Does Stroke Affect Upper Esophageal Sphincter Distention?

by

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Differences in Upper Esophageal Sphincter Distention After Stroke

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Swallowing is a complex process that takes place using various muscles and cranial nerves across three phases: the oral phase, the pharyngeal phase, and the esophageal phase. For the pharyngeal phase to end and the esophageal phase to begin, the upper esophageal sphincter (UES) needs to open and allow the bolus to clear. Should muscle or nerve damage occur, for example during a stroke, the safety and efficiency of swallowing may be impaired. This disruption could happen for any phase of the swallow, and different signs and changes to physiology during the swallow may be visualized during a modified barium swallow study (MBSS). The goal of this study was to provide insight into what effect stroke has on UES distention. In this study, MBSS videos were labeled in order to measure UES distention (UESD) for individuals swallowing small-volume (i.e., approximately 5mL) liquid boluses. The population under investigation for this study were individuals post-stroke. The UESD values from the cohort of post-stroke individuals were compared to UESD values of an age-matched, healthy, control group of individuals. A comparison of UESD between these two groups was completed to describe changes in UESD following stroke. Results of this comparison indicated that there was no significant difference in UESD between healthy individuals and individuals post-stroke. Furthermore, the UESD of individuals post-stroke was slightly larger than their age-matched healthy cohorts. There are a number of factors which may account for these results, including bolus size, participant ages, the small sample size, and the presence of a nasogastric (NG) tube in some post-stroke participants. Clinically, this information can be used to help inform disorder diagnosis and treatment.

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1.0 Background/ Nature of the Problem

The following literature review provides an introduction to the swallow mechanism and specific anatomy and physiology of the upper esophageal sphincter (UES). A list of key terms and abbreviations used in this paper is included below:

- Upper esophageal sphincter opening (UESO) = the process of UES opening/ distending to accommodate bolus passage
- Upper esophageal sphincter distention (UESD) = measurement used in this study; anterior-posterior view of UES opening
- Modified barium swallow study (MBSS) = fluoroscopic imaging of the oral phase, pharyngeal phase, and clearance into the esophageal phase of swallowing while an individual drinks barium solutions of various thicknesses; also known as a "videofluoroscopic swallow study"
- Modified Barium Swallow Study Impairment Profile (MBSImP) = standardized program for viewing and interpreting swallow studies

1.1 Swallow Physiology and Nature of UESO

Matsuo and Palmer (2008) describe healthy swallowing physiology as a process that occurs over multiple steps. The oral preparatory stage begins when liquid taken into the mouth is held in the posterior oral cavity. The tongue and soft palate provide a seal of the pharynx while the liquid is held in the mouth. At the start of the oral propulsive stage, the back of the tongue drops and allows the liquid back into the pharynx. The soft palate, or velum, rises to cover the nasopharynx and prevents regurgitation of material into the nasal cavity. This marks the beginning of the pharyngeal stage, as the bolus begins to move toward the upper esophageal sphincter (UES) and into the esophagus. The airway is protected by the epiglottis, a flap of cartilage which moves to cover the larynx and trachea during a swallow (Matsuo & Palmer, 2008).

The opening of the UES is necessary for the esophageal stage to begin (Matsuo & Palmer, 2008). According to Matsuo and Palmer (2008), the UES remains in a closed position at rest. It is important to note that the UES does not open by itself, but rather through a combination of cricopharyngeus muscle and inferior constrictor muscle relaxation and contraction of the suprahyoid and thyrohyoid muscles (Sivarao & Goyal, 2000). The cricopharyngeus muscle receives bilateral innervation from a pharyngeal plexus formed by the pharyngeal and superior laryngeal branches of the vagus nerve, the glossopharyngeal nerve, and nerve fibers of the cranial cervical ganglia (Sivarao & Goyal, 2000). In normal, healthy individuals, cricopharyngeus relaxation begins before the bolus reaches the UES. The inhibition and relaxation of these muscles also allow for the UES to open. Additionally, during the swallow but before UES opening, the arytenoids tilt anteriorly and the hyoid and larynx move anteriorly and superiorly (Matsuo & Palmer, 2008). This hyolaryngeal excursion (HLE), is a large factor in UES opening. During HLE, the suprahyoid and thyrohyoid muscles contract and pull the hyolaryngeal complex further anteriorly which completes UES opening (Matsuo & Palmer, 2008; Sivarao & Goyal, 2000). The UES is further distended by the volume of the bolus and the pressure generated by it. This intrabolus pressure is another essential contributor to the opening of the UES. For UES closure to occur, the resting tone of the UES, which is managed by the cricopharyngeal and inferior pharyngeal constrictor muscles, must be re-initiated (Sivarao & Goyal, 2000).

The physiology of the UES helps prevent reflux from entering the airway, as well as preventing air from entering the digestive system (Sivarao & Goyal, 2000). Kahrilas (1997) reported that reflexes of the UES are not enough to protect the regurgitation of stomach materials from entering the airway when they force UES distention. Additionally, the UES is protected from opening beyond its maximum and optimal length of distention (Sivarao & Goyal, 2000). These mechanisms of protection help regulate UES opening, ensuring that the opening occurs with appropriate balance and equilibrium.

