Laryngeal activity during upright vs. supine swallowing

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Barkmeier, Julie M., Steve Bielamowicz, Naoya Takeda, and Christy L. Ludlow. Laryngeal activity during upright vs. supine swallowing. J Appl Physiol 93: 740–745, 2002. First published March 15, 2002; 10.1152/japplphysiol.00380.2001.—Previous investigations of human pharyngeal muscle activation patterns during swallowing found a relatively invariant muscle activation onset sequence in the upright position. However, different gravitational forces influence a liquid bolus when supine and could modify the central timing control of laryngeal airway protection during swallowing. The purpose of this study was to determine whether laryngeal muscle onset timing during swallowing differed between the supine and upright positions. Nine subjects performed six swallowing trials with a 2-ml water bolus in each position. Simultaneous electromyographic recordings were obtained from the submental complex (SMC) and the right and left thyroarytenoid (TA) muscles. Regardless of body position, the timing, amplitude, and duration of the TA muscles did not vary relative to the SMC. Therefore, the sequence of TA muscle activation relative to the SMC during swallowing appeared unaffected by gravitational influences.

central pattern generator; larynx

SWALLOWING CONSISTS OF TWO phases of muscle patterning. The first, the oral phase, is variable and thought to be largely under volitional control. The second, the pharyngeal stage, appears to be controlled by a central pattern generator (CPG) once the swallow is initiated (10). The pharyngeal stage of deglutition begins with activation of the mylohyoid and superior constrictor (SC) muscle (4, 18, 19) and ends when the bolus passes into the esophagus subsequent to the relaxation of the upper esophageal sphincter (17).

Invariant sequential activation of oropharyngeal muscles during swallowing has been reported in several animal models (2, 4, 12, 16) and in humans (5, 19). This stereotypical sequence of pharyngeal stage muscle activation is considered to be under the control of a CPG within the medulla. This CPG consists of two regions located bilaterally within the medulla that control and coordinate each side of the pharynx during a swallow (9–11). In addition, a complete swallow appears triggered only when afferent excitation is transmitted to the CPG through the internal branch of the superior laryngeal nerve (SLN) (10, 16). Once triggered, the muscle sequence for swallowing is controlled within the solitary-ambiguous pathway (10, 13, 16).

Cortical and other supramedullary regions can modify the swallowing CPG during the volitional “preswallowing” oral stage of deglutition (10). During the oral stage of deglutition, afferent information is obtained by oral structures related to bolus size and consistency. In addition, the pharyngeal phase of swallowing appears to be triggered by stimulation of afferents in the SLN branch of the vagus and the glossopharyngeal cranial nerves (7, 10). Based on the size and consistency of a bolus, the amplitude and duration of muscle contractions during swallowing can be modified (7). However, the sequence of muscle activation during swallowing remains consistent in the upright position, regardless of changes in the duration and amplitude of muscle contraction (7, 19).

The stereotypical muscle contraction during the pharyngeal phase of deglutition is associated with two purposes. The first purpose is to continue the propulsion of the bolus toward the stomach, and the second is to keep the bolus from entering the airway. Thus the larynx serves the dual role of protecting the airway during swallowing and regulating the entrance to the lower airway during respiration. This dual role requires coordination of respiration with swallow onset, as demonstrated by the observation that normal humans typically initiate swallowing during expiration (14, 22).

Most research investigating intact humans swallowing has primarily described muscle patterns in the upright swallow (14, 19, 22). However, previous investigations have suggested that body position (e.g., upright vs. supine) may have gravitational effects on the speed of the bolus during pharyngeal transport (8) and pharyngeal peak pressures (3). In the upright position, gravitational forces appear to facilitate faster movement of the bolus through the pharynx with subsequent early peak pharyngeal pressures. In contrast, the bolus appears to travel more slowly through the pharynx in the supine position and is associated with later maximum pharyngeal peak pressures. These
findings suggest that the onset of the laryngeal protective response may need to alter when swallowing occurs in different body positions.

Assuming that gravitational effects on oral bolus transport differ from those reported for pharyngeal transport, a liquid bolus could be predicted to move more quickly from the oral cavity into the pharynx during supine than in the upright position. Earlier findings of a later onset of peak pharyngeal constriction in the supine position compared with the upright position, however, might leave the airway unprotected and at greater risk for aspiration. Thus to provide airway protection, the laryngeal adductor muscles might need to activate earlier, before the onset of the swallow, in the supine position compared with a later onset time in the upright position.

The purpose of this investigation was to determine whether the timing and activation of laryngeal adductor muscles differ when airway safety is modified by body position. We hypothesized that laryngeal adduction might occur earlier relative to the initiation of a swallow when there is a possibility of an earlier entry of the bolus into the pharynx in the supine position than in the upright position.

