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Effect of Body Position on Pharyngeal Swallowing Pressures Using High-Resolution Manometry

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Abstract

Objectives—The effect of body position and gravitational pull on the complex pressure-driven process of pharyngeal swallowing remains unknown. Using high-resolution manometry (HRM), this study aims to identify positional adaptations of pharyngeal physiology by evaluating swallowing pressure patterns in a series of inverted body positions.

Methods—Ten healthy adults each underwent swallowing tasks with pharyngeal HRM at six body positions using an inversion table (0°(upright), 45°, 90°(supine), 110°, 135°, and 180°(fully inverted)). Repeated measures ANOVA was used to assess impact of position on pressure parameters, and pharyngeal-UES pressure gradients.

Results—Velopharyngeal pressures varied by position ($P<0.001$), with significantly higher pressures generated with inversion 90°, compared with upright and 45°. Change in position did not significantly affect common mesopharyngeal pressures or swallowing pressure durations. UES valving mechanisms were preserved during inversion, with subtle variations observed in integral pressures ($P=0.011$). Pharyngeal-UES pressure gradients changed with position ($P<0.01$), increasing with inversion $>90^\circ$ compared to upright and 45°.

Conclusions—Mechanisms of deglutition may differ with position and relative direction of gravity, particularly when at $>45^\circ$ inclination. Increased palatal pressure is generated in the upside-down position to achieve nasopharyngeal closure and prevent regurgitation. While other classically measured pressures may not consistently differ with positioning, many individuals exhibit adaptations in pressure gradients when inverted, likely due to a combination of changes in pharyngeal driving force and UES opening mechanisms. Identification of these changes, relative to

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position, further builds on our understanding of the adaptability of the pharyngeal swallowing system.

Keywords

deglutition; high-resolution manometry; inversion; gravity

INTRODUCTION

Pharyngeal swallowing is a fundamental human function that, when employed for digestion, is carried out primarily in an upright position.[1] This posture is not only considered socially acceptable for eating behavior, but is clinically recommended for many individuals as it is thought to contribute to effective delivery of ingested material to the esophagus and protection of the upper respiratory tract. Moreover, standard clinical evaluation of pharyngeal functioning is routinely performed while upright.[2] At the same time, it is accepted that both involuntary and volitional swallowing occur irrespective of body position in the healthy individual.

Initiation and facilitation of bolus movement through the pharynx requires precise neuromuscular coordination of motor events involving the oral and pharyngo-laryngeal anatomy. Control of this complex reflex cascade is thought to be primarily brainstem-driven, programmed within the medulla oblongata.[3–6] However, motor accuracy can also be ensured by neural modulation as a result of input obtained from peripheral sensory receptors and descending pathways from the cerebral cortex, sub-cortex, and cerebellum.[7,5,8] Changes in motor timing and force due to different bolus properties[8,9] and behavioral commands such as effortful swallowing,[10,8] are factors known to influence this physiological adaptability.

It has been suggested that swallowing reflexes may also be uniquely influenced by body posture. While gravity has been demonstrated to assist in distal esophageal bolus movement in the upright position,[11] it remains unclear to what extent position affects pharyngeal and proximal esophageal physiology. Clarifying swallowing mechanisms in non-upright positions has implications for various clinical and research based scenarios. Non-upright assessment of deglutition in hospitalized patients is frequently required when standard positioning is clinical contraindicated or is difficult to maintain.[12] Positional techniques are also important in dysphagia therapy. For example, therapeutic maneuvers largely include altering head placement, such as chin-down or head-back techniques, but can also involve the entire body. Reclining and side-lying positions are two body maneuvers that have been reported to reduce aspiration and bolus residue in cases of oropharyngeal dysphagia.[13–16] Improvement in swallowing safety is thought to result from change in the route of bolus flow and reduction of oropharyngeal residue, as a consequence of alteration in anatomical positioning, optimization of gravity, and or modulation of sensory stimuli.[12,17,18] While the value of non-upright maneuvers is clear, what constitutes normal swallowing physiology in these positions has not been fully investigated. Further, this lack of scientific knowledge has led researchers to question the generalizability of findings using imaging modalities, such as computed tomography and magnetic resonance imaging (MRI), that evaluate

deglutition in a semi-recumbent or supine position.[19] Thus, further study of the variations in swallowing mechanisms elicited by change in body position among healthy individuals is essential.

