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THE IMPACT OF TEMPORAL RESOLUTION ON CLINICAL DECISION-MAKING FOR INDIVIDUALS WITH DYSPHAGIA

by

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B.A., INTERNATIONAL STUDIES,
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THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

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DEDICATION

To my family, who has now heard me discuss swallowing more than they ever wanted to.

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THE IMPACT OF TEMPORAL RESOLUTION ON CLINICAL DECISION-MAKING FOR INDIVIDUALS WITH DYSPHAGIA

by

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ABSTRACT

INTRODUCTION: Dysphagia, or a disordered swallow, affects up to 1 in 25 individuals in the United States. The gold standard for assessing dysphagia is the videofluoroscopic evaluation of swallowing (VFES). This allows the clinician to observe the swallow anatomy in motion via an X-ray movie, which historically was recorded at 30 frames per second. In recent years VFES have been performed at less frames per second due to radiation concern. This project investigates the effect of using lower temporal resolutions on assessment of video-fluoroscopic swallow studies.

METHODS: In this investigation, 30 swallow studies, all acquired at 30 frames per second, were obtained from a repository at Presbyterian Hospital, with 6 studies chosen per each of the five categories of the international dysphagia diet to reflect varied levels of dysphagia. These studies were altered to simulate 15 and 5 frames per second. Temporal and kinematic measures were determined for thin and pudding/puree swallows per study at each of the 3 frame rates. Temporal measures included pharyngeal transit time (PTT), pharyngeal delay time (PDT), and duration of upper esophageal sphincter opening (UESOD). Kinematic measures included extent of hyolaryngeal elevation (HLE) and extent of upper esophageal sphincter opening (UESOE). A panel of 3 experienced speech—language pathologists viewed each study at the three frame rates in randomized order, without being given any indication as to frame rate per study. Each panel member gave their ratings of safety, efficiency, and two treatment target recommendations. The primary investigator then used the DIGEST (Hutcheson, et al., 2017) method to translate ratings of safety and efficiency into overall swallow severity.

RESULTS: Temporal and kinematic measures of PTT, PDT, and UESO, UESOD, and HLE were significantly impacted by reduced temporal resolution. Measures of safety, severity, and efficiency were not impacted by changes in frame rate.

CONCLUSION: Changes in temporal resolution had a significant effect on perception of temporal and kinematic measures but did not significantly affect ratings of safety and efficiency or treatment target selection. These findings indicate that, although perception of overall swallow severity was not greatly impacted, there was quantitative change as temporal resolution decreased. In clinical application, this means that diagnosis may not change as frame rate decreases, but perception of physiology is altered, which may guide decision-making. The direction of change was unpredictable, meaning that sensitivity and specificity are both affected as temporal resolution decreases.

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Chapter 1

Introduction

Despite its routine, dining does not lose its sentiment and gratification, particularly when enjoyed with loved ones. Sharing a meal is a universal act of comradery. However, for those with a swallow disorder, or dysphagia, mealtimes may be ripe with anxiety. In addition to greatly affecting quality of life, dysphagia may contribute to an inefficient or unsafe swallow, allowing material to enter the airway. This can cause aspiration pneumonia, which is potentially detrimental to an individual's health.

Speech-language pathologists (SLP) uphold the task of diagnosing and treating individuals who suffer from dysphagia. The gold standard for instrumental swallow assessment is the videofluoroscopic evaluation of swallowing (VFES), which is a video x-ray that allows a clinician to view the swallow mechanism's motion in real time. Historically, videofluoroscopic evaluations were recorded at thirty frames per second. Now with technological advances many hospitals have chosen to decrease the frames per second with the justification that a lower frame rate correlates with a lower radiation dose to the patient. While this a worthy consideration, a lower frame rate has the consequence of reducing temporal resolution thereby eliminating some of the details which may be required to determine diagnoses and decisions.

This study asks where the balance lies between reducing radiation exposure by lowering the frame rate and maintaining sufficient visual consistency to detect dysphagia and therefore design effective treatment plans. This was done by comparing different parameters of the swallow at varying frame rates. The purpose of this investigation is to determine at what point the diagnosis and treatment plan are impacted by the variations in frame rate that are used in clinical practice. The specific questions that will be answered are:

1. Does a change in VFES frame rate affect the temporal and kinematic scores of a swallow diagnosis?

   Hypothesis: When frame rate is decreased, temporal and kinematic scores will decrease in accuracy due to loss of temporal information

2. Does a change in VFES frame rate affect the safety, efficiency, and severity ratings of a swallow diagnosis?

   Hypothesis: As frame rate is decreased, ratings of safety, efficiency, and severity will decrease in accuracy due to loss of temporal information

3. Does a change in VFES frame rate affect the treatment targets chosen for a patient with a swallow disorder?

   Hypothesis: As frame rate is decreased, treatment targets for a patient with a swallow disorder will change due to loss of temporal information.

The evidence found in this study may be directly applicable in the clinical setting as the SLP and radiology community continue to improve the VFES procedure, thereby advancing medical practice and the wellbeing of humanity.

Chapter 2

Review of Related Literature

The Swallow

In order to grasp the intricacies and proper assessment of a swallow disorder, or dysphagia, one must first understand the mechanisms of a safe and efficient swallow. In a "normal" swallow, the pre-oral components may include the smell and sight of food, hunger, a memory of an experience with the food, and physically transporting the substance to one's mouth (Palmer, 2017). The sensory input from the substance can increase (or decrease!) one's desire to consume it. Once the food or drink enters the oral cavity, the swallow has officially commenced.

Oral Phase

The swallow is commonly divided into three phases: oral, pharyngeal, and esophageal. The oral phase can be further divided into preparatory and transport phases. Ideally in the oral preparatory stage, food or drink is placed in the oral cavity in a position that will aid in the subsequent steps necessary for an efficient swallow. Often, the sensory input or memories associated with a certain type of food or drink will activate the salivary glands. As the chewing pattern generator is initiated, the reduction component of the preparatory phase begins (Palmer, 2017). Through this combination of saliva and mastication the food is broken down and formed into a cohesive unit referred to as the bolus. The tongue and buccal muscles of the cheeks assist in tidy bolus formation. If the tongue is weak, spastic, or hypertonic, an individual may experience difficulty in proper bolus position, propulsion, and/or formation. A cohesive bolus is more conducive to a timely and residue-free swallow. Ideally, the bolus is contained in the oral cavity for the full duration of the oral phase. This requires anterior closure to prevent the bolus from exiting through the mouth. While liquids do not require chewing, both solids and liquids can result in anterior spillage. This may be caused by weakened muscles, motor or sensory deficit, structural abnormalities, or a combination of factors. While not necessarily unsafe, anterior spillage would constitute an inefficient aspect of the swallow. Posteriorly, the tongue base rises to meet with the soft palate, or velum. This is imperative to prevent premature spillage, which refers to a bolus entering the pharyngeal cavity before the swallow has been triggered and may result in a fragment of the oral bolus substance entering the airway.

As our young bolus moves on to the oral transport phase, pressure is created by the contraction of the lips, buccal muscles, and velum elevation. The tip of the tongue often assists by pressing superiorly against the palate to form a central groove, which can funnel the bolus posteriorly. Simultaneously, the velum lifts to protect the nasal cavity and allow for passage into the pharyngeal cavity. During the final moments of the oral phase the tongue sweeps the oral cavity, searching for residue and ensuring that there will be no post-swallow surprises entering the pharynx. Much like premature spillage, oral residue can sneak into the pharyngeal cavity when the swallow mechanisms are not prepared, putting an unsuspecting airway at risk.

Although a swallow trigger can occur anywhere in the pharynx, in young healthy adults, it typically occurs as the bolus passes the faucial pillars and enters the posterior oral cavity. Steele, et al. (2019) have found the trigger to occur when the bolus is as low as the pyriform sinuses in a perfectly healthy swallow, which may be due to natural variations across individuals and bolus textures. Viscosity of the substance consumed affects the swallow trigger as well; when swallowing liquids, trigger may be put into effect during oral propulsion (Matsuo & Palmer, 2009). In elderly adults or individuals with dysphagia, the swallow trigger is often delayed or not present. While a delayed swallow trigger is part of the normal aging process, a severely delayed or absent trigger means that the bolus may enter the pharynx without the proper safety mechanisms put into effect to protect the airway. When this occurs, the individual is at risk for residue, penetration, or aspiration, which may deem the swallow unsafe rather than simply inefficient. Sensory input from the bolus causes the afferents from mechanoreceptors to travel to the brainstem swallow center, or the central pattern generator. This area responds by releasing efferents to initiate a series of involuntary movements referred to as the swallow trigger (Jean & Dallaporta, 2006). These movements aid in a safe and efficient journey through the pharynx.

