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ORIGINAL ARTICLE

Effects of Bolus Volume on Pharyngeal Contact Pressure During Normal Swallowing

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Abstract This cross-sectional study investigated the effect of bolus volume on contact pressure within the pharynx and upper esophageal sphincter (UES). Three solid-state manometric pressure sensors were placed transnasally into the pharynx and the proximal esophagus of 40 participants (gender equally represented and between the ages of 20 and 45 years). Participants completed five repetitions each of three swallowing conditions: 5-, 10-, and 20-ml water bolus swallows. Repeated-measures ANOVA revealed no significant differences in the amplitude of pharyngeal contact pressure between the three swallowing conditions (sensor 1: $p = 0.627$, sensor 2: $p = 0.764$). Similarly, for durational measures nonsignificant main effects were found at both sensor 1 ($p = 0.436$) and sensor 2 ($p = 0.350$). Significant differences were found in UES pressure between the three conditions of bolus swallows ($p = 0.000$), with negative pressure in the UES inversely proportionate to bolus volume. However, durational measures of UES relaxation pressure were not significantly different between all conditions ($p = 0.473$). This study demonstrates no significant pressure differences of amplitude and duration between swallowing conditions in the pharynx. At the level of the UES, smaller boluses generated greater negative pressure.

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Over the past 20 years there has been an abundance of research investigating swallowing physiology and biomechanics. Using techniques such as videofluoroscopy, manometry, and electromyography, adaptation of swallowing physiology has been studied with the goal of understanding basic biomechanics and potential for rehabilitation. Interpretation of current research is clouded by discrepancies in methods; in particular, there have been inconsistencies in how measurements were defined and the use and volume of bolus evaluated. The effect of bolus volume has implications not only in research but also in clinical practice, as the safety and competence of swallowing in the patient with dysphagia may be significantly affected.

Early research investigating normal swallowing suggested that pharyngeal clearance was largely the result of the "peristaltic wave" of the pharyngeal constrictor muscles. However, it is now widely accepted that approximation of the base of the tongue to the posterior pharyngeal wall is likely to be the primary mechanism for propulsion of the bolus through the pharynx [1–3]. Once the majority of the bolus has passed through the upper esophageal sphincter (UES), there is an increase in activity by the pharyngeal constrictors, detected manometrically as an increase in pressure [1]. Therefore, the main role of pharyngeal contraction is to clear the pharynx of residue before the larynx reopens on completion of the swallow [1].

Previous research has investigated biomechanical modifications to the pharyngeal swallow with changes in bolus volume [4–8]. Although reconfiguration of the pharynx (such as tongue loading and closure of the laryngeal vestibule) has been found to change with alterations in bolus volume, pharyngeal clearance mechanisms (tongue pulsion and pharyngeal contraction) have been found to remain relatively stable [9].

Propagated pharyngeal contraction has been described as "a highly stereotyped event" [6, p. 135], such that bolus volume has been found to have no great effect on characteristics of pharyngeal constrictor activity [6]. In particular, the rapidity of pharyngeal wave contractions [4, 5, 8] and the maximal anterior bulge of the posterior pharyngeal wall during a contraction were found to be unaffected by bolus volume [6, 7]. These previous studies differ in their focus and design, with relatively small numbers of subjects and differences in method (combining videofluoroscopy with manometry versus manometry alone) and catheter design. Furthermore, these previous studies have provided a range of pharyngeal biomechanical measures rather than specifically investigating pharyngeal contact pressure necessary for the clearance of pharyngeal residue.

Shaker et al. [9] used manometric strain gauges to investigate changes in intrabolus and pharyngeal contact pressure in 26 healthy participants. This research studied the variables of aging, temperature, consistency of the bolus, and bolus volume. Results demonstrated that bolus volume had no significant effect on the amplitude or duration of pharyngeal contact pressure in both young and elderly age groups.