Shaw et al. (1995) investigated the effects of normal aging on UES functioning. Their study compared a group of young control individuals (n=11), with a mean age of 21 years (range=18-24 years), to a group of older individuals (n=14), with a mean age of 76 years (range=52-85 years), and no history of dysphagia (Shaw et al., 1995). Results of this study revealed that the cohort of older individuals had UES pressures that were slightly lower than the cohort of younger individuals. Both cohorts revealed the same outcome: as the bolus size increased, so did the UES opening diameter; however, the older cohort showed a smaller degree of opening. The length of time for which the UES took to open correlated with bolus volume and showed no significant differences between the cohorts. Moreover, the time at which the UES opened and closed occurred earlier in the process of the swallow for the older cohort than the younger cohort.

1.2 Impaired UESO

Upper esophageal sphincter opening impairment may occur, in part, as a result of pharyngeal weakness and incoordination that impacts UES contraction and relaxation. This impairment may result in a potentially insufficient swallow with poor bolus clearance, in which bolus residue may linger in the pharynx after the UES is closed. It is important to note that this residue may lead to aspiration. There are numerous causes of dysphagia and patient populations for which UESO may be impaired. Bian et al. (2009) looked specifically at UESO in individuals following medullary infarctions. Nine patients who had survived medullary strokes that lesioned different areas of the brain, as determined by Magnetic Resonance Imaging (MRI), participated in this study. These patients, previously identified as having an oral, pharyngeal, or oropharyngeal dysphagia, underwent videofluoroscopic swallow studies (VFSS). A number of variables were measured, including penetration, aspiration, residue, oral and pharyngeal transit times, pharyngeal delay time, and elevation of the larynx. Of the nine patient participants, seven were identified as having impaired UESO. The lesion locations of these patients with UESO impairment were located mainly in the dorsolateral and inferior dorsolateral medulla. Pharyngeal weakness was determined to be the main cause of dysphagia in participants. UESO weakness was noted in this study, which may have been caused by pharyngeal weakness because of the connection between effective HLE and successful UESO.

Domer et al. (2014) investigated UES distention in adult patients with unilateral vocal fold immobility. A number of etiologies may contribute to vocal fold paralysis, including damage to brainstem nuclei, the vagus nerve, or the recurrent laryngeal nerve. In other cases, the specific cause may be unknown. In this study, individuals with iatrogenic or idiopathic unilateral vocal fold immobility (n=25) were selected to participate, the results of which were compared to a control group of age-matched individuals with no history of dysphagia or vocal fold impairments. VFSS were performed and an analysis of UES distention was completed, among other variables. UES maximal distention showed no significant difference between any of the groups. The results of this study suggest that UES distention may not be an impairment in individuals with unilateral vocal fold immobility. However, depending on the location of the lesion, and cranial nerve nuclei impacted, there may at times be some concomitant UES and vocal fold impairments. The incorporation of a group with idiopathic etiologies may have diluted the results toward there being no correlation between vocal fold immobility and UES distention, when in fact there may be depending on lesion site or etiology.

Swallowing following hemispheric strokes was studied by Wilmskoetter et al. (2018). This retrospective study compared the swallowing of patients who had experienced a single stroke; participant groups included and compared were those who had left unilateral strokes (n=22) and patients who had right unilateral strokes (n=24). Other variables besides hemisphere of lesion were well controlled for by selecting individuals without additional diseases or history which may cause dysphagia. Brain lesion volumes were calculated for each patient, and the modified barium swallow study (MBSS) of each patient was analyzed and rated in accordance to the Modified Barium Swallow Study Impairment Protocol (MBSImP; Martin-Harris, et al., 2008). Patients who presented with right unilateral lesions had more severe pharyngeal impairments than patients presenting with left unilateral lesions, which indicates that the UES may be impacted as part of the pharyngeal phase of swallowing. These results suggest that the hemisphere in which a lesion occurs may influence the swallowing process (Wilmsokoetter et al., 2018).

1.3 Measurement of UES

Upper esophageal sphincter opening and distention can be quantified using imaging or other signal-based modalities. High resolution manometry (HRM) quantifies UESO through the measurement of pressure. Pharyngeal automated impedance manometry uses simultaneous flow and pressure analyses of the bolus to determine opening of the UES during swallowing. UES opening diameter was studied using impedance and manometry in a study done by Omari et al. (2012). For this study, adult patients with dysphagia (n=40) and healthy control subjects (n=8) were intubated with a manometric and impedance catheter before they underwent a series of swallows, which were recorded by fluoroscopic imaging. The catheter readings were paired and compared with clinician ratings of fluoroscopic imaging. Results showed that the lowest impedance value was most highly correlated with the greatest diameter of UES opening. Conversely, higher impedance values correlate to the narrowest diameter of UES opening (Omari et al., 2012). This means that the impedance testing correlates to UES opening diameter; the muscles that are most relaxed when the diameter of the UES is at its widest are the muscles that are the tightest when the UES is at its smallest diameter. This aligns with what is known about relaxation and UES opening: when the UES is open, it is because muscles have relaxed to allow it to open, and when the UES is closed, it is because muscles have tightened to keep it closed.

Silva et al. (2013) studied the pressure of the UES and pharynx of healthy adults using high-resolution manometry. Transnasal pharyngoscopy was also used in a small number of participants in this study to measure the distance of structures of focus from the nostril. This study provided manometric readings and measurements for a healthy, "normal" population of adults, as well as the distance of focus structures from the nostril. These measurement strategies could also be used with people with dysphagia, and the normal values in this study could be used as a point of comparison between healthy individuals and those with dysphagia. Pressure readings of the UES offer information about how the UES relaxes and contracts.