Pharyngeal Phase

As the bolus transitions to the pharyngeal phase, the journey shifts from horizontal to vertical. The goal of the pharyngeal phase is to propel the bolus inferiorly through the pharyngeal conduit and towards the esophagus. Successful execution means that the bolus does not enter the nasal cavity or the airway, and leaves little to no residue in the pharynx. Thanks to the swallow trigger, multiple life-saving events should be set into motion, all occurring in about 800 milliseconds (Palmer, 2017). Pressure and timing are essential components of an efficient swallow. When the bolus enters the pharynx, the velum raises to meet the nasopharynx, creating a seal over the velopharyngeal port. This superior seal ensures that the bolus does not enter the nasal cavity. If the seal is inefficient, an individual may experience nasal penetration, an unpleasant symptom of an inefficient swallow. Simultaneously, the base of the tongue makes contact with the posterior pharyngeal wall to exert pressure upon the tail end of the bolus. The pharyngeal constrictor muscles contract to create a wave, applying pressure from top to bottom and thereby squeezing the bolus downwards. The pharynx shortens during this process to reduce the length of the bolus's vertical journey. Driving pressure is created within the pharynx by securely closing all pharyngeal ports, such as the velopharyngeal port, oral entrance, and laryngeal entrance. This requires both punctuality and strength. Optimal bolus propulsion therefore relies on pharyngeal muscles and bolus cohesion. Deficiency in any of these areas may prevent the entire bolus from successfully reaching its next destination.

Throughout the pharyngeal journey there are multiple opportunities for residue to accumulate. Between the base of the tongue and the epiglottis is a recess referred to as the vallecula of the pharynx. The bolus passes over this space before splitting into two paths on either side of the larynx. These paths are known as the pyriform sinus. They are situated right above the upper esophageal sphincter (UES). The vallecula and the pyriform sinuses are tempting locations for residue or pooling to accumulate. This can be dangerous if it spills over into the airway while the swallow trigger is not in full effect and the airway is not protected. Residue can be a result of many circumstances including but not limited to muscle weakness, structural abnormalities, sensory deficit, or gastrointestinal reflux.

At the end of the pharynx, there is a fork in the road. The anterior passage leads through the laryngeal vestibule, past the vocal folds and into the respiratory tract. The posterior passage leads through the UES, into the esophagus and the gastrointestinal tract.

While this has proven to be an efficient model for survival for many thousands of years, there are risks involved. When we eat or drink, we are not only consuming our lunch, but also the bacteria that inevitably gathers on our food and in our mouths. The gastrointestinal tract has a complex system of filters and acids designed to manage this bacteria and gain nutrients from our consumption (Said & Ghishan, 2018). Alternatively, the respiratory tract relies on healthy lungs to provide optimal oxygenation. These lungs want nothing besides oxygen to enter their domain. But because the entrance to the airway is positioned in the pharynx, it goes without saying that food—and all the bacteria that comes with it—occasionally goes “down the wrong pipe”. If the traveling bolus or residue enter the airway and the material stays above the vocal folds, this is considered penetration. With enough sensory input penetration may be expelled with a simple cough. When residue travels *below* the vocal folds it is considered aspiration. Inferior to the vocal folds we find the trachea, which continues on to the lungs. When bacteria or particulate material enter the lungs they can cause aspiration pneumonia, which can be fatal, particularly in populations with compromised immune systems. Unfortunately, these are often the same individuals that struggle with dysphagia.

Esophageal Phase

After the pharyngeal phase, the bolus will pass through the upper esophageal sphincter (UES), the gateway between the pharyngeal and esophageal conduits. The UES must have proper extent and duration of opening in order for the bolus to make a smooth and complete transition from the pharyngeal phase to the esophageal phase. If the UES does not open sufficiently it may cause residue to pool around the UES in the aforementioned pyriform sinus. Alternatively, if the UES does not have an adequate seal to contain the bolus inferiorly, gastrointestinal reflux may occur. Both of these scenarios may result in residue spilling over into the airway. The UES is unique in that it is tonically active, meaning at rest it is closed, and when muscles are active it relaxes and opens. In a healthy swallow this opening should occur only during the bolus's passage inferiorly. Pharyngeal pressure and hyolaryngeal elevation further assist in opening the UES.

The esophageal phase begins when the bolus has passed through the UES. In the esophagus, a peristaltic wave commences to carry the bolus down to the lower esophageal sphincter and ultimately into the stomach. Once the bolus enters the gastrointestinal tract, assessment is no longer within the scope of the SLP. However, it is crucial that the healthcare team takes a multidisciplinary approach, using teamwork and communication to ultimately give the patient comprehensive services and optimal treatment.

Safety

Although it is everyone's best interest that the bolus makes a swift and orderly entrance into the esophagus, not all hope is lost if it is misled towards the airway. To combat penetration-aspiration, the airway has three layers of protection, all of which are involuntarily mobilized by the swallow trigger. This is an intentionally redundant design. The larynx resides between the oral cavity and the trachea, anterior to the pharynx. It is suspended by the hyoid bone, which is connected to the mandible (jaw) by the submental muscles. When the submental muscles are contracted, they pull the hyoid in a superior-anterior trajectory. The larynx tags along, deeming the term "hyolaryngeal complex". During a swallow, the hyolaryngeal complex is pulled anteriorly and superiorly thereby pulling the airway out of the trajectory of the bolus. The hyolaryngeal trajectory assists with epiglottic inversion as well, causing the epiglottis to fold over the laryngeal vestibule. This action intercepts a bolus that may be headed towards the airway, guiding it towards the path of safety. The vocal folds serve as the final layer of protection. During a swallow, the arytenoid muscles tilt towards the base of the epiglottis to tighten the aryepiglottic folds and squeeze the vocal folds securely shut.

It is unclear exactly how far the hyolaryngeal complex must move to ensure a safe swallow. Steele et al. (2011) conducted a study to determine if the extent of anterior and superior hyolaryngeal movement can predict aspects of a swallow. This was done by rating penetration-aspiration, vallecular residue, and pyriform sinus residue in 28 participants who were referred for assessment of dysphagia. The study affirmed that those with reduced range of movement were more likely to experience penetration-aspiration and were at greater risk for post-swallow pharyngeal residue. To measure hyoid excursion, the pre-swallow rest position was compared to the height of displacement, as viewed in frame-by-frame analysis of a recording of the entire swallow. To account for variations in patient height, the distance from the anterior inferior corner of the C2 vertebra to the anterior inferior corner of C4 vertebra served as a reference scalar. Hyolaryngeal elevation was quantified as a percentage of the reference scalar. This anatomical scaling is important because although males generally show longer spine length, upward hyolaryngeal displacement was similar between genders when scores were adjusted to scale, totaling from 51-66% of the C2-C4 distance. Anterior hyoid movement ranged from 33-42% of the C2-C4 distance. This study concluded that hyolaryngeal movement below the first quartile boundaries are associated with risk for penetration-aspiration and residue. Furthermore, it concluded that it is specifically important for clinicians to deduce if reduced anterior displacement is affecting swallow abilities.

Initiation of the pharyngeal swallow after the oral phase is ideally done in a timely manner. Perlman et al. (1994) use the term Delayed Pharyngeal Swallow (DPS) to indicate whether or not laryngeal elevation occurs within 1 second of the bolus entering the vallecula, then scaling the delay according to increments of time. Robbins et al. (1992) use the term Stage Transition Duration (STD) to measure time from when the bolus passes the ramus of the mandible until maximum hyoid excursion is initiated. Logemann, Pauloski, Rademaker, and Kahrilas (2002) use similar reference points, measuring the time from when the bolus head reaches the intersection of the lower mandible edge and the base of the tongue to when laryngeal elevation begins. Logemann refers to this as Pharyngeal Delay Time (PDT).