Previous researchers have used videofluoroscopy, electromyography (EMG), and other instrumented techniques to investigate effects of position on specific aspects of oropharyngeal anatomy and swallowing-related physiology; namely musculoskeletal kinematics,[12,17] timing and amplitude of muscular contractility,[20,21] and measures of bolus flow.[22,23,16,24] In addition, the influence of position on pharyngeal pressure events has been evaluated using conventional pharyngoesophageal manometry.[23,22,25,26] However, accurate characterization of the rapidly-changing pressures in the asymmetric pharynx demands greater spatiotemporal resolution than those allowed by previously-used manometry systems. Development of high-resolution manometry (HRM) has provided the ability to capture and report significant events simultaneously along the length of the pharynx.[27,10] With HRM, subtle adaptations in upper esophageal sphincter (UES) activity with head position maneuvers,[28] have been identified. These findings suggest the potential of HRM to more thoroughly evaluate position and pharyngeal pressurization.

The aim of this study was to use HRM to investigate the extent of pharyngeal and proximal esophageal swallowing-related pressure change in body position in healthy individuals. We hypothesized that in inverted positions we would see adaptations in velopharyngeal closure and pharyngeal clearance pressures. Further, we predicted intrabolus pressure, during pharyngeal transit, would change relative to body position and manifested as higher nadir UES pressures with inversion. Awareness of positional variations in pressurization can build on our current understanding of the adaptability of the volitional pharyngeal swallowing system in relation to stimuli, and may have important implications for clinical assessment and management of patients with dysphagia.

MATERIALS AND METHODS

Participants

Three males and seven females (mean age 27; range 20–51 years), without history of swallowing, respiratory, or neurological deficits participated in the study. The research protocol was approved by the University of Wisconsin-Madison Institutional Review Board and informed consent was obtained from each subject prior to participation. Participants were instructed to withhold from eating for four hours and drinking for two hours before taking part in the study to reduce the effects of satiety and potential for gastroesophageal reflux.

Data Collection

A solid-state, high resolution manometer (ManoScan360 High-Resolution Manometry System, Medtronic, MN) was used for data collection. This catheter has a diameter of 2.75 mm, with 36 circumferential pressure sensors (each 2.5 mm in length) spaced 1cm apart. Each sensor receives input from 12 circumferentially placed sectors that are averaged to yield one data stream per sensor. Catheter calibration was completed before each use to

record pressures between -20 and 600 mmHg, with a fidelity of 2 mmHg and a sampling rate of 50Hz. To lubricate passage of the catheter and act as an anesthetic, less than 1mL total of topical 2 % viscous lidocaine hydrochloride was applied to the nasal passages and catheter exterior before insertion. The catheter was subsequently inserted transnasally until it was positioned in the proximal esophagus. Prior to performing swallowing tasks, participants adjusted to the catheter by resting in the upright position. Each participant then swallowed three 5 mL boluses of water, delivered orally via a syringe, in each of the following body positions: 1) 180° (fully inverted); 2) 135°; 3) 110°; 4) 90° (supine); 5) 45°; and 6) 0° (upright) using a commercially available inversion table (Ironman LXT850). (Fig. 1). Participants were instructed to maintain a neutral head position during all swallowing tasks and to hold the liquid in the mouth until given a cue to swallow by the examiner. All participants tolerated instrumentation and completed the tasks without complication. Trials were completed in the order listed for both tolerability and safety reasons. Specifically, fully-inverted tasks were carried out first to reduce the likelihood of discomfort and gastroesophageal reflux secondary to gastric fluid accumulation. To further minimize anxiety and the unfamiliarity of using an inversion table, participants were given ample time before catheter insertion to experience and adjust to each of the six positions.

Data Analysis

A customized Matlab program (Mathworks Inc., Natick, MA) and automated analysis program[29,30] were used for data analysis. Regions of interest, including velopharynx, mesopharynx, and UES, were defined using recognized manometric trace features.[31,32] The velopharynx includes the two or three most superior sensors with bimodal, swallowing-related pressure waveforms. The mesopharynx is a combination of sensors located in the tongue base and hypopharynx regions and are identified by onset of pressure elevation which begins following onset of velopharyngeal activity. The unique pressure behavior generated within the UES region, is captured by sensors directly inferior to the mesopharynx region.[33] The proximal esophagus region includes the sensors directly inferior to the UES region to the superior margin of the pressure trough indicating the esophageal transition zone.[32] This transition zone was defined manometrically as a drop in pressure to below 20mmHg.