As an alternative to HRM, Chitose et al. (2019) proposed a three-dimensional HRM as a more accurate way to measure the UES. Pressure in the UES is variable throughout the swallowing process, especially in those with dysphagia, so it is challenging to use HRM to measure features of the UES. Healthy individuals (n=17) underwent a series of measurements using a catheter and 3D-HRM system. Measurements were done at times of participants breathing normally, holding their breath, and performing the Valsalva maneuver (breath holding while executing an effortful swallow). The results indicated no statistically significant difference in UES length between each of the tasks. Additionally, average UES pressure was highest during normal breathing. Anterior and posterior directions showed different pressure levels as well (Chitose et al., 2019). Studying pressure of the UES contributes information regarding its contraction and relaxation, allowing researchers to infer how it may work during the swallow.

A combination of simultaneous VFSS imaging and high-resolution pharyngeal manometry (HRPM) was utilized by May et al., (2020) to quantify UESO in distinct phases. In conjunction with Computational Analysis of Swallowing Mechanics (CASM), the influence of individual structures over UES pressure changes was identified. Data for 18 patients, the diagnosis of whom were not shared, were used for analysis in this retrospective study. Six phases of UES pressure waves were identified as a result of these analyses. These analyses provided a detailed description of the functional anatomy of the UES during the process of the pharyngeal and the start of the esophageal phases of swallowing.

Nakane et al. (2006) used a VFSS to measure UESO in healthy young and elderly participants. This study was designed to determine a plane which could be used to most accurately measure UESO and its relationship to hyolaryngeal elevation (HLE). Nakane et al. explained that having stable anatomical reference points, such as with Camper’s plane, measurements of swallowing physiology could be made more accurately. This plane was compared to other planes of measurement and was found to be the only plane of measurement to show a significant correlation between UESO and HLE. Lead markers were placed on the chin, nose, and tragus to offer spatial markers during the VFSS. On average, UESO size for the young group was 0.30 +/-0.09cm during the swallow. The elderly group had an average 0.72+/-0.17cm UESO size during the swallow. Though the purpose of this study was not to ascertain the difference in UESO size between healthy young and healthy elderly participants, the descriptive results indicated that young participants had a much smaller UESO size than elderly participants.

High resolution cervical auscultation (HRCA) uses sensors and machine learning to evaluate an individual's swallow. In a recent study, Donohue et al. (2020), compared the UES opening and closing for patients with dysphagia and healthy individuals as determined by HRCA sensors data to the ratings of UES opening and closing on the MBSImP (Martin-Harris, et al., 2008). The HRCA signals were found to analyze swallows close to that of trained human analysists (Donohue et al., 2020). Of the 100 swallows rated with the MBSImP in this study, 74% of the swallows had complete, normal UES distention with no bolus flow obstruction. The remaining 26% of the analyzed swallows had partial UES distention or duration and partial bolus flow obstruction and were categorized as "impaired".

2.0 Study Goals and Design

The aim of this study was to compare measurements of maximum anterior-posterior UES distention (UESD) in people with stroke to healthy age-matched individuals, with the goal to provide insight into what effect stroke has on UES distention. The investigation was based on measurements of UES distention in individuals who have survived strokes, and UES distention of healthy individuals. A comparison of the values of UESD in these two groups was completed, as measured by a UES Matlab application in an attempt to identify changes that occur in individuals' swallowing function, regarding the UESD, post-stroke.

2.1 Hypothesis

The review of the literature indicates that hemispheric and medullary lesions resulting from stroke have an effect on the integrity of a swallow, specifically UES opening and distention; therefore, it is hypothesized that individuals post-stroke will exhibit significantly less UES opening distinction than an age-matched group of healthy individuals.

2.2 Significance

There is currently a gap in knowledge in the literature about UES distention in individuals following stroke when compared to age-matched healthy individuals with no history or symptoms of dysphagia. Treatment for dysphagia may be better implemented if it is understood how an individual’s UES may be impacted after stroke. If a treatment is not a good fit for a patient based upon their anatomical or physiological differences, harm could be done to that patient, including the worsening of swallow safety and an increase in the incidence of aspiration and penetration. Treatment of dysphagia is most successful when it is aligned with the disease mechanism of action. The findings of this study will help promote the most effective dysphagia treatment. Finally, this study is part of a larger body of research which will ultimately lead to automated interpretation of swallowing.

2.3 Methods

This study was approved by the University of Pittsburgh IRB (PRO 19040040; PRO 19030185).

2.3.1 Participants

Comparison between healthy control swallows (n=63) and post-stroke swallows (n=33) were used to investigate differences in UES distention after stroke. Twice as many healthy swallows as post-stroke swallows were used, but there were the same number of participants in each group. Of the 33 post-stroke swallows, eight swallows were from individuals who had a nasogastric (NG) feeding tube. Stroke survivors who were scheduled to have a VFSS at the University of Pittsburgh Medical Center Presbyterian Hospital, based on symptoms of dysphagia, were included as participants in this study. No information regarding diagnosis (i.e., lesion site) was provided. Inclusion criteria for post-stoke participants was that they had experienced a stroke and displayed signs of dysphagia during a bedside evaluation, qualifying them for an instrumental study. All patients provided informed consent with research staff after being invited to learn about the study from their treating speech-language pathologist (SLP).

Age-matched healthy individuals were recruited as a control group, via registry and advertisements posted in the UPMC facilities. All participants provided informed consent. Inclusion criteria for healthy individuals was that they had never experienced a stroke or symptoms of dysphagia, and had no history of head-neck surgery or radiation therapy. Individuals in groups were age-matched by year. Individual ages in both cohorts ranged from 44 to 89 years with a mean of 66.2 years.