Kim, McCullogh, and Carl (2005) performed a study comparing these three approaches for measuring the speed of the swallow trigger. They reviewed the swallows of 40 individuals of varying ages and genders, with twenty aged 21-51 and twenty aged 70-87. They found that both PDT and STD were initiated before the bolus reached the ramus of the mandible in younger populations. With age, laryngeal elevation and initiation of maximum hyoid excursion were delayed. Older participants showed increased laryngeal penetration and increase in trace residue but no increase in aspiration. All swallows were considered normal. It can be inferred that the increase in residue and penetration is due to delayed pharyngeal swallow but should be noted that this is a normal effect of aging and does not immediately constitute an unsafe swallow. In fact, Kim, McCullogh, and Carl (2005), point out that delayed onset for the swallow may be a natural evolutionary compensation for changes in motor and sensory function. The study performed by Kim, McCullogh, and Carl (2005) found that STD and PDT were sensitive to changes with age but DPS showed no significant differences. This may be because younger subjects on average held a negative value for DPS, meaning that the swallow was initiated before the bolus reached the vallecula. Furthermore, DPS was developed to distinguish normal from disordered swallowing, rather than catch subtle differences between normal swallows. No significant gender differences were noted across the measures. This study underlines the minute differences in the terminology and measurements used when assessing swallow physiology.

Steele et al. (2019) provides recent and thorough data on values for bolus flow and swallow physiology for a range of viscosities in a normal population. They assessed the temporal and kinematic aspects of the swallows of 40 individuals aged 21-58, all of whom had no history of dysphagia. This investigation found that 67% of participants had a maximum PAS score of 1 across consistencies, and 25% experienced a PAS of 2 on single swallows of thin, slightly thickened, or mildly thickened liquids. The remaining four participants showed more frequent penetration, at levels of 1, 2, and one at level 5, but none experienced aspiration. This particular study suggests that minimal penetration may be normal in a population, but a healthy individual should not expect to experience aspiration. UES opening duration was found to range from a mean of 458 milliseconds with thin liquid swallows to 402 milliseconds in extremely thick liquid swallows. Swallow reaction time, defined as the time between the bolus passing the mandible to hyoid burst onset, ranged from a mean of 109 milliseconds for thin liquids to 347 milliseconds for thick liquids. The time between the hyoid burst onset to the UES opening, or pharyngeal transit time, ranged from a mean of 116 milliseconds for thin liquid swallows to 155 for extremely thick liquid swallows. UES opening extent was measured as a percentage of the C2-C4 reference scale, for the sake of standardizing according to patient height. These results ranged from a mean of 20.6% for thin liquids to a mean of 15.6% for moderately thick liquids, which was smaller than the mean for extremely thick substances. Hyoid peak position was measured as a percentage of the C2-C4 distance for the same reason. Steele et al. included the X value, Y value, and hypotenuse to account for anterior and superior movement of the hyoid. They found anterior movement to be significantly greater than the vertical movement. Results are listed in Table 1 below.

Table 1

"Descriptive statistics for hyoid peak position by consistency and plane of movement, measured as percentage of the C2-C4 reference scalar." (Steele, 2019)

Plane of movement	Consistency	M	SD	Lower bound (% confidence interval)	Upper bound (% confidence interval)
Horizontal (X)	Thin	144	14	140	149
	Slightly Thick	142	14	138	147
	Mildly thick	143	14	139	148

	Moderately thick	142	14	137	146
	Extremely thick	142	15	138	147
Vertical (Y)	Thin	91	23	84	98
	Slightly thick	89	24	82	96
	Mildly thick	94	22	87	101
	Moderately thick	93	23	86	100
	Extremely thick	92	20	85	99
Hypotenuse (XY)	Thin	170	16	165	175
	Slightly thick	168	17	163	173
	Mildly thick	170	16	165	175
	Moderately thick	168	18	163	173
	Extremely thick	168	16	163	173

This study affirmed that in thin and thick liquids it is typical to see complete laryngeal vestibule closure and pharyngeal constriction, and minimal post swallow residue. While penetration was rare in both, it was much less significant with thicker liquids. The scores can be used as a norm to reference when considering severity of a swallow in future studies.

Dysphagia

Swallowing is a complex process; there is a synchronization of physiologic events necessary to achieve this seemingly simple yet life-sustaining task. For each discrete event involved in a swallow, there lies potential for error. It unsurprising—albeit not well known—that dysphagia is common. Every year, 1 in 25 adults in the United States are affected by dysphagia (Bhattacharyya, 2014). This experience can dramatically alter the entire health status of an individual. One must only consider the value that culture and society places on food and drink to imagine the effect this would have on quality of life as well. A study done by Bhattacharyya (2014) found that presence of dysphagia had resulted in an additional 8 days of lost work per year, and 48% of adults with dysphagia self-reported their dysphagia to be a moderate to very big problem. Dysphagia may induce "dehydration, malnutrition, pneumonia, or airway obstruction" (Matsuo & Palmer, 2009), each of which has profound effect on an individual's quality of life (Padilla, 2019). Despite the combination of life-altering symptoms and high annual prevalence, most individuals suffering from dysphagia do not to seek out medical care (Bhattacharyya, 2014). Ideally dysphagia would always be treated with a combination of rehabilitative and compensatory strategies. However, effective rehabilitative plans depend on sufficient cognition and muscle mass. These two factors that may be decreasing as dysphagia progresses, depending on the individual's medical status and comorbidities. For this reason, it is best to seek services as soon as possible and it is imperative that assessment and treatment measures are accurate and effective.

Assessment

Videofluoroscopic Swallow Study

It is within the scope of an SLP to not only diagnose the presence of dysphagia, but to investigate the source as well. Because this can often be traced to the innerworkings of the swallow mechanism, there is a need for critical analysis of swallow anatomy and physiology. A number of imaging techniques have been developed for viewing the swallow phenomenon. These include but are not limited to fiberoptic endoscopic examination of swallowing (FEES), 3-D imaging, and ultrasound (Steele, 2014). Although the complexity of a swallow deems any singular study insufficient for capturing all variables, the videofluoroscopic evaluation of swallowing (VFES), formerly known as the modified barium swallow study, is considered the gold standard for detailed swallow assessment (Steele, 2014). In this procedure, an X-ray captures the movement of the swallow while simultaneously recording the study onto a digital video file. The SLP can watch the swallow as it is happening and replay the entire swallow for visual frame by frame analysis afterwards. This is helpful because the speed of the swallow and multitude of co-occurring actions make it difficult to adequately analyze each piece of the puzzle in real time. VFES allows SLPs to obtain information in an inexpensive, relatively quick, and noninvasive manner. In addition to viewing the anatomy and physiology of the oral, pharyngeal, and esophageal cavities, VFES gives visibility to residue, penetration-aspiration, and reflux. The information gathered from the VFES guides the SLP in making decisions regarding additional diagnostic tests, referrals, and treatment recommendations for a patient with dysphagia.

VFES History

Since its beginnings in the twentieth century, the VFES has been modified and standardized to become what is now considered the most efficient way to assess dysphagia. Initially, the patient was placed between an X-ray tube and a fluorescent screen. The screen was coated in barium platinocyanide or another fluorescent substance (Levine & Rubesin, 2017; Schueler, 2000). The fluoroscopist stood on the other side of the screen, sometimes behind leaded glass for radiation protection. X-rays passed through the patient, thus generating visible light as the rays hit the fluorescent screen. However, the images produced by these early models were dim, making it difficult to decipher details. Furthermore, in order to have dark adaptation for maximum visibility, the fluoroscopist would often spend ten minutes in a dark room before the procedure. Red adaptation goggles were developed, allowing the fluoroscopist to achieve some work while maintaining dark adaptation. This is similar to the tactic used by astronomers and photographers in the darkroom who need a degree of visibility to move about whilst working. Red light does not interrupt dark adaptation because the retinas of the eye are insensitive to longer light wavelengths (Allen & Triantaphillidou, 2010). Thus, a fluoroscopist was able to use red light to engage in work without losing view of the image at hand. Despite this innovation, the image quality remained less than ideal.

In 1953, image intensifiers were developed (Schueler, 2000). These drastically enhanced the visibility of images by using a series of optical lenses and mirrors to magnify the output of the fluorescent screen. The drawback of this system was that the frame of view was drastically decreased, so that only one person at a time could observe the image, and the operator's positioning needed to be frequently adjusted. As a remedy to this setup, a video camera was used to display the output image onto a monitor, and image intensifiers were made larger to encompass a full frame of view. In the 1990s analog systems were replaced with digital fluoroscopy systems (Levine & Rubesin, 2017). Flat panel fluoroscopes now digitize x-ray images through a series of detectors. The benefits of the digital switch were greater contrast resolution, faster acquisition of images, and the ability to archive them in computer-based picture archiving communications systems (PACS) to save and review the images. Furthermore, PACS allowed adjustment of the image with regards to contrast, brightness, or magnification of specific areas.