In the velopharynx and mesopharynx, mean values were calculated for the following parameters: *maximum pressure*, *pressure integral*, and *duration of pressure activity above baseline*. Pressure integral (pressure*time) is a global measure of regional pressure, calculated from area under the pressure curve between onset of pressure elevation to depression to baseline.[10] UES parameters included *maximum pre-opening pressure*, *maximum post-closure pressure*, *minimum pressure*, and *nadir pressure duration*. [32,10] *Pre-swallow average* and *maximum baseline UES pressures* were also calculated. For the proximal esophagus region, *pressure integral (pressure*time)*, *maximum pressure*, and *pressure duration* were calculated. Measuring variables that combine spatial and temporal parameters may add additional insight regarding pharyngeal physiology. In this study, we also analyzed novel measurements of *pharyngeal-UES pressure gradient*, calculated as the summation of pharyngeal pressures (velopharyngeal and mesopharyngeal) minus UES pressures. (Fig. 2). Specific variables included 1) *maximum pressure gradient*, or the

magnitude of pressure difference above zero mmHg; and 2) *integral of pressure gradient*, an estimation of overall difference above zero mmHg during a swallow. In contrast to other existing pressure gradient metrics, which describe the variable pressures exerted on a bolus, [34] *pharyngeal-UES pressure gradient* captures differences in contraction and distension pressures during a swallow. The relative difference in pressure generated between the regions may contribute to overall swallowing success. However, future study using this parameter in a heterogeneous group of swallowers is needed to determine its role as a marker of swallowing effectiveness.

Statistical Analysis

IBM SPSS Statistics Version 23 was used for analysis. Effect of the six positions on each parameter was assessed using one way repeated measures ANOVA. Greenhouse-Geisser correction was used when assumption of sphericity was not met. Pairwise comparisons were performed using Fisher's Protected Least Significant Differences test, without adjustment for number of comparisons. An alpha-criterion of $P = 0.05$ defined significance.

RESULTS

Example spatiotemporal plots of swallowing tasks in each of the six body positions are provided in Figure 3. Summary descriptive statistics, with results of main effects, are provided in Table 1. All data are reported as mean $\pm$ standard error. Graphs of maximum and integral pressure parameters, by pharyngeal region and degree of inversion, are illustrated in Figure 4.

Velopharynx

In the velopharynx, there was a significant main effect of position on maximum pressure ($F(2.619, 23.575)=9.603$, $P<0.001$). Significantly lower values were generated in the upright position (125 9mmHg) compared to 90° (146 15 mmHg), 110° (165 17 mmHg), 135° (159 12mmHg), and 180° (170 13 mmHg). Swallowing pressures at 45° incline (130 9mmHg) were similarly lower than pressures generated at 110°, 135°, and 180°. Pressures at 90° and 135° were also significantly lower than 180°. The same effects of position were identified for pressure integral ($F(2.108, 18.972)=9.737$, $P=0.001$). Duration of pressure was not affected by position.

Mesopharynx

Mesopharyngeal pressures trended upward with increasing degrees of inversion, with mean pressures ranging from 184 to 208 mmHg, though differences were not statistically significant. Duration of pressure was not affected by position.

Upper Esophageal Sphincter

Pre-opening maximum, post-opening maximum, and baseline pressures did not significantly differ with change in body position. A statistically significant main effect of position on minimum pressure was identified ($F(5,45)=2.599$, $P=0.038$) with minimum pressures generated at 45° and 90° higher than those at upright and 180°. No significant differences in nadir duration were observed.

Pharyngeal - UES Pressure Gradient

Position had a significant effect on maximum pressure gradient ($F(5,45)=6.758$, $P<0.001$). Differences were greater when swallowing at 90°, 110°, 135°, and 180°, compared to upright and 45° ($P<0.05$). Integral pressure gradient was also significantly affected by body position ($F(1.779,16.010)=6.926$, $P=0.008$). Integral pressure gradient increased at 90°, 110°, 135°, and 180°, compared to 45°, with a larger gradient at 180° in comparison to all other positions.

Proximal Esophagus

Position had a significant main effect on proximal esophageal maximum pressure ($F(5,45)=2.618$, $P=0.037$). Pressures generated were higher when at 90° and 135° compared to upright, and when at 135° compared to 110°. There was, however, no effect of position on pressure integral. Effect of position on pressure duration was significant ($F(5,45)=2.523$, $P=0.043$), with durations longer at 90° compared to 45° and 180°.