2.3.2 Materials

Videofluoroscopy was captured outside of the Radiology Department patient identification system by splitting the output from the fluoroscopy unit to the in-house TIMS (medical video platform; TIMS Medical, n.d.) unit and the video capture board. Patients were administered barium sulfate solutions in thin liquid (Varibar Thin liquid, barium sulfate for oral suspension, 81% w/w, manufactured by E-Z-EM Canada Inc.; Bracco Diagnostics, 2019), Varibar Nectar (barium sulfate oral suspension, 40% w/v, manufactured by E-Z-EM Canada Inc.; Bracco Diagnostics, 2020), and Varibar pudding (barium sulfate for oral paste, manufactured by E-Z-EM Canada Inc.; Bracco Diagnostics, 2016), and a cookie coated with Varibar pudding, and were video-recorded in the lateral plane while swallowing under fluoroscopy.

2.3.3 Procedures

Patient participants underwent a VFSS, performed by their SLP (not research staff), and organized based on the clinical hypothesis for the examination. Swallows were captured at 30 frames per second (Kurosu, et al. 2019; Mahoney, et al. 2022). To minimize fluoroscopic exposure, healthy participants were examined with only small-volume thin liquid boluses for 10 total trials. Mean fluoroscopy time for healthy participants was .96 minutes (equivalent to 57.6 seconds).

A customized Matlab drawing application was developed by one of the study's engineers for performing UES distension measurements. All accrued VFS videos were analyzed with this application. Swallows of small bolus volumes for patients and age-matched healthy participants were selected for analysis (i.e., 3mL thin liquid; self-administered thin liquid from a cup). Two healthy swallow measurements were performed for each patient swallow.

The routine for annotating UESD on the chosen frames for each swallow involved several steps (Khalifa et al., 2023). UESD is considered the maximum distance of separation from the posterior to anterior wall of the UES. Because UES maximum distension tends to occur at the time of maximal hyoid displacement, the frame of maximum hyoid elevation was first identified in each swallow study video. UES distention was then measured for this frame with maximum hyoid elevation, and then re-measured on the two preceding, and the two following frames to account for variability in the timing of UES opening across participants and patients. This method yielded a total of five UES measurements per swallow, producing a total of 165 patient frames analyzed, and 315 healthy participant frames analyzed. The frame in which the maximum UESD was recorded, was the frame used in the analysis for each participant.

Measurements were scaled to individual participant height according to methods published by Molfenter et al. (2014). According to these methods, a line segment is drawn from the bottom of the C2 vertebra to the bottom of the C4 vertebra. This C2-C4 distance is the standard scalar of height for participants, and UESD was normalized to this scalar before data analysis. Next, a line segment is drawn from the superior-anterior corner of C3 vertebra (C3) to the inferior-anterior corner of C3, representing the C3 height. The C3 line is moved to the inferior-posterior border of the tracheal air column. The height of the C3 is an approximation of the length of the UES, so this placement allows a standardized measure of UES height from which to mark the UESD. A mixed-model analysis was performed to compare UESD between healthy participants and post-stroke participants.