Penetration-Aspiration Scale

In the 1990s, a scoring system was devised to aid clinicians in quantifying the presence of penetration or aspiration while conducting VFES. Using the Penetration Aspiration Scale (PAS), clinicians were able to standardize their findings with regard to the depth reached by the bolus in the vocal folds and the patient's reaction to the intrusion (Rosenbek, Robbins, Roecker, Coyle, & Wood, 1996). The PAS was designed by four clinical scientists working in the Veterans Administration/University of Wisconsin Swallowing Laboratory. After trial runs and necessary adjustments, they decided upon an 8-point scale, depicted in Figure 1. The dimensions being measured are the depth of bolus journey into airway and the patient's response to the material in the airway. Response to penetration-aspiration is indicative of intact sensation in the larynx. When an individual has no response to aspiration, it is considered "silent aspiration", which can be dangerous because an individual is unlikely to seek help if they do not know that they are aspirating, allowing bacteria to continue to accumulate in the lungs undetected. The PAS is ordinal, meaning that a higher score correlates to more severe behavior. This scale is built upon the understanding that simply noting penetration or aspiration is not sufficient information; it is important to gauge the depth of the material passage and the patient's reaction as well. The PAS is still used today as a method for quickly determining these aspects of the swallow, which contributes to an understanding of dysphagia and aides in the construction of a treatment plan.

Figure 1

The 8-Point Penetration-Aspiration Scale scoring system (Rosenbek, Robbins, Roecker, Coyle, & Wood, 1996)

1. Material does not enter airway
2. Material enters the airway, remains above the vocal folds, and is ejected from the airway.
3. Material enters the airway, remains above the vocal folds, and is not ejected from the airway.
4. Material enters the airway, contacts the vocal folds, and is ejected from the airway.
5. Material enters the airway, contacts the vocal folds, and is not ejected from the airway.
6. Material enters the airway, passes below the vocal folds, and is ejected into the larynx or out of the airway.
7. Material enters the airway, passes below the vocal folds, and is not ejected from the trachea despite effort.
8. Material enters the airway, passes below the vocal folds, and no effort is made to eject.

It should be noted that not all penetration and aspiration is created equal. The severity of penetration/aspiration is determined by the amount, duration, and frequency of aspiration. The risk of this aspiration is determined by the material being aspirated. For example, implementation of the Frazier Free Water Protocol has shown that in certain individuals who aspirate, drinking water in between meals can be an effective method for improving life quality and hydration. However, this requires strict adherence to protocol and is only deemed safe in individuals with adequate cognition and oral and pulmonary health (Gillman, Winkler, & Taylor, 2017). Nonetheless, identifying penetration and aspiration can provide key clues to detecting an unsafe swallow and an indicator that further investigation on the *cause* of the penetration-aspiration should be performed.

Modified Barium Swallow Impairment Profile

Although the PAS contributed to the standardization of assessment terminology, the steps taken to come to such conclusions still varied greatly. In other words, the VFES became commonly available in the medical setting before a clear order of operations for execution of the assessment was established. This created ambiguity in interpretations of the assessment. In order to standardize the procedure, thus strengthening the common dialogue amongst clinicians and across settings, the Modified Barium Swallow Impairment Profile ™ was devised by Martin-Harris, Humphries, and Garand (2017). The MBSImP has been applied since 2005 to incorporate a consistent range of volumes and viscosities of barium into the VFES. This aims to allow clinicians to observe an individual consuming a simulation of the food and drink of a normal day and note any changes across substances. Along with protocol for consistency and volume of substance, the MBSImP incorporates a script for the clinician to instruct the patient while guiding the procedure to further standardize the procedure. Viscosities included in the MBSImP are thin liquid (via 5 mL spoonful twice, 20 mL cup sip once, and 40 mL sequential swallow once), nectar-thick liquid (via 5 mL spoonful twice, 20 mL cup sip once, and 40 mL sequential swallow once), honey-thick liquid (5 mL spoonful), pudding-thick consistency (5 mL spoonful), and ½ cookie. The nectar-thick and pudding-thick swallows are repeated in the anterior-posterior position.

In the lateral view, the clinician is watching for residue, bolus clearance, airway entrance, and anatomy and physiology of the swallow mechanisms to gauge the safety and efficiency of the swallow. The anterior-posterior view is incorporated to watch for asymmetrical residue, pharyngeal contraction and esophageal clearance. After implementing the full protocol, the clinician assigns overall impression (OI) scores to 17 physiologic components of swallowing. These quantifiable scores allow for direct interpretation across healthcare professionals and help guide the focus of treatment recommendations. The components of the MBSImP are divided into the 3 domains of a swallow: oral, pharyngeal, and esophageal. The creators of the MBSImP acknowledge that “standardization does not imply rigidity” (Martin-Harris, Humphries & Garand 2017) and deviations from the protocol may be warranted. This may mean implementing compensatory strategies during the procedure to assess potential techniques to combat the symptoms of dysphagia. Furthermore, if a certain consistency is deemed unsafe for a patient to attempt to swallow, they will perform an incomplete MBSImP.

Studies have shown that using the full MBSImP protocol minimizes radiation exposure to average less than 3 minutes (Bonilha, 2013), with high probability for capturing impairment (Martin-Harris, 2017). These scores should be used in congruence with qualitative scores such as patient reported outcomes to paint a holistic picture of the cause and effects of dysphagia in a given patient.

Dynamic Imaging Grade of Swallowing Toxicity

The National Cancer Institute's Common Terminology Criteria for Adverse Events (CTCAE) uses a five-point scale to grade dysphagia. Although used as a universal framework in oncology trials, the criteria do not account for the physiologic aspects of a dysphagia. Thus, it was proposed that a five-point, CTCAE-compatible MBS rating scale could be used to encompass the safety and efficiency of swallow. The Dynamic Imaging Grade of Swallowing Toxicity (DIGEST) accounts for pharyngeal residue and laryngeal penetration-aspiration. This framework was designed as a method to gradethe severity of pharyngeal dysphagia (Hutcheson et al., 2017). The conceptual model for the DIGEST states that a safety impairment refers to the presence of penetration or aspiration. An efficiency impairment refers to pharyngeal residue, which may result in nutritional compromise. DIGEST uses a consolidated version of the PAS to account for safety, and an estimate of percentage and frequency of pharyngeal residue to determine efficiency. These quantifiable scores have been converted into a five-point scale of severity, providing one single grade for pharyngeal swallow function. The DIGEST score of a swallow bridges the gap between SLPs who perform VFES examinations, and investigators of oncology trials. Furthermore, it allows for a quantifiable grade to encompass the two major determinants of dysphagia: swallow safety and efficiency.

ImageJ and Fiji

Much of interpreting VFES relies on the clinician's ability to make deductions from simply viewing frames of the swallow video. However, because this information is now stored digitally, there are processing systems that can be used to calculate temporal and kinematic measures. ImageJ is an image processing and analysis program that can be used to analyze and edit files that are uploaded. It can calculate area, distance, and angles, as well as temporal measures by stacking images (Ferreira & Rasband, 2012). ImageJ's functionality has been popular among researchers across a wide variety of fields. Fiji was created as an open-source distribution of ImageJ to ensure the accessibility of these tools while expanding upon its capabilities via more plugins (Schindelin et al., 2012). These programs can be used to make temporal and kinematic measurements on aspects of the swallow when used in conjunction with a high resolution videofluoroscopic swallow study.

Pulse Rate and Frame Rate

The use of standardized protocols combined with advances in technology have helped VFES become the well-established procedure that it is today. Beyond improvements in assessment accuracy, speed, and standardization, one more major shift has occurred: the ability to alter pulse rate. This option was brought about by the digitization of images. To understand the effects of altering pulse rate, one must have a thorough understanding of what this rate signifies.