METHODS

Subjects. Nine normal volunteers, four men and five women, between the ages of 25 and 57 yr (mean = 41 yr) participated. After informed consent to participate in an Institutional Review Board-approved protocol was obtained, subjects completed a medical history questionnaire and received a physical examination. An otolaryngologist used nasolaryngoscopy to confirm normal laryngeal structure and function. All subjects were without swallowing or neurologic abnormalities. Subjects were excluded if they used central nervous system depressants or muscle relaxants.

Electrode placement and recording procedures. Two-volt, peak-to-peak, square-wave calibration signals were recorded for each electromyographic (EMG) channel on a TEAC multiple-channel FM data recorder before a study. Subjects were electrically grounded and placed in a supine position with the neck extended for placement of the electrodes. To reduce discomfort during electrode insertion into the right and left thyroarytenoid (TA) muscles, 1% Xylocaine with epinephrine (1:100,000) was injected subcutaneously over the cricothyroid membrane before insertion of the EMG electrodes. A bipolar needle electrode (27 gauge) was used to locate each of the laryngeal and extralaryngeal muscles before placement of bipolar hooked-wire electrodes (6). Verification of correct placement in the right and left TA muscles was determined by increased activation during sustained phonation and effort closure. Muscle bursts at the onset and offset of phonation, without sustained activity during phonation, indicated electrode placement in the lateral cricoarytenoid rather than the TA muscle. When this occurred, the electrode was moved to a more anterior and superior position. Submental complex (SMC) electrodes were placed posterior to the mental symphysis and off the midline in the region of both the mylohyoid and geniohyoid muscles. Verification of electrode placement in the SMC was indicated by increased activation during swallow onset, as well as on tongue extrusion (19). Electrodes were inserted into the SC muscle lateral to the median raphe of the posterior pharyngeal wall, inferior to the lower boundary of the soft palate. Verification of electrode placement into the SC muscle was indicated by increased activation with the onset of a pharyngeal swallow (18). After satisfactory activation patterns were determined with the bipolar needle electrode probes, bipolar insulated hooked-wire electrodes were inserted into a muscle with a 27-gauge, 30-mm carrier needle. Verification gestures confirmed satisfactory placements.

EMG signal recordings were band-pass filtered between 100 and 5,000 Hz, amplified, and recorded onto a TEAC multiple-channel FM recorder. A Siemens piezoelectric movement transducer was placed on the skin overlying the thyroid cartilage to monitor movement of the larynx during the pharyngeal stage of the swallow (21).

All subjects were tested in the supine position and then the upright position. Because electrode placement was performed in the supine positions, the supine position was tested first to reduce the risk of electrode extrusion, which would have increased with multiple repositioning movements.

Signals were recorded during quiet breathing and before the onset of swallowing. Six swallows of a 2-ml water bolus were recorded in each position. During each trial, the 2-ml bolus of water was placed in the subject’s oral cavity with a syringe. The subjects were instructed to hold the water bolus in their mouth until a cue was given to them to swallow. After completion of six such swallows in the supine position, the subject was moved to the upright position, and the recordings were repeated in the same fashion.

Data analysis. The EMG recordings and piezoelectric and calibration signals were digitized off-line at 5,000 samples/s with anti-aliasing, low-pass filtering at 2,000 Hz. Linear interpolation from the calibration signals was used to convert the EMG signals into microvolts. Nonrectified data were averaged for each EMG channel during 10 s of quiet respiration, and the mean value was subtracted to correct each EMG channel for direct-current offset. After correction for offset, the signals were then rectified, and the minimum level between motor unit firings during quiet respiration was determined. This was subtracted from all EMG recordings for an electrode to correct for differences in electrode impedance. This correction was usually <1 μV.

The EMG signals were then smoothed by computing the mean at a decimation ratio of 1:20 with MITSYN command language (Henke, Boston, MA) software. Thus each display point represented the smoothed amplitude (in μV) over 20 ms for each EMG signal (Fig. 1). By using a smoothed EMG signal, the peak EMG signal was less affected by individual motor unit firings and a more reliable indication of overall muscle activation.

The onset of laryngeal movement during a swallow was identified by using the piezoelectric laryngeal movement transducer signal. The onset and offset of a laryngeal movement during swallowing was defined as a significant departure from the resting position and a return to the resting position of the piezoelectric signal (see onset and offset markers in Fig. 1). The piezoelectric signal had been previously shown to be accurate for locating laryngeal movement onset associated with the onset of the pharyngeal stage of a swallow (21).