Similarly, Kahrilas et al. [7] used combined videofluoroscopy and manometric strain gauge sensors to investigate a variety of measures pertaining to pharyngeal clearance. Included in this study were data on the timing and amplitude of peak pharyngeal contact pressure. Results revealed that the only effect of increasing bolus size on manometric pressure wave formation was sequentially later luminal closure. In other words, the period of intrabolus pressure preceding the main pressure wave was slightly prolonged, resulting in a slightly later main pressure rise, representing luminal closure as the pharyngeal constrictors made contact with the sensors [6]. However, this study did not systematically investigate water boluses of increasing volume, but compared 5- and 10-ml water boluses [6].

Castell et al. [11] used a solid-state manometric transducer to study temporal sequencing of contact pressure within the pharynx and UES during dry, 5-, 10-, and 20-ml water swallows. Although the range of peak manometric pressure values was cited, there was no comment on whether bolus volume had any significant effect on the amplitude of pharyngeal contact pressure. This group, however, did report increases in the duration of pharyngeal contraction as bolus size increased from 5 ml to 20 ml. In addition, differences between dry and wet swallows were observed, with slower and more sustained periods of pharyngeal contraction with wet swallows.

Bolus volume-related changes in the UES have also been widely documented [4, 5, 11, 12]. Research has found anterior hyoid movement, which is necessary for UES opening, is minimally affected by increases in bolus volume [4]. However, the extent of UES opening increases proportionate to bolus volume [4, 5, 11, 12], with larger bolus volumes resulting in lower UES nadir pressure prior to UES opening and consequently a dramatic rise in UES intrabolus pressure during transsphincteric flow [4]. This suggests that intrabolus pressure, and therefore bolus volume, is an important factor in maximizing UES distension during cricopharyngeal relaxation [4].

Bolus volume affects not only the extent of UES opening, but also its duration [4, 5, 10, 13]. Videofluoroscopic swallowing studies (VFSS) have shown that larger bolus volumes significantly increase the duration of hyolaryngeal excursion, and thus result in proportionately longer UES opening periods [4, 13]. Similarly, manometric studies have shown increased duration of positive intrabolus pressure during UES relaxation as bolus volume increases [5, 10].

Much of the previous research has concentrated on reconfiguration of pharyngeal structures and the timing of a number of swallowing events within the pharyngeal phase [4–7, 9, 11, 13]. Other research has investigated the effect of bolus volume on intrabolus pressure in the pharynx and UES [4, 11, 12]. However, little research has focused solely on pharyngeal contact pressure, which is vital for clearance of pharyngeal residual. The present study aimed to investigate pharyngeal contact pressure during swallows of increasing bolus volume. In addition, the effect of bolus volume on relaxation pressure in the UES was recorded to compare with previous research. It is hypothesized that bolus volume will have no effect on amplitude and duration of pharyngeal contact pressure, as previous research has overwhelmingly described propagated pharyngeal contraction as constant regardless of bolus volume. In addition, it is hypothesized that as bolus size increases there will be increasingly negative intraluminal pressure in the UES and the duration of UES relaxation will also increase proportionate to bolus volume.

Method

Participants

Forty young healthy volunteers (age range = 20–45 years, mean age = 25.8 ± 5.9 years; gender equally represented) provided data for this project. No participant reported a history or current symptoms of swallowing difficulty, medication known to interfere with swallowing, or history of neurologic and/or muscular diseases. Informed consent was obtained from all research participants prior to initiating data collection. Ethics approval was obtained by the appropriate institutional review board.