In 2015, Steele wrote an open letter asserting the importance of the SLP understanding frame rate versus pulse rate in VFES. This was made necessary by the common misconception that the terms frame rate and pulse rate may be used interchangeably. Pulse rate, or fluoroscopy rate, refers to the number of X-ray beams being administered per second. When fluoroscopes were analog machines, the only two options were administering a continuous X-ray beam or being turned off. After the digitalization of fluoroscopy, the radiation beam could be altered to deliver short pulses of radiation as opposed to a continuous beam. In the United States, the common options for pulse rate are 30, 15, 7.5, 4, or 2 pulses per second (Steele, 2015).

VFES frame rate depends on the recording system and refers to the number of images per second generated by the fluoroscope. When using analog fluoroscopes, the video systems' output was 30 frames per second (FPS), which is why a "continuous" pulse rate equates to 30 frames per second. This means that the SLP has 30 images per second of the study to analyze. Now that pulse rate can be altered, the frame rate is set to match it for optimal viewing quality. If the frame rate is higher than the pulse rate, the result will be image replicas. If the frame rate is lower than the pulse rate, the clinician will be missing images from the recording, thus risking a choppy visual effect because the recording machine will have failed to capture all images provided by the fluoroscopy machine (Peladeau-Pigeon, 2015). The fluoroscope settings are determined by the radiology technologist or the radiologist, but the SLP should be informed and involved in the conversation as they are the ones who will be analyzing the images (Zarzour, Johnson, & Canon, 2018).

ALARA

Ionizing X-ray beams are potentially cancerous in very large doses, and thus many facilities have opted to lower pulse rate to minimize risk of cancer. However, one must keep in mind the concept of ALARA, or As Low as Reasonably Achievable

(Strauss and Kate, 2006). ALARA means that any procedure involving ionizing radiation exposure must keep that exposure as low as possible while still achieving the task at hand. It is a widely accepted philosophy in the world of medical radiology that the benefit of radiation exposure should always exceed the risk of radiation itself in order to justify the procedure. When lowering pulse rate, the trade-off is that temporal resolution of an assessment will be affected. With fewer pulses per second, the matching frame rate gives us fewer images per second to assess for diagnostic information. The optimal image acquisition rate depends on how short the events are that the clinician is trying to view, and the consequences of missing that event. Given the rapid events of a swallow, crucial details may fall through the cracks if acquisition rates are altered. To put this into perspective, to decrease from 30 to 15 frames per second is the equivalent of blindly throwing away every other image taken with the hope that the discarded frames did not contain any important information. Across New Mexico, frame rate varies from 30 to four frames per second (Tibbetts & Palmer, 2019). Steele (2015) maintains that 30 images per second is the optimal image rate for the sake of temporal resolution, despite the potentially heightened risk of radiation exposure.

Radiation Risk

The risk of cancer associated with VFES refers to the biological ramifications caused by X-rays and gamma rays. Excess cancer risk is typically considered stochastic, meaning that it can occur at any level of radiation exposure, and risk increases as the dose increases (Lin, 2010), hence the effort to keep it as low as possible. Effective dose of exposure is often used to assess cancer risks and genetic bioeffects across procedures (Nickoloff et al., 2008). This is calculated by multiplying the radiation dose administered to each organ by that organ's tissue weighting factor, which accounts for the carcinogenic sensitivity of an organ. The sum of these products is considered the effective dose and is measured in millisieverts (mSv).

With history's harsh lessons, we can attempt to make sense of the implications of different ranges of effective dose. To put radiation exposure into perspective: the average dose of mSv per year is approximately three mSv (Lin, 2010). Japanese atomic bomb survivors received a dose *above* 100 mSv (Lin, 2010). There is solid evidence for the stochastic effects of radiation in this population. In comparison, a single abdominal computed tomography (CT) scan is around 10 mSv. This is a controversial range, although CT scans are a common medical procedure. CT scans serve as an example where the benefit of the procedure is considered in conjunction with the risk of radiation. In other words, a CT scan may not be justified for a healthy individual but is warranted for an individual who is suffering from internal injuries or even as a preventative screening procedure for individuals at high risk.

Reports of effective dose from VFES vary slightly across literature. Lin (2010) reports that one VFES gives 1.5 mSv, equivalent to six months of accumulating natural background dose. Crawley, Savage, and Oakley (2004) reported a median effective dose of .85 mSv in 21 patients who underwent VFES. Hersh et al. (2016) report that in a study of 78 children the mean effective dose per VFES was only .16 mSv while using continuous fluoroscopy. This low report may be due to extra precautions that are taken with the pediatric population. Not all studies report the frame rate used, and it should be noted that data comes from various countries, where fluoroscope models may have differences in what is considered "continuous" fluoroscopy. However, even with the slight range of data, all reports of effective dose from VFES are well below 10 mSv. There is no empirical evidence to support an increase in cancer risk in this range, as considerably large statistical power would be needed for detection (Lin, 2010).

Quantifying the risk of an exam contributes to practitioners' informed decision-making process. In VFES, the organ of primary concern is the thyroid because it is radiosensitive and receives the highest exposure during the procedure. Bonilha, Huda, Wilmskoetter, Martin-Harris, and Tipnis (2019) recently sought to investigate the excess cancer risks associated with VFES and how those risks vary according to age and sex. This study found that the excess risk of thyroid cancer is highest in younger adults, compared with individuals above 40 who have more risk of leukemia and lung cancer. Examiners performed VFES on 53 adult patients using the full MBSImP protocol. The results showed VFES caused excess cancer risk of 32 per million exposed 20-year-old females, 11 per million exposed 20-year-old males, 7.2 per million exposed 60-year-old females, and 4.9 per million exposed 60-year-old males (Bonilha, Huda, Wilmskoetter, Martin-Harris, & Tipnis, 2019). These numbers suggest that age is the most prominent determinant of patient cancer risk, while sex plays a smaller role. Younger patients possess a higher excess cancer risk because they have more time to develop cancer over the course of their remaining life. These numbers contribute to the discussion of radiation exposure because optimal safety measures may vary depending on the patient demographics.

The Speech Language Pathologist

The American Speech-Language-Hearing Association states that 60% of SLPs spend their time delivering services to adults, and in those adult settings, 39% of the time is spent treating swallowing disorders (ASHA, 2017). Clinicians in medical setting often rely heavily on VFES. ASHA asserts the importance of SLPs understanding radiation and X-Ray function ("Radiation Safety", 2019) in order to make educated decisions with the radiologist regarding radiation exposure and patient safety. Master's programs for speech and hearing sciences often offer only one term of dysphagia coursework, where they must cover normal swallow physiology, evaluation of dysphagia, and treatment methods. This leaves little time to discuss the physics or ethics of specific assessment procedures. Consequently, new SLPs are entering the workforce without the tools necessary to partake in a conversation with the radiologist regarding the settings for VFES or make a strong case for patient wellbeing. Although it is within the SLPs scope of practice to advocate for the necessary frame rate for a patient, this task is often deferred to the radiologists or radiology techs. In order to contribute to this interdisciplinary dialogue, an SLP should have basic understanding of the benefits and risks of VFES, particularly with regard to radiation exposure.

Evidence

In recent years, the collective awareness of inconsistent clinical practice has spurred the desire to quantify the effects of altered frame rate on assessment. Cohen (2009) was among the first to conduct a study intended to understand the consequences of altering VFES frame rate. Noting that the pediatric population has a heightened risk of radiation-induced cancer, Cohen sought to investigate if it was plausible to maintain sufficient temporal resolution while using a decreased frame rate. The VFES of 10 children participants, ages one month to 33 months, were observed. Supraglottic penetration was observed in all participants. The studies were conducted at continuous fluoroscopy, and the bolus was a drink of non-thickened barium. Frame by frame analysis was performed to determine how many image frames displayed penetration. Cohen found that in seven of the 10 studies, full-depth penetration was visible in only one frame. There were no studies in which full depth penetration was visible in more than two frames. Additional frames showing partial penetration ranged between zero to two frames. This study shows that certain swallow abnormalities, such as deep penetration, occur so rapidly that they are only visible in one frame, or for 1/30 of a second. By reducing the frame rate to 15 frames per second (fps), and thereby losing 50% of frames, a clinician risks foregoing crucially telling images. When this occurs, the risk of inaccurate clinical diagnosis negates the justification of performing the VFES.