DISCUSSION

Identification of specific positional changes in pressure helps to inform researchers and clinicians about normal human swallowing physiology. As a result of this study, we observed adaptations in pharyngeal pressure amplitude but not pressure duration with change in position. Most notably, adaptations were evident in the velopharynx, where soft palate and associated lateral and posterior pharyngeal wall contraction protects the nasal airway from regurgitation of bolus material.[35] We found that there was a significant increase in pressure amplitude when subjects swallowed in positions ranging from supine (90°) to fully inverted (180°), compared to upright and 45°. It has previously been suggested that at rest the soft palate may assume a slightly more posterior position when supine compared to upright, which could affect the diameter of the velopharyngeal cavity.[36,37] However, as more recent studies have determined that the gravitational effect on velopharyngeal kinematics is minimal,[38,12] the notable pressure differences observed across positions in this study likely illustrate a neural compensatory change in muscular activation ensuring adequate closure in positions when gravitational force directs the bolus towards the nasopharynx, rather than away. Using conventional manometry, Nakayama et al[26] identified lower velopharyngeal pressures when swallowing in semi-inclined positions versus upright. In contrast, we did not find any notable differences between 0° and 45°. The similarities between physiological pressure behavior in upright and 45° positions add support to the validity of investigative modalities evaluating pharyngeal function in semi-reclined positions.

Evaluation of UES opening pressures illustrated that sub-atmospheric pressurization is achievable regardless of position. We had predicted that post-opening UES pressures would increase when swallowing in inverted positions to prevent retrograde bolus flow. Although pressures in most participants trended upward when inverted, differences between positions were not statistically significantly different. Many participants also exhibited a decrease in UES minimum pressures when swallowing in upside down positions, particularly when compared with supine positioning. These data suggest that subtle changes in the mechanical

state of the UES facilitate compensatory relaxation in response to altered direction of flow and intrathoracic pressure level. These changes may be exhibited via neural inhibition of the tonic baseline sphincter activity and or suprahyoid muscle contraction. Due to restrictions in using the inversion table, it was not feasible to carry out concurrent imaging as part of this study. Therefore, we were unable to correlate relative musculoskeletal kinematics with UES pressurization. However, previous studies have suggested that variations in anterior displacement of the hyoid bone in female subjects,[12] suprahyoid EMG activation duration, [17] and maximal UES sphincter diameter[22] may occur when swallowing in non-erect positions and are all in support of greater UES relaxation. Use of concurrent videofluoroscopy and/or EMG with HRM may be indicated in future analyses.

In the upright position, a bolus is propagated through the pharynx from high to low pressure areas.[31] When subjects in our study completed swallowing trials in supine to fully inverted positions, increased measures of pharyngeal-UES pressure gradient were exhibited. These differences identify amplification of the classic physiological state in these positions and appear to be attributed largely to the combination of changes in palatal force and UES relaxation described above. In the upright position, velopharyngeal closure is located superior to the bolus, and high driving pressures primarily are generated via tongue base retraction and pharyngeal constriction. However, when maneuvers result in velopharyngeal positioning inferior to the bolus, it is plausible that this regional pressure absorbs an additional role assisting in pressure gradient generation. The adaptations in pharyngeal and UES pressurization observed with body inversion also notably parallel the compensatory changes elicited with other tasks that challenge the system, including increased bolus volume [39,40] and effortful swallowing [10,41].

Previous studies have suggested that pharyngeal propulsion and laryngeal muscular activity may be stereotyped phenomena in relation to gravity and body position.[20,23,25,21] Interestingly, we observed an upward trend of mesopharyngeal pressure integral with increasing degrees of inversion. This indicates that subtle adaptations in pharyngeal driving and propulsion forces may also contribute to bolus residue removal and maintenance of gradient in different positions. Our results suggest, however, that while proximal esophageal maximum pressures and durations vary slightly, the overall striated muscle contraction may often be similar regardless of body position.

Positional changes to oral sensory input and pressurization, in addition to vestibular indicators of body placement and/or cortical modulation, may produce subtle adjustments in the motor planning of pharyngeal activity. Our study is also limited by the use of young, healthy participants. Moreover, with the sample size, we did not evaluate for differences in gender. Future study evaluating compensatory changes by age, gender, and swallowing dysfunction, using variability in bolus type and volume, is required to clarify gravitational pressure modifications specific to these situations. Additional study would need to be carried out to identify differences in prone inversion. It is also possible that completing swallowing tasks in a non-randomized order led to some adaptation of swallowing behavior. Finally, we were unable to comment on pressure changes in the distal esophagus due to limitations of catheter length.