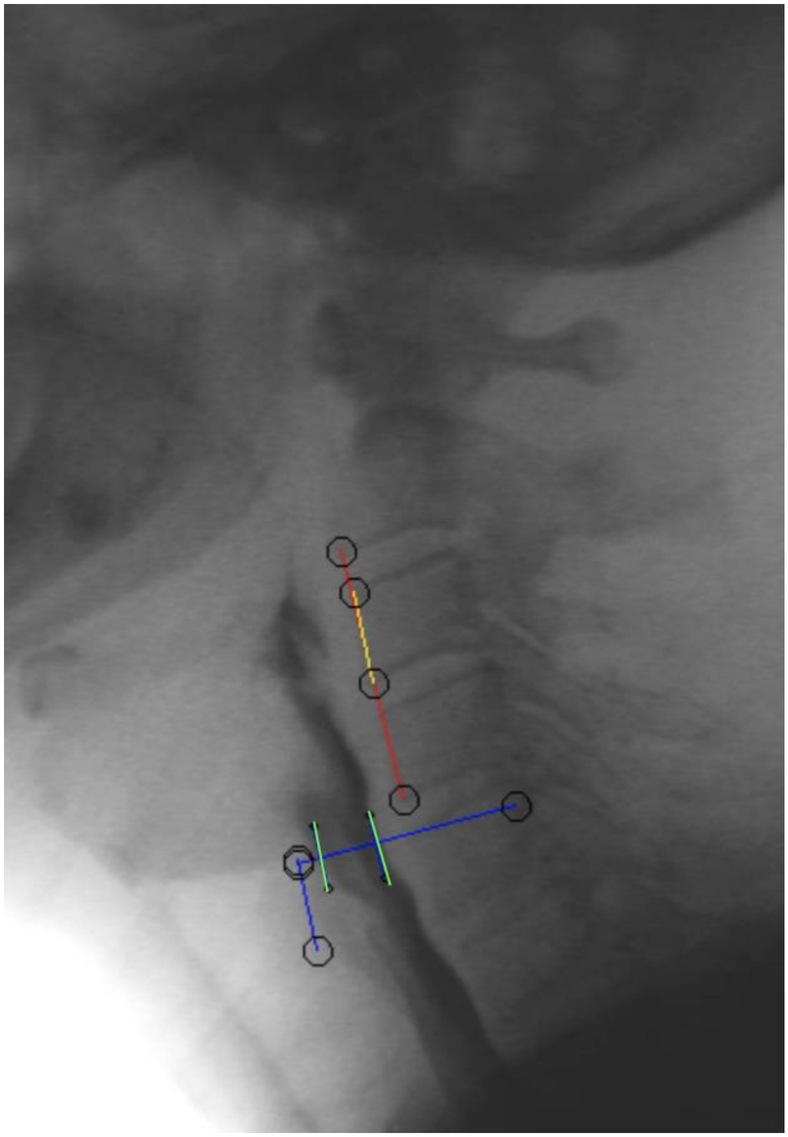

Figure 1 Process for Obtaining UESD Measurements

The yellow line marks the height of C3. The red line marks the distance from the bottom of C2 to the bottom of C4. The vertical blue line is the length of C3, determining the position and length of the UES. The horizontal blue line accounts for patient movement and head flexion. The short green lines running perpendicular to the horizontal blue line mark the anterior and posterior points of the UES.

2.4 Reliability

The principal investigator of this study completed multiple tests of reliability prior to beginning measurements for this study. Reliability tests included identifying maximum hyoid elevation, and measurement of UESD. Following the initial labeling, inter-rater and intra-rater reliability were completed for a random selection of 10% of the swallows in each cohort. Inter-rater reliability was performed with the assistance of a lab member who had been trained to complete these types of measurements. When intraclass correlation coefficient (ICC) was calculated, inter-rater and intra-rater reliability were above .9, indicating excellent reliability of UESD measurement. Intra- and inter-rater reliability specifics are included below:

Table 1 Inter-rater reliability – Healthy Cohort

	UESDantX	UESDantY	UESDpostX	UESDpostY
Intraclass Correlation Coefficient Average Measures	.993	.980	.994	.974

Table 2 Inter-rater reliability – Stroke Cohort

	UESDantX	UESDantY	UESDpostX	UESDpostY
Intraclass Correlation Coefficient Average Measures	.983	.936	.992	.913

Table 3 Intra-rater reliability – Healthy Cohort

	UESDantX	UESDantY	UESDpostX	UESDpostY
Intraclass Correlation Coefficient Average Measures	.994	.983	.992	.985

Table 4 Intra-rater reliability – Stroke Cohort

	UESDantX	UESDantY	UESDpostX	UESDpostY
Intraclass Correlation Coefficient Average Measures	.990	.978	.990	.976

3.0 Results

No significant difference was found between UESD in individuals post-stroke when compared to an age-matched cohort of healthy individuals based on the mixed-model analysis that was completed. A mixed-model analysis was selected after consulting with a biostatistician; the sample did not meet the assumption of independence, given that multiple healthy swallows from the same individuals were used. The frame of maximum UESD (the variable MaxUESD) was identified for each swallow from the total 5 frames that were obtained for each swallow and used in an f-Test. Analysis yielded the following results:

Table 5 f-Test Results

Comparison	Estimate	Standard Error	DF	t-Value	p-Value	Alpha
Post-Stroke vs. Healthy	0.01394	0.02185	39	0.64	0.5272	0.05

Table 6 Group Means – Healthy Cohort

Variable	Mean	Standard Deviation	Minimum	Maximum	50th Percentile
C3 length	46.062	5.866	26.306	57.925	47.886
C2-C4 length	116.259	13.678	85.212	142.667	117.809
Max UESD	33.779	8.183	21.663	56.164	33.484

Table 7 Group Means – Post-Stroke Cohort

Variable	Mean	Standard Deviation	Minimum	Maximum	50th Percentile
C3 length	58.025	10.167	41.645	90.28	57.929
C2-C4 length	149.313	25.96	113.089	220.095	142.376
Max UESD	45.956	13.209	19.235	69.584	46.922

The effect size in this study (Cohen's d) was 0.17. This effect size indicates that on average, post-stroke swallows had a 0.17 greater standard deviation than healthy swallows. Additionally, there is a small clinical significance/difference between participants.