Bonilha et al. (2013) was among the first to simulate lower frame rates to determine the effect on judgement. They conducted three experiments within one study to assess different parameters of these effects. The first experiment had two SLPs score Modified Barium Swallow Impairment Profile (MBSImP) and the Penetration-Aspiration Scale (PAS) components in five randomly selected swallow studies that followed MBSImP protocol. These studies covered a range of viscosities and were assessed before and after lowering the frame rate from 30 to 15 frames per second. The results were that six of the 17 MSBImP components differed between the two frame rates. Initiation of pharyngeal swallow was the most prevalent score to change. The PAS scores of thin liquids differed for one of the patients, going from a score of two when viewed at 30 frames per second, to one with lowered frame rate.

For the second experiment of the study, the scores from the first experiment were given to five other SLPs who made treatment recommendations regarding diet, compensatory/treatment strategies, and patient prognosis. This experiment epitomizes the bridge between quantitative scoring systems and clinical application. The ten patient profiles were represented as if they were ten individuals, rather than five patients with two sets of frame rates. The results were that 60% of patients would be put on a different diet going from 30 to 15 frames per second. All treatment strategies differed due to differences in swallowing severity scores, and 36% of prognoses changed between good and fair.

The third experiment aimed to focus on judgements of penetration and aspiration. In this investigation, 15 previously assessed swallow studies with a wide range of PAS scores were recorded at 30, 15, 7.5 and 4 pulses per second. The two SLPs from the first experiment rated them on PAS, and then compared the results across raters. They found a difference in PAS scores for 80% of patients when frame rates were decreased from 30 to various other rates. The highest agreement was found between 30 and 15 frames per second while the lowest agreement was between 7.5 and 4 frames per second. Compared to the first experiment, PAS scores were in much higher jeopardy when frame rate was altered more and when the population was larger. This is crucial information because in the reality of clinical application, frame rate does not stop at 15 frames per second. In order to provide applicable evidence, studies must encompass all of the real-life scenarios before making judgement calls. The takeaway from these three experiments is that a lower frame rate affects both judgement and treatment recommendations for swallowing impairment, making it clinically relevant.

In 2019, Mulheren et al. expanded on existing research by assessing measures of timing, airway protection, and swallowing physiology in 20 patients after ischemic stroke. Patients had reports of normal swallows to severe dysphagia (Mulheren et al., 2019). Continuous fluoroscopy was performed in this study. Then every other frame was removed to simulate 15 frames per second. The MBSImP protocol was followed, although anterior-posterior view was not available in all studies, and the oral cavity was not visible in all studies. To standardize ratings, the corresponding components of the MBSImP protocol with these aspects of the swallow (Components 1-6) were not included. Using a blinded comparison model, two MBSImP certified raters analyzed the randomized and de-identified videos with both sets of frame rates. This study found that PAS scores showed no difference between the two frame rates, contradicting Cohen's pediatric study (2009). However this may be due to the differences in the study population (pediatric vs. mean age of 56.6) and medical etiology that caused the dysphagia. This distinction begs for more investigation into the impact of temporal resolution on the severity of the swallow.

All patients in Mulheren et al.'s study (2019) displayed a consistent set of temporal and PAS measures. In solid swallows, the bolus entered the pharynx later when the study was analyzed at 30 frames per second rather than 15 fps. However, in nectar-thin liquid swallows, the bolus entered the pharynx later in 15 frames per second. The bolus entered the UES later in sequential thin liquids at 30 FPS than 15 FPS, and the pharyngeal transit time was longer at 30 FPS for pudding thick substances. These findings point to the importance of distinguishing the effect of temporal resolution on differing swallow viscosities.

Interestingly, the 15 FPS studies received more severe ratings for oral residue and pharyngoesophageal segment opening than the studies viewed at 30 FPS. However, an oral residue score of one is still within normal limits, as it denotes only trace residue lining the oral structures and therefore would not change anything regarding treatment. This highlights the importance of looking at clinical application of variation in scores, and not just the numbers themselves. Bolus transport/lingual motion and initiation of pharyngeal swallow scores, on the other hand, were more severe at 30 FPS during solid swallows.

Mulheren et al. (2019) concluded that the simulated 15 FPS videos resulted in distorted swallowing measures with quantifiable differences, supporting the use of continuous fluoroscopy and warranting the need for further larger-scale research on this topic. The disagreement between 30 and 15 frames had varying effects on the severity of the swallow, highlighting that the more severe rating is not necessarily always the correct one. Perceiving and therefore treating normal physiology as disordered may present an unnecessary economic burden and impact on patient quality of life. One must be sure that treatment is necessary before asking a patient to make the life changes that therapy may entail.

One of the most recent studies done on the effect of frame rate reduction in VFES was conducted by Layly et al. (2019) in Tours, France. This study compared the PAS scores from studies performed at 30 and a simulated 15 frames per second. With a sample size of 32 participants, it had a larger participant population than most previous frame rate investigations. Participants were between the ages of four months to 16 years, all of whom had suspected deglutition or neuromuscular impairment. The study does not state if the full MBSImP was followed but acknowledged that textures varying from liquid to solid were given to the patients, depending on their age and abilities. Layly makes the case that the pediatric population has an increased risk of leukemia and brain cancer linked to radiation exposure, and therefore the ALARA concept is especially crucial when conducting VFES with this population. Investigators began with 190 VFES at 30 frames per second, then modified them to simulate 15 FPS by deleting every other frame. Studies were randomized and viewed by an otorhinolaryngologist-phoniatrician and a radiologist, who rated each study using the PAS scale. Although sensitivity and specificity were slightly lower at 15 FPS than 30 FPS, the final interpretations were consistent. Raters found that a change in frame rate did not change the PAS score for any of the patients, and therefore the authors suggest reconsidering the use of 15 FPS in the pediatric population (Layly, 2019). However, one must keep in mind that the PAS scale was the only scoring system used in this investigation, and the creators of the PAS scale recommended that the scale be used as a supplementary tool to a more comprehensive swallowing assessment (Rosenbek, Robbins, Roecher, & Coyle, 1996). Although the detection of penetration or aspiration plays a major role in defining the severity of the disorder, it does not offer full understanding of the state of swallow mechanisms, was never meant to be solely sufficient for diagnosis and treatment planning.

Conclusion

In the past century, the medical community has made strides in the development of the VFES procedure in order to improve dysphagia assessment. Radiologists have achieved a fluoroscope design that allows clear vision of the inner workings of an individual’s swallow mechanism while preserving patients’ comfort and clinicians’ time. SLPs have improved the efficiency of assessment and communication via protocols such as the MBSImP, DIGEST, and PAS scale. However, because technology has provided the power to alter pulse rate, there is a new discussion at hand: what constitutes ALARA? In a world of technology that changes seemingly exponentially, it is up to researchers and clinicians to maintain evidence-based practice. The discrepancy in frame rates across facilities demonstrates that despite being considered the gold standard of assessment, the VFES *itself* lacks standardization. There is no reason why geographic location should affect the quality of care when clinics possess the same resources. In order to establish precisely what the ideal frame rate is, one must determine the effect of altering frame rate. Due to the investigations conducted in recent decades, it is clear that this has become a topic of increasing interest to medical professionals working with dysphagia. This thesis project will expand the current pool of knowledge by considering multiple factors that have not been analyzed for the same sample size before: temporal, kinematic, safety/efficiency, and treatment recommendations. By observing quantitative changes in these measures for a sample size of 30 swallows across frame rates, this study will paint a more comprehensive picture of the particular aspects of the swallow that may be affected by variations in temporal resolution. This evidence found in this study may be directly applicable in the clinical setting as the SLP and radiology community continue to improve the VFES procedure, thereby boosting medical practice in application and ethics.

Chapter 3

Methodology

Introduction

In this retrospective investigation, temporal and kinematic swallow measures including pharyngeal delay time, pharyngeal transit time, swallow-related hyoid displacement, and upper esophageal sphincter opening extent/duration were scored across three frame rates: 30, 15, and 5 frames per second (FPS). Safety, efficiency, overall dysphagia severity, and treatment targets were determined across 30, 15, and 5 FPS as well. Nonparametric statistics included a Friedman's one-way analysis of variance for repeated measures. If findings were significant, a post-hoc pairwise comparison was completed to decipher specifically at which frame rate the significance was found. The impact of consistency on continual data was assessed separately to determine if thin liquid or pudding puree swallows were affected differently by reduction in temporal resolution.