CONCLUSION

Overall, we observed that subtle adjustments in pharyngeal and UES pressure amplitude occur with change in body position in order to maintain the physiological requirements that result in a successful swallow. Importantly, we identified that variations in pressure are most significant when swallowing in horizontal to fully inverted positions. These changes are prominent within the velopharynx, exhibiting adaptability of nasopharyngeal seal mechanics. Positional variations in pharyngeal-UES pressure gradient are also seen, as well as preservation of intra-UES valving mechanisms, regardless of position. Clinically, these adaptations are important to consider when carrying out dysphagia evaluations in non-standard positioning. Moreover, manipulation of gravitational advantage for deglutition may have therapeutic value for some individuals with swallowing difficulties and should be examined specifically. The similarity in pressure physiology between upright and 45° also provides support for the comparability of manometric studies, or other imaging techniques, undertaken in semi-supine positions with studies carried out while upright. Fundamentally, these results corroborate the idea that neural modulation of the brainstem-driven swallowing reflex may physiologically compensate for changes in body position in order to complete this fundamental task. Investigation into the specific sensory or cortical mechanisms that result in these changes is key to understanding the control of these adaptations, and thus should be a focus of future study.

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Fig 1. 5ml swallowing trials with concurrent high-resolution manometry evaluation were completed using a commercially available inversion table (Ironman LXT850) in the body positions illustrated above: 0° (upright); 45°; 90° (supine); 110°; 135°; 180° (fully inverted).

Fig 2.

Depiction of a pressure gradient waveform (above) with the corresponding spatiotemporal plot (below) from a 5ml swallowing task in the upright position and at 180° (fully inverted). Pressure gradient is calculated from the summation of pharyngeal pressures minus upper esophageal sphincter (UES) pressures. Negative pressure gradient values convey high UES and/or low pharyngeal pressure amplitude, while positive values indicate high pharyngeal and/or low UES pressures. Novel parameters are illustrated and include a) maximum pressure gradient (mmHg); and b) integral of pressure gradient above zero mmHg (mmHg*seconds). Regions of interest are also provided for reference on the spatiotemporal plot.

Fig 3.

Example spatiotemporal plots of swallows from a single subject in the six body positions exhibiting differences in velopharyngeal and upper esophageal sphincter pressures as a result of change in body position.

B) Pressure Integral

A) Maximum Pressure

Fig 4.

Box and whisker plots summarizing differences in pharyngeal maximum pressure (A) and pressure integral (B) parameters with repeated measures ANOVA main effects between the six body positions. Horizontal lines specify median values and interquartile range. Error bars indicate minimum and maximum values. * $P < 0.05$. † $P < 0.01$. ‡ $P < 0.001$.

TABLE 1
Summary statistics for swallowing pressure parameters during 5mL swallowing tasks by degree of body inversion

REGION	PARAMETER	0°	45°	90°	110°	135°	180°	P						
Velopharynx	Maximum pressure (mmHg)	125	9	130	9	146	15	165	17	159	12	170	13	0.000*
	Integral pressure (mmHg*s)	106	13	116	11	131	15	143	15	146	14	156	15	0.001*
	Duration above baseline (s)	.69	.03	.72	.03	.73	.03	.74	.03	.74	.03	.75	.03	0.207
Mesopharynx	Maximum pressure (mmHg)	184	15	184	10	190	12	192	13	208	19	196	14	0.174
	Integral pressure (mmHg*s)	109	13	116	10	121	12	131	14	136	17	142	8	0.114
	Duration above baseline (s)	.64	.04	.66	.04	.68	.05	.71	.05	.71	.06	.72	.02	0.487
Upper Esophageal Sphincter	Pre-opening maximum (mmHg)	98	9	89	8	88	9	92	11	92	11	97	11	0.854
	Post-closure maximum (mmHg)	186	21	192	17	182	13	202	20	192	20	209	17	0.167
	Minimum pressure (mmHg)	-2.0	1.5	0.4	1.5	.20	1.6	-.57	2.1	-1.8	2.2	-2.8	2.1	0.038*
Pharyngeal-UES Pressure Gradient	Nadir duration (s)	.58	.03	.57	.04	.50	.03	.53	.04	.56	.04	.59	.03	0.179
	Maximum gradient (mmHg)	465	34	484	32	530	31	551	33	553	36	568	34	0.000*
	Integral gradient (mmHg*s)	15527	15746	17819	18600	19140	21118	0.008*						
Proximal Esophagus	Maximum Pressure (mmHg)	91	5	105	7	111	6	106	9	115	10	111	11	0.037*
	Integral Pressure (mmHg*s)	33393	37739	45903	42681	40234	38609	0.314						
	Duration (s)	2.7	.16	2.6	.20	3.1	.26	3.1	.20	2.7	.12	2.7	.21	0.043*

All data reported as mean +/- standard error.

Results of repeated measures ANOVA for each variable are reported with corresponding *P*-values and were determined significant (*) if *P* < 0.05. (UES=Upper Esophageal sphincter; s= seconds)