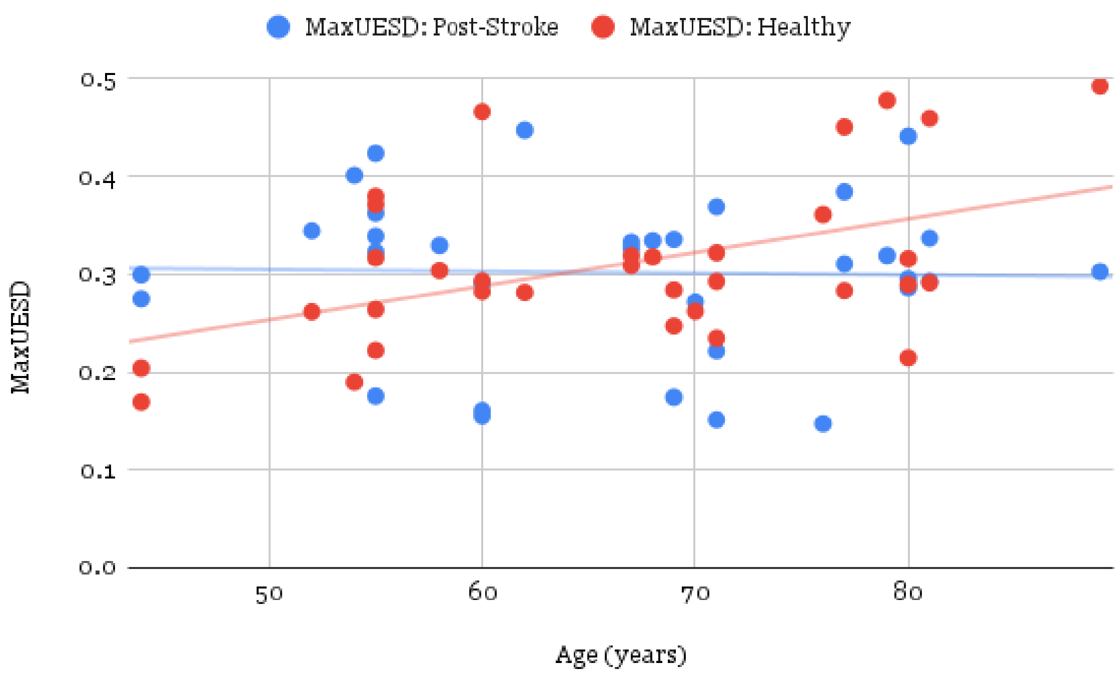

Figure 2 Comparison of Post-Stroke MaxUESD to Healthy MaxUESD

This chart demonstrates an overlay of MaxUESD values for individuals post-stroke (blue line) and healthy individuals (red line).

4.0 Discussion

This study sought to investigate whether there is a difference in the maximum anterior-posterior distention of UES opening in individuals who have survived strokes when compared to an age-matched cohort of healthy individuals. The results from this study found that there was not a statistically significant difference in UES distention between healthy individuals and individuals post-stroke, but there was a small clinical effect size indicating greater UES anterior-posterior distention for healthy participants.

4.1.1 Methodological Considerations

There are numerous considerations with regard to these results, one of which is the bolus size. The target bolus size for swallows used in this study was 5mL, or one teaspoon. For healthy participants, the bolus was measured exactly to 5mL for each swallow, since the individuals completing these studies were researchers. For patient participants, the bolus size was not as regulated; the clinicians completing these studies were not as meticulous in using the measurement tools that researchers used. The bolus was likely less than 5mL at times (e.g., 2-4mL bolus sizes), due to the clinical conditions under which the studies were performed. Although the literature does not confirm swallowing physiologic differences between 5mL and smaller liquid boluses in healthy people, bolus size differences may have different consequences in patient populations (Dodds et al., 1988; Kahrilas et al., 1989). Increased bolus volume aids in UES opening, as well as adequate coordination and activation of the anatomical structures of the UES (Kahrilas, 1997).

If this study were repeated with larger bolus sizes, we may hypothesize that there may be a statistically significant difference in UES distention between these two groups.

Another consideration for these results is the small sample size. In this study, there were only 96 swallows (33 post-stroke and 63 healthy) labeled and analyzed. This small sample may not be representative of UES anterior-posterior distention in individuals following stroke, or in healthy individuals. Additionally, these measurements were only collected by one individual, and errors may have arisen because of this. Though reliability was completed, and deemed excellent, there was only a small number of swallows re-labeled for reliability and errors may not have been caught in this small re-labeling. This study is part of a larger body of research being conducted with the goal of developing an automated sensor-based system for dysphagia screening and diagnosis. The investigation of human error of interpretation and machine-based interpretation is a critical focus of this work. Clinician measurement occurs with a level of subjectivity, which could have played a role in this study, whereas machine-learning algorithms would yield more objective measurements, while continuing to improve accuracy over time.

4.1.1.1 NG Tube Inclusion

Of the 33 post-stroke swallows, eight occurred with a nasogastric (NG) tube in place. The presence of NG tubes for 24% of the post-stroke swallows is also important to consider in these results. The presence of NG in these individuals may have skewed the UES anterior-posterior distention by either enhancing or diminishing it (Pryor et al., 2015; Nam et al., 2006; Wang et al., 2019). Beyond UES anterior-posterior distention being impacted by the presence of an NG tube, epiglottic inversion may have also been impacted, reducing intrabolus pressure which is a component of UES opening. An additional review of the literature, included below, was completed after the study to investigate possible effects that an NG tube may have on UESD:

An NG tube may be used as a brief alternate means of nutrition for individuals with dysphagia. An NG tube travels from the nose through the pharynx and into the esophagus, stopping in the stomach. While an NG tube is in place, individuals may still engage in oral trials of food and liquid, if deemed appropriate by a clinician. When considering physiology, it is important to remember that the UES will remain open while an NG is in place.

Pryor et al. (2015) explored the impact of NG tubes on individuals' swallows. This study examined the swallow of healthy, older individuals (median age = 65) with no history of dysphagia. Two NG tubes of different sizes were placed for these individuals, and swallow studies were conducted. A comparison of the individuals' swallows with the NG tubes in place, and no NG tube, were compared. It was found that with an NG tube in place, individuals demonstrated an increase in the incidence of penetration/aspiration, an increase in pharyngeal residue, and a prolonged transit of the bolus through the pharynx. In the older individuals included in this study the NG tube created an additional barrier to UES opening by limiting the opening further due to the obstruction. The width of the tube also impacted the swallow, with wider tubes further prolonging the transit duration.

Nam et al. (2006) trialed different timelines for NG removal in relation to swallow study. In this study, individuals completed swallow studies immediately following NG removal and five hours following NG removal. The swallow studies completed immediately following NG removal demonstrated a more discoordinated swallow than studies completed longer after NG removal. The NG tube was determined to desensitize the swallow which caused discoordination, specifically in the pharyngeal phase, which includes UES opening and closure.