This combination of analyses contributes to a comprehensive understanding of the intricate differences that are seen across varying frame rates and how they correlate with viscosities used in a swallow examination. Approval for this database review was granted from the Institutional Review Boards of Presbyterian Hospital and the University of New Mexico (UNM).

Participants

Thirty swallow studies recorded using continuous fluoroscopy were obtained from the retrospective videofluoroscopic swallow study database at Presbyterian Hospital in Albuquerque, New Mexico. This included six studies per each of the five levels of the

National Dysphagia Diet used at Presbyterian Hospital. The translation to the International Dysphagia Diet Standardization Initiative scale (IDDSI), which is more familiar to SLPs globally, is seen in Table 2. Obtaining participant representation across diet levels ensures that the sample population portrays a generalizable variation in dysphagia severity. Inclusion criteria within diet levels was that VFES was recorded and stored at 30 FPS. All VFES studies were stripped of identifiable information prior to being analyzed.

Table 2

Presbyterian diet types compared to the IDDSI.

Presbyterian Diet	**IDDSI**	**Examples & Criteria**
NPO (nil per os, or "nothing by mouth") or free water protocol	NPO	N/A
Dysphagia 1	Puree IDDSI 4	Pudding-like, requiring very little chewing, such as thick cereal, pudding, or pureed foods; some liquid limitation
Dysphagia 2	Minced and moist IDDSI 5	Cohesive, moist, semisolid foods that require some chewing, such as finely minced fruit & vegetables, mashed fish, soaked breads May or may not have liquid limitation.

Dysphagia 3	Soft and bite sized IDDSI 6	Soft foods that require more chewing ability, such as cooked tender meat, steamed vegetables, stew with thick liquid portion. Likely no liquid limitation
Mechanical soft/Regular	Soft/Regular IDDSI 7	Chewable foods, thin liquids allowed

Data Collection

The radiology unit of a hospital saves videofluoroscopic studies in Digital Imaging and Communications in Medicine ® (DICOM) format using a proprietary software that specializes in storage of swallow studies called TIMS Dicom Review Software ™ (TDRS). All 30 studies were imported to TDRS for viewing on a computer in the Dysphagia Laboratory at UNM. When viewed in TDRS software, each full study is divided into separate swallow clips. Each clip displays one of the various bolus viscosities, compensatory strategies used, and/or patient positions that were implemented during the swallows throughout the examination. A swallow study is broken down into multiple views. Between each bolus presentation, the fluoroscope is turned off. This decreases radiation exposure and allows a clinician to easily navigate to which swallow they would like to observe when watching the recording. There is typically *one bolus presentation per view* within a full study. In this investigation, four specific views from each study were selected to be exported: 5 mL thin liquid, 5 mL nectar, a spoonful of pudding or puree, and a solid. In the case of studies that did not implement all four of these viscosities, any of the four viscosities that were included were selected. These four viscosities were chosen to provide opportunity to observe the swallow physiology across a range of viscosities while maintaining consistency across studies. In all selected views, the patient was seated in a lateral position, with no compensatory strategies imposed. The selected views were concatenated into one single video per study as they were exported from TDRS.

Video Alteration

Studies were imported into Fiji which is a software designed to make biological image analysis possible (Schindelin et al., 2012). This includes editing videos or measuring aspects of an image. Using Fiji, the viscosity of each swallow was labeled with text in the upper portion of the screen as “5mL Thin”, “5 mL/Cup Nectar”, “Pudding/Puree”, or “Masticated”. Using Fiji, the primary investigator altered all 30 videos to simulate 15 and 5 FPS, thus providing the three frames rates to be compared in this investigation. The concatenation and labeling was done with the help of undergraduate volunteers in the Dysphagia Lab at UNM.

Presentation Movie for Panel of Experts

All 30 studies (each containing up to four views of viscosities) at each frame rate were replicated into a slow-motion version at half speed using Fiji. Using Camtasia video editing software, the swallow videos (90 in total) were compiled into five movies. In a randomized order, each study is displayed first in regular motion, then in slow motion. There is a 15-second pause between the regular motion view and the slow-motion view, and another 30-second pause between each new study displayed. These movies were utilized for the rating of the efficiency, safety, and treatment recommendations for each swallow. Randomization was achieved by the primary investigator writing each study’s code name onto a slip of paper, putting them all into a plastic bag, shaking the bag until mixed well, and blindly choosing study names one by one to decide the order of appearance in the movies. These 90 studies were split into five movies, each roughly one hour in length. Movies were uploaded to a OneDrive file that requires an invitation to access to maintain privacy.

Temporal and Kinematic Data

Across all 30 studies and three frame rates, temporal and kinematic data were calculated for two bolus types: 5 mL thin and spoonful of pudding or puree. Because Presbyterian's Dysphagia Diet 1 encompasses both pudding and puree viscosities, the two viscosities were combined into one category for the sake of this study. These data were calculated by the primary investigator.

Steele, et al. (2019) described a method for reaching these data points: the Analysis of Swallowing Physiology: Events, Kinematics and Timing, or ASPEKT. This method was used for all temporal and kinematic calculations. The ASPEKT method asks the investigator to note specific landmarks throughout the swallow, to be used when calculating temporal and kinematic data points. Normalizing temporal and kinematic area was completed by calculating all data points across all three frame rates as a percentage of the maximum data point. Using 30 FPS as the benchmark for the desired measurement, 15 and 5 FPS were compared by calculating a difference between the data obtained from each lower frame rate and the maximal frame rate.

Temporal Data

For temporal data, landmarks of the swallow were noted and referenced by the frame number. These landmarks included: bolus passing the mandible (BPM), onset of hyoid burst (HYB), upper esophageal sphincter opening (UESO), and upper esophageal sphincter closure (UESC). The definitions used to identify each point are displayed in Table 3. These points were then used to calculate pharyngeal delay time, pharyngeal transit time, and UES opening duration. The definitions used to identify each point are displayed in Table 4.

Table 3

Definitions of swallow landmarks (Steele et al., 2019)

Landmark	Definition
Bolus passing mandible (BPM)	The point at which the leading edge of the bolus touches the ramus of the mandible, before it dumps into the valleculae
Onset of the hyoid burst (HYB)	The initiation of the hyoid movement associated with the jump for the swallow
UES opening (UESO)	The first frame where the bolus clearly enters the superior aspect of the UES
UES closure (UESC)	The first frame where total contact is achieved at any one level of the UES

Table 4

Landmark equations used to calculate temporal data points

Equation	Temporal Data Point
Interval between BPM and HYB	Pharyngeal delay time
Interval between BPM to UESC	Pharyngeal transit time
Interval between UESO and UESC	UES opening duration

Kinematic Data

Kinematic data was collected for hyolaryngeal trajectory and UES opening extent. Data points were rated by the primary investigator for all views of the 5 mL thin and spoonful pudding/puree views at each of the three frame rates. This was done using the measurement tool in Fiji software in conjunction with the ASPEKT Videofluoroscopy Rating Method (Steele, 2019). The procedure for determining these kinematic data points are listed in Table 5.

Table 5

Procedure for determining kinematic data points (Steele, 2019)

Data point	**Procedure**

Hyoid displacement	• In a frame containing hyoid at rest, identify:
	  ○ Most inferior-anterior point of second cervical vertebra (C2)
	  ○ Most inferior-anterior point of fourth cervical vertebra (C4)
	  ○ Most superior-anterior point on hyoid bone
	  ○ Fiji's measurement tool calculates the hypotenuse of this angle, thus giving us the measurement for the hyoid at rest (Resting Peak XY)
	• In frame with maximum hyolaryngeal elevation, identify:
	  ○ Most inferior-anterior point of C2
	  ○ Most inferior-anterior point of C4
	  ○ Most superior-anterior point on hyoid
	  ○ The hypotenuse of this angle provides the peak XY for the maximum hyoid elevation (Maximum Peak XY)
	• Equation: Maximum Peak XY-Resting Peak XY=Maximum Hyoid Displacement, or Hyolaryngeal elevation (HLE)

UES opening extent	• Using the temporal data of UES open/close, identify the frame with the fullest invasion of UES while the hyolaryngeal complex is still in full elevation. • Set a reference scalar by drawing a line from C2-C4 • Using the angle tool, use C2-C4 to build a 90-degree angle

	• Measure the narrowest section of the UES opening between C4-C5, parallel to the angle

Interrater Reliability

Interrater reliability was assessed for a minimum of 15% of each temporal landmark using an agreement of plus or minus 30% of the identified frame. Due to the varying frame rates, each landmark was assessed using ±10 frames for 30 FPS acquisition, ±5 frames for 15 FPS acquisition, and ±2 frames for 5 FPS acquisition. A goal of 85% agreement was identified as the cutoff.