Onset of the swallow was defined as the peak amplitude of the smoothed SMC signal in all nine subjects (18, 19). The SMC was used because accurate placement of the SC hooked-wire electrode could be maintained for both the supine and upright positions in only three of the subjects. To determine whether the SC and SMC recordings demonstrated similar timing for swallow onset, a correlation analysis was performed between the SC muscle onset and the smoothed peak of the SMC signal. The peak of the SMC signal was highly
correlated with the onset of the SC muscle in the three subjects, with a Pearson correlation of 0.95 in the upright position and 0.99 in the supine position (Fig. 2). The average difference in onset time between the peak SMC and SC signals varied, however, to a similar extent in the supine and upright positions. The mean difference in the supine position was $0.116 \text{ ms}$ (ranging from $0.640$ to $0.030 \text{ ms}$) and was $0.148 \text{ ms}$ (range from $0.550$ to $-0.020 \text{ ms}$) in the upright position. Although the SC and SMC differed in onset time, they were highly correlated and differed to a similar degree in the two positions. The time of the peak SMC amplitude, therefore, was used as the reference time for comparing the activation onset and offset of all of the other muscles (see the right and left TAs, SC, and the SMC in Fig. 1).

Resting baseline EMG amplitude measures for each muscle (SMC, SC, TA) were obtained from a 100-ms window beginning 1 s before the peak SMC. Onset of muscle activity relative to SMC peak was then defined as the point in time at which the EMG signal exhibited a threefold increase in amplitude from its average resting baseline. Offset of muscle activity was defined as the point subsequent to EMG onset at which activity returned toward the resting baseline and became less than a twofold increase from its average baseline.

The onset and offset of TA muscle activity relative to the peak SMC signal were normalized across subjects by coding the peak SMC signal time as the 0 point and computing the difference between onset times and the time of the peak of the SMC signal. A negative time difference indicated that the TA muscle onset preceded the peak of the SMC. In contrast, muscle onset after the timing of the peak SMC was a positive time difference. Duration of muscle activity was computed as the offset time minus the onset time (in ms). Average EMG

### Table 1. Results of repeated ANOVAs examining effect of laryngeal muscle side, body position, and side-by-position interactions in time of muscle onset relative to the peak SMC, the total area under the curve measuring muscle amplitude of activity for swallow, and the duration of muscle activation for swallow

<table>
<thead>
<tr>
<th>Measure</th>
<th>Side</th>
<th>Position</th>
<th>Side by Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of onset</td>
<td>F</td>
<td>P</td>
<td>F</td>
</tr>
<tr>
<td>Amplitude</td>
<td>0.517</td>
<td>0.493</td>
<td>2.19</td>
</tr>
<tr>
<td>Duration</td>
<td>1.256</td>
<td>0.295</td>
<td>0.103</td>
</tr>
</tbody>
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Fig. 1. Superior constrictor (SC), submental complex (SMC), right thyroarytenoid (RTA), and left thyroarytenoid (LTA) muscle onset patterns relative to the piezotransducer signal (Piezo) in upright and supine positions. The solid vertical lines indicate the onset and offset of a swallow as determined from the piezosignal. The arrows indicate the peak of SMC activation.

Fig. 2. Relationship between the SMC and SC muscle onset.
amplitude (in μV) was automatically calculated for the duration of muscle activity. The total area under the curve was calculated by multiplying muscle activation duration (ms) by the average EMG amplitude (μV).

All measures were obtained for six trials in the upright and supine positions for all nine subjects. EMG amplitude comparisons were only made within the same electrode recordings in a muscle from a subject in the two positions.

Repeated ANOVAs were computed to compare means in the two positions within subjects for each of the dependent measures: onset time for the TA muscles relative to the time of the SMC peak, and the duration and amplitude of muscle activity. In addition to comparison of the upright and supine positions (a repeated factor), between-subjects’ effects were examined both for muscle side (right vs. left) and interactions between body position and muscle side.

RESULTS

Each of the repeated ANOVAs between the supine and upright positions was nonsignificant (P > 0.05) on the measures of muscle onset times relative to the time of the peak SMC, the area under the curve (amplitude), and duration of muscle activity. F ratios were also computed to compare the right and left sides and the side-by-position (supine vs. upright) interactions. None was significant at the 0.05 level (Table 1).

The onset of the SMC preceded the SMC peak by >200 ms in three of the nine subjects (Fig. 3). The onset of the right and left TA muscles, however, preceded the SMC peak by <100 ms in eight of nine subjects, was either <100 ms before the SMC peak or followed the SMC peak in eight of the nine subjects in the supine position, and was within 100 ms or after the SMC peak in six of the nine subjects in the upright position (Fig. 3). These findings indicated that onset of the TA muscles in both positions tended to occur coincident with or after the peak SMC or onset of the swallow.