Procedure

All data were collected in a specialized swallowing research laboratory, located in a freestanding research facility. Participants were seated in an upright position facing forward. A manometric catheter (Medical Measurements Inc.; Model CT/S3 + emg, 2.1 mm in diameter) with three solid-state manometric pressure sensors was placed transnasally, through the pharynx and into the proximal esophagus. Correct catheter placement was confirmed using a pull-through technique, until the most distal sensor was in the high-pressure zone of the UES at rest and an "M" wave was clearly observed on swallowing. The catheter was then secured to the nose with tape to minimize sensor movement. The sensors were thus placed in the following pharyngeal locations: manometric sensor 1 (most proximal) was positioned approximately even with the superior tip of the epiglottis, manometric sensor 2 was placed approximately at the superior edge of the arytenoid cartilages, manometric sensor 3 (most distal) was positioned at the upper border of the high-pressure zone of the UES. Following placement of the catheter, research participants were asked to rest quietly for several minutes while instructions were read and time was allowed for sensorimotor accommodation to the catheter *in situ*.

Data Collection

Each research participant completed five repetitions of three swallowing conditions: water swallows of 5, 10, and 20 ml. The order of bolus swallows was randomized for each participant. Manometric data were visually displayed and stored on the Kay Elemetrics Digital Swallowing Workstation (Lincoln Park, NJ). Amplitudes and durations of manometric pressure measurements were collected offline. These measures were defined as follows:

- *Peak Manometry* Peak value in mmHg recorded at the apex of the waveform during a swallow.
- *Duration Manometry* Time between the onset and offset of swallowing-related pressure change. The onset of the swallow was defined as the point before the main pressure rise when the increments of positive pressure change are equal to or greater than 2 mmHg. The offset was defined as occurring at the point when the graph returned to baseline and the increments of negative pressure change were less than 2 mmHg.
- *Peak UES Manometry* Peak negative value in mmHg during UES relaxation.
- *Duration of UES Manometry* The duration of manometrically recorded change during UES relaxation was defined as the time between the two high pressure peaks surrounding the drop in UES pressure. These peaks were found where the increments of pressure change either reach the highest value or was equal to or less than 1 mmHg.

The above measures were then subjected to statistical analyses. Inter- and intrarater reliabilities were assessed using a randomly selected 20% of the data set using the intraclass correlation coefficient (ICC) based on variance estimates obtained through analysis of variance (ANOVA). Bolus volume effects on measures of pharyngeal biomechanics were compared using repeated-measures ANOVA.

Results

Intra- and Interrater Reliabilities

Intra- and interrater reliabilities were satisfactory, with ICCs ranging from a high of $r = 0.993$ for identification of peak manometric pressure, and a low of $r = 0.877$ for identification of duration of manometric pressure.

Analyses of Bolus and Bolus Volume at Manometric Sensors

Nonsignificant main effects for bolus volume were found for peak pressure amplitude of manometric sensor 1 ($F = 0.386$ [1, 1.539], $p = 0.627$) and sensor 2 ($F = 0.204$ [1, 1.580], $p = 0.764$). However, at sensor 3 (UES) significant main effects were found for pressure amplitude ($F = 8.743$ [1, 2], $p = 0.000$). Mean pressure data across trials as a function of bolus and bolus volume are presented in Table 1. Post-hoc paired-samples t tests were completed on data from sensor 3 which revealed significant differences between all conditions ($p < 0.05$), with less negative pressure in the UES as bolus size increased.

No significant main effects of bolus size were identified for duration of pressure at manometric sensor 1 ($F = 0.802$ [1, 1.719], $p = 0.436$) and sensor 3 ($F = 0.756$ [1, 2], $p = 0.473$). At sensor 2 significant main effects were found ($F = 3.733$ [1, 2], $p = 0.028$); however, paired sample t tests did not identify any significant differences between conditions in isolation. Mean duration of pressure data

Table 1 Mean pressure data across trials as a function of swallow condition (bolus volume)

	5 ml (mmHg)	10 ml (mmHg)	20 ml (mmHg)	p value for main effects
Sensor 1	94.535 ± 37.175	93.415 ± 32.711	93.815 ± 32.204	0.627
Sensor 2	91.695 ± 33.397	89.825 ± 26.912	91.635 ± 31.391	0.764
Sensor 3 (UES)	−7.897 ± 5.237	−6.329 ± 5.290	−4.398 ± 4.334	0.000

Values in columns 1, 2, and 3 are mean ± standard deviation

across trials as a function of bolus volume are presented in Table 2.

