto the CPG, thereby ensuring the “success” of the swallow (i.e., avoidance of aspiration).

Another possibility is that the adjustments to PAD did not occur before the onset of the motion pattern. If the swallow is viewed as a single act occurring within the context of different levels of Psub, then a perturbation may have occurred when the true vocal folds closed and a change in Psub was detected. Perchance the increased duration in the RV condition is indicative of the swallow being “reprogrammed intramovement” at the level of the CPG to minimize or avoid the possible detrimental influence of swallowing without sufficient Psub (36).

Dynamic Systems Theory

Another explanation for motor control is the “action systems” approach, also known as the “dynamic” systems theory. The dynamic paradigm is a nonlinear model intended to encompass all levels of motion, from the psychological to neural substrates. Action and perception are tightly coupled with motor control and executed in a bottom-up fashion through the employment of “coordinative structures,” as opposed to the top-down control model represented by open-loop theory (2, 7, 37). Such coordinative structures operate within environmentally controlled constraints that ultimately impact the number of degrees of freedom available for movement pattern execution. The dynamic system seeks the condition of highest equilibrium known as an “attractor state” (47). The findings from this study can also be explained by the dynamic paradigm, if one would consider swallowing at higher lung volumes and positive Psub (FRC and TLC) to be viewed as attractor states.

Based on the results of this experiment that show an influence of the respiratory system on swallowing, the larynx and pharynx, along with their neural substrates, may serve as coordinative structures. In the dynamic model, the mechanoreceptors of the subglottic larynx may have induced a new, unestablished attractor state, or applied a constraint on the swallowing structures, when low Psub (RV) was revealed during the swallow as the true vocal fold adducted. To ensure
the successful completion of the overall motion goal (i.e., swallowing without aspiration), the coordinative structures changed their synergistic motions via compensatory adjustments that prolonged PAD (20). The temporal changes that occurred during pharyngeal activity at the different lung volumes may yet be further explained by the direct application of dynamic theory to the CPG for swallowing.

**Dynamic Theory and CPGs**

Conceivably, dynamic systems theory can be used as a heuristic device for explaining the prolonged duration of PAD at RV compared with TLC and FRC. The durational difference between the conditions may be indicative of the underlying neural mechanisms within the brain stem CPGs for respiration and swallowing, wherein the neuronal network was forced to select alternative neural connections when signaled by the larynx as to the condition (pressure) of the airway during the swallowing sequence. A model that addresses such a concept has been proposed by Chiel et al. (10).

Chiel et al. (10) developed a quantitative model of the dynamics of CPGs in walking in an attempt to provide quantitative insight into their operation. They theorized that neural circuits might be dynamically reconfigured by intrinsic and extrinsic neuromodulation. The authors envisioned the CPG as possessing a "steady state" (attractor state), where it functions optimally with highest speed and efficiency. Whereas these authors performed complex mathematics using a three-neuron model for walking, several of the analogies they described can be used to help to understand a possible explanation for the increased duration of the PAD in the RV condition. Because swallowing is currently believed to be governed by a CPG, as is walking, it is not unreasonable to make comparisons between gait and swallowing at the level of the CPG.

Time constraints within a CPG originate from the relationships of their synaptic connections to one another. Variations exist in the strength of both inhibitory and excitatory connections between all neuronal components. Steady-state function within a CPG would most likely have the strongest of both types of synaptic connectivity. Within the steady-state condition, the rate of change of the output would be zero. Neural circuits can be phasically altered by sensory feedback that can transiently inject synaptic currents into different neurons more loosely bound to the steady-state group. This condition would result in the need for the CPG to make a transition away from the steady state by using alternative connections and neurons. A new set of constraints would then exist and be dependent on the duration of the transition and the sensitivity or robustness of the briefly reconfigured module. Mathematically, if, for example, five transitions were required, the sum of their durations would then equal the total duration of the resulting motor pattern. Therefore, increased durations would be measured in motor patterns or sequences that occur away from the steady-state function compared with the steady state.

Applying this logic to our experiment, swallowing at TLC or FRC may be at the steady-state condition or nearest to the actual attractor state for swallowing. Swallowing at RV, however, may have prompted the need for several transitions within the CPG in order for successful swallowing to occur. As was previously stated, the number of transitions and robustness of the synaptic currents, when summed, would equal the total duration of the motor pattern. Therefore, the PAD was significantly longer when swallows occurred at RV (lowest entropy/furthest away from steady-state or attractor state) compared with swallows occurring at both TLC and RV.

In summary, swallowing is an essential motor pattern that incorporates peripheral sensory information into its motor output. There is now a strong implication, based on this experiment and others, that a portion of the afferent information may come from the respiratory system. This determination would dispel the current conception of the interaction between respiration and swallowing as a simple reciprocity and expand the understanding to that of an interactive cooperation.

The value of continued exploration into this matter could ultimately benefit individuals who suffer from neurological insults, such as stroke or Parkinson's disease. For example, in patients with stroke, prolonged pharyngeal transit times have been identified as one of the risk factors for developing aspiration pneumonia (17). Furthermore, it has been suggested that persons with neurological impairment may show a disorganization of the normal coordination of respiration and swallowing and may swallow at points in the respiratory cycle when lung volumes (and subsequently Psub) are low (39). Perchance the omission of respiratory information in the diagnosis and treatment of dysphagia in today's clinical practice may reduce diagnostic accuracy and treatment effectiveness if normal respiratory patterning during deglutition is critical to safe swallowing. Ultimately, the development of treatment paradigms for oropharyngeal dysphagia may take respiratory status into consideration.

Future experiments that seek to measure swallowing muscle activity and respiratory measures may reduce data loss by employing submental EMG measurements that will not be subject to dislodgment from bolus passage or by using a bipolar suction electrode (30). To minimize respiratory data loss, subjects could be briefly trained before data collection with the Respiration in place; however, this could pose a threat to internal validity, because habituation may take place before data collection.

DISCLOSURES

This study was supported by the Veterans Affairs Geriatric Research Education and Clinical Center.
REFERENCES