Wang et al. (2019) looked specifically on the impact of NG tubes on individuals' swallow following stroke. These individuals (n=30, age 71.43+/- 4.06 years) had used NG tubes for longer than a two-month period following survival of a stroke. A swallow study was performed for participants prior to NG removal, and then repeated five hours following NG removal. The results of this study indicated that prolonged NG placement has a negative impact on swallowing physiology; specifically, swallows with the NG in place were characterized by longer pharyngeal transit time, increased amounts of pharyngeal residue following the swallow, and insufficient epiglottic inversion, when compared to swallows following NG removal. In addition, and relevant to the present study, the NG was found to infringe on UESD, and caused bolus adherence to the NG, which impacted the swallow. The NG placement caused an overall disruption to the pharyngeal phase of the swallow in these participants.

Recalling from the aforementioned research regarding NG impact on swallowing, the overall impact is considered negative since the UES anterior-posterior distention is reduced by the NG, and it may cause desensitization and discoordination by being in place (Pryor et al., 2015; Nam et al., 2005). Though the width of opening is considered to be “reduced”, in this study we focused on a different interpretation of “reduced”; the overall UES distention, measuring wall-to-wall from UES, was considered, rather than the portion through which the bolus could travel.

Figure 3 NG Tube in Post-Stroke Patient

The red circle in this image identifies the area of the UES and presence of NG tube. This demonstrates the NG tube impact: holding the UES open at rest.

4.2 Implications for Clinical Practice

An application of the results of this study to clinical practice may include the awareness that UES anterior-posterior distention may look typical in individuals following a stroke. This knowledge may facilitate further exploration as to why an individual may present with dysphagia after a stroke. Clinicians may seek causes of dysphagia elsewhere, knowing UES anterior-posterior distention might not be impaired. However, since this study only offered preliminary data for a small sample size, it cannot be entirely ruled out that UES anterior-posterior distention impairment may be a factor in dysphagia following stroke. Likewise, we did not investigate the duration of UES opening during swallowing.

An additional consideration as a clinical implication is the presence of NG tubes during swallow studies, and swallowing in general, and their impact on the result. Knowing that the presence of an NG tube has this impact on swallow physiology (i.e., typically reducing the patency and efficiency), will allow clinicians to make better informed decisions regarding when/if an NG tube should be removed for a swallow study (Pryor et al., 2015; Nam et al., 2006; Wang et al., 2019).

4.3 Limitations

As mentioned previously, a small sample size (n=96) of swallows was used in this study. The healthy (n=63) and post-stroke (n=33) swallows may not be representative of healthy swallowing and swallowing post-stroke in general. Also mentioned above, which is a limitation of this study, is that only a single individual labeled the swallows for this study. It is not uncommon for natural human error to occur when completing such measurements. In addition, human variability likely occurred from the clinicians carrying out the swallow studies themselves; bolus size was not measured exactly by these clinicians, whereas bolus size was measured exactly by researchers carrying out control group studies. This potential difference is another limitation to this study.

4.4 Future research

This study provided an overview of the differences in UES anterior-posterior distention with and without stroke. As discussed in the results and study limitations, the sample size of this study was small. In the future, a more complete study, including power analysis to ascertain a goal sample size, should be completed. The preliminary data provided by this study will be beneficial for generating an appropriate sample size. Additionally, continued use of the tool used for measurements in this study will allow multiple users to perform consistent measurements for entry into machine learning analysis, to automate the interpretation of swallow studies. This will be beneficial to reduce clinician error and improve accessibility of instrumental swallow studies. Future research to distinguish the impacts of location-specific lesions on different UES-opening processes (i.e., relaxation and traction forces) may also be beneficial in determining the specific cause of UES distention impairment or normalcy in individuals following stroke. Intrabolus pressure is another contributor to UES opening, so it may be beneficial to see how boluses of different sizes impact the physiological process of UESD following stroke. Finally, the considerations of NG tube placement may lead to more conversation and research regarding the impact of an NG tube on swallowing and the timeline of when an NG tube should be removed in relation to initiating oral trials of food and swallow studies.

4.5 Conclusion

This study provided an exploration of the effect of stroke on UESD. Though the results indicated no significant difference in UESD following stroke, this study did provide preliminary data required for future, in-depth studies and work to be completed in this area. The results of this study indicated additional areas of need within research, including conducting a similar study with a larger sample size.

Bibliography

Bian, R., Choi, I., Kim, J., Han, J., & Lee, S. (2009). Impaired opening of the upper esophageal sphincter in patients with medullary infarctions. *Dysphagia, 24*(2), 238-245.

Bracco Diagnostics (2016). Full prescribing information: Varibar pudding. Retrieved from https://www.bracco.com/en-us/x-ray-ct.

Bracco Diagnostics (2019). Full prescribing information: Varibar thin liquid. Retrieved from https://www.bracco.com/en-us/x-ray-ct.

Bracco Diagnostics (2020). Full prescribing information: Varibar nectar. Retrieved from https://www.bracco.com/en-us/x-ray-ct.

Chitose, S., Shin, Y., Sato, K., Hamakawa, S., Fukahori, M., Ono, T., & Umeno, H. (2019). Three-dimensional imaging of the upper esophageal sphincter resting pressure. *Laryngoscope Investigative Otolaryngology, 4*(6), 645-652.

Dodds, W. J., Man, K. M., Cook, I. J., Kahrilas, P. J., Stewart, E. T., & Kern, M. K. (1988). Influence of bolus volume on swallow-induced hyoid movement in normal subjects. *American Journal of Roentgenology, 150*(6), 1307-1309.