Six of the nine subjects had an earlier onset of the right TA in the upright position than in the supine position (Fig. 3). Similarly, six subjects had earlier onsets in the upright position than in the supine position in the left TA. Neither of these trends for earlier TA muscle onset in the upright than in the supine position, however, was statistically significant (P > 0.05).

The total amplitude (area under the curve) for either the right or the left TA muscles tended to be greater in the upright position than in the supine position in about one-half of the subjects. The total amplitude of laryngeal muscle activation either stayed the same between the two positions or increased in all but one subject in the upright position (Fig. 4).

No group trends were found for a directional change in the duration of the SMC or TA muscle activations for swallow in the upright and supine positions on either
side of the larynx (Fig. 5). Finally, the sequence of timing of the muscles relative to the peak SMC did not change in the two positions (Fig. 6). On average, the onset of the SMC preceded onset of the SC, and onset of the SC was followed by onset of the TA muscles, in both positions.

**DISCUSSION**

The results of this study demonstrated that the TA muscles did not activate in a different sequence for swallowing in the upright and supine positions. Therefore, the sequence of activation of laryngeal muscles appeared invariant, despite changes in the direction of gravity on the swallowing mechanism. Our hypothesis that laryngeal muscle activity would occur earlier in the supine position because of gravity was not supported by the results.

Of particular interest was the finding that the amplitude of TA activation did not differ significantly between the upright and supine positions. There were nonsignificant trends, however, for earlier and greater laryngeal muscle activation in the upright position. This latter trend was opposite from our prediction that the supine body position would require earlier onset of laryngeal muscle activation because of the potential for earlier entry of the bolus into the pharynx. Perhaps one explanation might be that, in the upright position, the bolus (in this case, water) is propelled along the anterolateral walls of the pharynx in such a way that penetration into the laryngeal vestibule may be more likely. On the other hand, in the supine position, the liquid may project toward the posterior pharyngeal wall and may be less likely to enter the laryngeal vestibule. These possible differences in the direction of flow might explain a need for the vocal folds to adduct for liquids more rapidly and to a greater degree in the upright position.

In this study, the timing of oral transit from the oral cavity into the laryngopharynx was not measured in either body position. Ingervall and Lantz (8) demonstrated faster pharyngeal transport of a bolus during upright than during supine swallowing. Videofluoroscopy could be used along with EMG recording to determine whether laryngeal muscle activation is influenced by the speed of bolus transit from the oral to the pharyngeal cavity. Given the lack of a consistent pattern of difference in laryngeal muscle activation timing between the two positions across subjects, it might be worthwhile to determine whether variations in bolus transit would closely relate to laryngeal muscle timing during swallowing.

Previous work investigating the effect of bolus size and viscosity on the pharyngeal swallow in the upright position demonstrated associated changes in laryngeal closure duration, cricopharyngeal opening, and contact time between the tongue base and the posterior pharyngeal wall (15, 20). Perlman et al. (19) demonstrated that these changes in the pharyngeal phase were not associated with an altered sequence of pharyngeal muscle activation in the upright position. Thus the pharyngeal stage of the swallow maintains the same sequence of muscle activation but accommodates
changes in size and viscosity by altering the amplitude and duration of muscle activity. In our study, the TA muscle activity was not altered consistently between upright and supine body postures. In five subjects, onset of the right or the left TA muscle preceded the peak SMC (Fig. 3). This indicated that some individuals had an earlier onset of laryngeal closure relative to their swallow onset. Alternatively, peak SMC activity may have been affected by position such that it did not accurately reflect onset of the swallow in some individuals. In the three subjects in whom the SC muscle was studied, there was a high correlation between the peak SMC and SC onset at the beginning of swallowing (Fig. 2). However, the interval between the onsets of the two muscles varied considerably: the mean difference was 148 ms, but, in one instance, onsets differed by as much as 780 ms. If SC muscle recordings could be obtained across all subjects, it could be determined whether those individuals with TA muscle onset ahead of peak SMC showed the same finding relative to SC muscle onset.

The water bolus used in this study was only 2 ml rather than a larger bolus size (5–15 ml), such as those used in previous investigations of the pharyngeal swallow in humans (1, 3, 5, 8, 15, 19, 20). The size of the bolus chosen for the present investigation is slightly larger than a saliva bolus. Perhaps variations in bolus size and viscosity might have provoked changes between the upright and supine body positions.

It is well known that the onset of swallowing can be influenced by stimulation of afferents in the SLN (10). Our results suggest that, although swallowing initiation may be triggered by the entry of the bolus into the hypopharynx, the timing of laryngeal muscle activation within the pharyngeal phase of swallowing was not altered by changes in gravity due to different body postures.

REFERENCES