Discussion

The purpose of this study was to examine the effects of bolus volume on pharyngeal and UES pressure generation in healthy, young adult subjects. The amplitude and duration of pharyngeal contact pressure and UES relaxation pressure were examined during swallows of 5-, 10-, and 20-ml water boluses. This research expands on the existing literature by providing data collected from a large subject group during three bolus swallowing conditions and exclusively investigates pharyngeal contact pressure rather than intrabolus pressure of the pharynx.

Pharyngeal Contact Pressure

No linear relationships were found between bolus volume and the amplitude and duration of pharyngeal contact pressure. These results support those of Shaker et al. [9], who also reported that bolus volume had no significant effect on the amplitude or duration of pharyngeal contact pressure in both young and elderly age groups. Further support is provided by research that demonstrated that the extent [7] and velocity of pharyngeal contraction is stable regardless of bolus volume [6, 11].

Previous research has shown that pharyngeal contact pressure is created when the pharyngeal constrictors contract onto a largely empty lumen. The principal purpose of this appears to be clearance of residual following passage of the bolus head through the pharynx [6]. Taken in the context of existing literature, it would appear that sensory perception of increased bolus size may alter oropharyngeal biomechanics to modulate intrabolus pressure for superior to inferior transfer. However, the adaptation would appear to be sufficient for complete bolus propulsion, thus not influencing pharyngeal contact pressure for clearance.

Upper Esophageal Sphincter Peak Relaxation

In contrast to results of contact pressure in the pharynx, changes in bolus volume did affect intraluminal pressure in the UES. All three swallowing conditions were significantly different, with a smaller drop in negative intraluminal UES pressure as bolus volume increased. This finding is contradictory to previous research by Jacob et al. [5] which demonstrated a trend toward lower UES intraluminal nadir pressure with larger bolus volumes prior to sphincter opening. This trend, however, was not reported to be statistically significant and thus should be taken in that context. In addition, changes in the specific anatomical site of sensor location as a result of catheter movement within the pharynx and UES may account for these differences. Precise sensor location in the middle of the high-pressure zone of the UES during swallowing may record changes in UES pressure generation more accurately than if it moved above or below this zone. A concurrent fluoroscopic study would improve reliability between studies.

Cerenko et al. [2] described movement of the bolus head into the UES as a “suction pump” (p. 62). Similarly, Jacob et al. [5] proposed that the negative pressure prior to sphincter opening reflects hyoid-related traction force applied to the sphincter. Interestingly, in this study bolus volume did not have an effect on anterior hyoid movement [4]. Therefore, factors other than anterior hyoid excursion influence the degree of UES opening during swallows of different bolus volumes. Future research investigating disordered swallowing is needed to compare the timing and extent of maximal contact pressure and negative pressure in the UES with overall effectiveness of luminal clearance. However, further research into normal swallowing is needed first to clarify discrepancies in the research.

Table 2 Mean duration of pharyngeal pressure across trials as a function of swallow condition (bolus volume)

	5 ml (mmHg)	10 ml (mmHg)	20 ml (mmHg)	p value for Main Effects
Sensor 1	0.425 ± 0.141	0.418 ± 0.143	0.438 ± 0.154	0.436
Sensor 2	0.346 ± 0.175	0.345 ± 0.188	0.332 ± 0.167	0.028
Sensor 3 (UES)	1.064 ± 0.229	1.088 ± 0.220	1.066 ± 0.258	0.473

Values in columns 1, 2, and 3 are mean ± standard deviation

Upper Esophageal Sphincter Relaxation Duration

The effect of bolus volume on UES relaxation duration was nonsignificant in the present study. This contradicts our hypothesis that relaxation pressure in the UES would increase in duration with increases in bolus volume. This hypothesis was based on research that demonstrated a positive linear relationship between bolus volume and duration of UES relaxation [4, 5, 9–11]. In addition, Ertekin et al. [15] published electromyography (EMG) data from the cricopharyngeus (CP) muscle that suggest increased duration of CP muscle inhibition as bolus volume increased.