Domer, A. S., Leonard, R., & Belafsky, P., C. (2014). Pharyngeal weakness and upper esophageal sphincter opening in patients with unilateral vocal fold immobility. *The Laryngoscope, 124*(10), 2371-2374.

Donohue, C., Khalifa, Y., Perera, S., Sejdić, E., & Coyle, J. L. (2020). How closely do machine ratings of duration of UES opening during videofluoroscopy approximate clinician ratings using temporal kinematic analyses and the MBSImP? *Dysphagia, 36*(4), 707-718.

Kahrilas, P. J., Logemann, J. A., Shah, V., & Ha, V. (1989). Upper esophageal sphincter opening and modulation during swallowing. *Gastroenterology, 97* (6), 1469-1478.

Kahrilas, P. J. (1997). Upper esophageal sphincter function during antegrade and retrograde transit. *The American Journal of Medicine, 103*(5), 56-60.

Khalifa, Y., Mahoney, A. S., Lucatorto, E., Coyle, J. L., & Sejdić, E. (2023). Non-invasive sensor-based estimation of anterior-posterior upper esophageal sphincter opening maximal distention. *Journal of Translational Engineering in Health and Medicine, 20*(11), 182-190.

Kurosu, A., Coyle, J. L., Dudik, J. M., & Sejdić, E. (2019). Detection off swallow kinematic events from acoustic high-resolution cervical auscultation signals in patients with stroke. *Archives of Physical Medicine and Rehabilitation, 100*(3), 501-508.

Mahoney, A. S., Khalifa, Y., Lucatorto, E. Sejdić, E., & Coyle, J. L. (2022). Cervical vertebral height approximated hyoid displacement in videofluoroscopic images of healthy adults. *Dysphagia*, 37, 1689-1696.

Martin-Harris, B., Brodsky, M. B., Michel, Y., Castell, D. O., Schleicher, M., Sandidge, J., Maxwell, R., & Blair, J. (2008). MBS measurement tool for swallow impairment – MBSImP: Establishing a standard. *Dysphagia, 24*(4), 392-405.

Matsuo, K. & Palmer, J. B. (2008). Anatomy and physiology of feeding and swallowing: Normal and abnormal. *Physical Medicine and Rehabilitation Clinics of North America, 19*(4), 691-707.

May, N. H., Davidson, K. W., Pearson, W. G., & O'Rourke, A. K. (2020). Pharyngeal swallowing mechanics associated with upper esophageal sphincter pressure wave. *Head and Neck, 42*(3), 467-475.

Molfenter, S. M., & Steele, C. M. (2014). Use of an anatomical scalar to control for sex-based size differences in measures of hyoid excursion during swallowing. *Journal of Speech, Language, and Hearing Research, 57*(3), 768-778. doi:10.1044/2014_JSLHR-S-13-0152

Nakane, A., Tohara, H., Ouchi, Y., Goto, S., & Uematsu, H. (2006). Videofluoroscopic kinesiologic analysis of swallowing: Defining a standard plane. *Journal of Medical and Dental Sciences, 53*(1), 7-15.

Nam, D. H., Jung, A. Y., Cheon, J. H., Kim, H., Kang, E. Y. & Lee, S. H. (2015). The effects of the VFSS timing after nasogastric tube removal on swallowing function of the patients with dysphagia. *Annals of Rehabilitation Medicine, 39*(4), 517-523.

Omari, T. I., Ferris, L., Dejaeger, E., Tack, J., Vanbeckevoort, D., & Rommel, N. Upper esophageal sphincter impedance as a marker of sphincter opening diameter. *American Journal of Physiology – Gastrointestinal and Liver Physiology, 302*(9), 909-913.

Pryor, L. N., Ward, E. C., Cornwell, P. L., O'Connor, S. N., Finnis, M. E., & Chapman, M. J. (2015). Impact of nasogastric tubes on swallowing physiology in older, healthy subjects: A randomized controlled crossover trial. *Clinical nutrition, 34*(4), 572-278.

Shaw, D. W., Cook, I. J., Holloway, R. H., Simula, M. E., Panagopoulos, V., & Dent, J. (1995). Influence of normal aging on oral-pharyngeal and upper esophageal sphincter functioning during swallowing. *The American Journal of Physiology, 268*(3), 389-396.

Silva, L. C., Herbella, F. A. M., Neves, L. R., Vicentine, F. P. P., Neto, S. P., & Patti, M. G. (2013). Anatomophysiology of the pharyngo-upper esophageal area in light of high-resolution manometry. *Journal of Gastrointestinal Surgery, 17*(12), 2033-2038.

Sivarao, D. V. & Goyal, R. K. (2000). Functional anatomy and physiology of the upper esophageal sphincter. *The American Journal of Medicine, 108*(4), 27-37.

TIMS Medical (n.d.). Swallow study recording. Retrieved from https://tims.com/timsmvpproduct/

Wang, Z. Y., Chen, J. M., & Ni, G. X. (2019). Effect of an indwelling nasogastric tube on swallowing function in elderly post-stroke dysphagia patients with long-term nasal feeding. *BMC Neurology, 19*(83).

Wilmskoetter, J., Martin-Harris, B., Pearson, W. G., Bonilha, L., Elm, J. J., Horn, J., & Bonilha, H. S. (2018). Differences in swallow physiology in patients with left and right hemispheric strokes. *Physiology and Behavior, 194*, 144-152.