The discrepancies in our findings may be explained by fundamental differences in the definition of UES relaxation. While we defined UES relaxation as the latency between the two peaks of the typical M-wave observed during relaxation [10], Kahrilas et al. [6] defined UES relaxation as the "period beginning when the sphincter pressure reached its minimal value and ending when a rapid upstroke in pressure began". In contrast, Jacob et al. [5] defined UES opening duration as the time between the beginning of intrabolus pressure recorded in the relaxed UES and the sudden rise of pressure at the end of UES relaxation. These differences in measurements may well account for the contradicting results of the current study. Physiologically, UES peak-to-peak relaxation measures the period between the very beginning of cricopharyngeal muscle relaxation with the hyoid in maximal anterior position and the very end of sphincter relaxation when the muscle contracts before the hyoid relaxes to resting position. This measurement of UES relaxation is therefore tightly related to active contraction of the cricopharyngeus during peak hyoid placement. In contrast, the measures investigated by Kahrilas et al. [6] and Jacob et al. [5] appear to be more sensitive to bolus volume effects, as they strictly limit measurement to bolus passage through the completely opened UES. Together with the data of the current study, these results suggest that bolus volume has an effect on peak intrabolus pressure and intrabolus pressure duration within the period of complete UES relaxation but does not affect the period of overall peak-to-peak UES relaxation.

Perlman et al. [16] used electromyography to measure the duration of EMG activity in a variety of muscles involved in swallowing. For the cricopharyngeus (CP) muscle, this group found no differences in swallowing-related EMG quiescence across bolus volumes (saliva, 5-, and 10-ml water boluses). For the submental muscle group (namely, suprahyoid muscles), which plays an important role in UES opening via hyoid-related traction forces [4], no bolus-dependent changes in the duration of EMG activity were reported. Similarly, Rademaker et al. [17] reported no differences in the duration of hyoid movement across bolus volumes in a mano-videofluoroscopic study.

These results, along with those of Kahrilas et al. [6] and the current study, support the idea that factors other than just cricopharyngeal relaxation, such as laryngeal elevation, contribute to UES opening. These data also tie in with the research on UES peak relaxation pressures discussed above. The nonsignificant effect of bolus volume on the duration of submental EMG activity [15] and hyoid excursion [16] support the findings of the current study. Because of the biomechanical relationship between hyoid movement and UES traction forces [4], it is not surprising that bolus volume also did not have an effect on UES peak-to-peak relaxation duration (based on the definition used in this study).

It is worthy of note that Ertekin et al. [15] reported contrasting results. This group documented a positive relationship between the duration of cricopharyngeal EMG quiescence and bolus volume. Furthermore, this group reported a positive relationship between the duration of submental EMG activity and bolus volume. Further research is clearly needed to investigate the effect of bolus volume on UES relaxation duration and other measures of swallowing biomechanics. It is critical that definitions of the measures investigated be standardized to allow for comparison between studies.

Conclusion

This study contributes to previous research investigating pharyngeal and UES pressure generation and highlights not only the complexity of the pharyngeal swallow but also the need for standardization of measurements that are typically used to describe deglutitive pressures. Specifically, this study sought to investigate pharyngeal and upper esophageal sphincter pressures during ingestion of boluses of increasing size. We conclude that contact pressures in the proximal and distal pharynx are not affected by bolus volume. However, a bolus volume effect was found within the UES, characterized by lower negative pressure as bolus volume decreased. This study will provide a useful comparison to future studies on bolus volume accommodation in disordered swallowing.

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