Safety & Efficiency Data

A panel of three experienced clinicians viewed the five movies and selected ratings of safety, efficiency, and treatment target recommendations. For randomization, each rater viewed the five movies in a different assigned order. Table 6 depicts the raters' level of experience reading VFES and MBS Certification status.

Table 6

Panel of expert raters: Experience with MBSImP

	Rater 1	Rater 2	Rater 3
Years of experience reading VFES swallow studies	3 years	10 years	7 years

MBSImP Certified?	Yes	Yes	Yes

Safety

For gauging safety of a swallow, most practicing clinicians are familiar with the Penetration-Aspiration Scale (PAS) (Rosenbek et al., 1996). This scale contributes to the three questions to consider regarding the penetration-aspiration of a swallow:

1. What is the severity according to the PAS scale?
2. What is the frequency of this penetration-aspiration?
3. What is the amount being penetrated-aspirated?

The Dynamic Imaging Grade of Swallowing Toxicity, or DIGEST scale (Hutcheson et al., 2017) consolidated the eight-point PAS scale into a series of four scores, while providing additional measures of frequency and amount aspirated. The DIGEST format was depicted in tables for the panel of raters to choose from per swallow when watching the movies. Table 7 depicts the rubric used by the panel of raters to indicate the PAS severity for each swallow.

Table 7

Scores of severity of penetration-aspiration (Hutcheson et al., 2017)

Score #	PAS Severity (on most severe observed)

1	1-2: No pen/asp or penetration above TVF with ejection
2	3-4: Penetration above TVF without ejection or contact with TVF with ejection
3	5-6: Penetration to TVF without ejection or aspiration with ejection
4	7-8: Aspiration not cleared, silent or sensate

Table 8 gives raters options for the *frequency* of penetration-aspiration. This rating was in reference to the swallow or swallows given the most severe rating from the previous table.

Table 8

Frequency of most severe penetration-aspiration (Hutcheson et al., 2017)

Score #	PAS Frequency (on most severe observed)

1	None → Single event
2	Intermittent: On multiple but <50% of trials on a single consistency
3	Chronic: Majority [>50%] of thin liquid trials and/or on >1 consistency

For the final rating of swallow safety, Table 9 indicates ratings for the *amount* that was penetrated-aspirated on the most severe swallow observed.

Table 9

Amount penetrated-aspirated

Score #	PAS Amount (on most severe observed)
1	None → Trace: Resembles faint coating, droplets, or trickle of barium on/below TVF
2	Neither trace nor gross

3	Gross: (>25% bolus volume)

Efficiency

Swallow efficiency is characterized by rapid and successful movement and clearance of the bolus through the pharyngeal system. To assess efficiency, pharyngeal residue is observed. The DIGEST (Hutcheson et al., 2017) breaks residue down into the amount observed and the viscosity on which the highest amount was seen. Table 10 gives scores for the most severe amount of residue observed on a swallow, as defined by percentages.

Table 10

Amount of residue observed

Score #	Residue Amount (most severe observed)
1	Less than 10%: Minimal to no residue
2	10-49%: Less than half residue
3	50-90%: Majority residue

4	Greater than 90%: Near complete residue

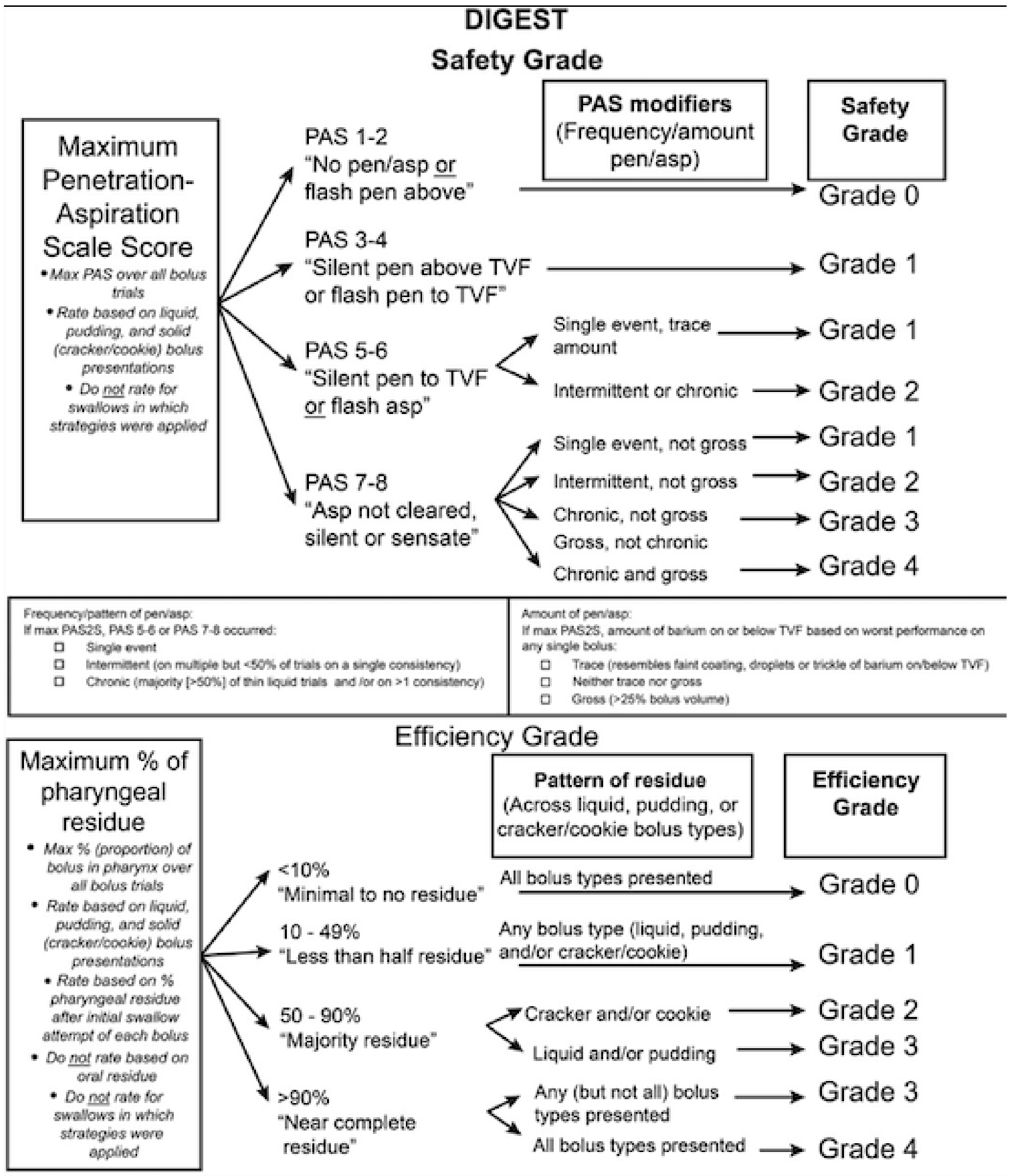
Raters were asked to place an "X" under each viscosity on which the highest amount of residue was observed, out of: thin & nectar, pudding/puree, or masticated because the DIGEST asks if residue was noted on none, any, or all viscosities. Thin and nectar were consolidated into one category because DIGEST does not discriminate between liquids. The combination of percent residue and viscosities on which that amount was seen can be combined to create the efficiency rating, as outlined in the DIGEST.

Overall Severity

Ratings of safety and efficiency from the panel of raters were used to measure overall swallow severity using the DIGEST chart, as seen in Figure 2. This was performed by the primary investigator.

Figure 2

Computing algorithms for the Dynamic Imaging Grade of Swallowing Toxicity (Hutcheson et al., 2017)



	S0	S1	S2	S3	S4
E0	0	1	2	3	3
E1	1	1	2	3	3
E2	1	2	2	3	3
E3	2	2	3	3	4
E4	3	3	3	4	4

Treatment Targets

The final scores given by the raters were treatment target recommendations, as seen in Table 11. Based on their observations of the deficits affecting the safety and efficiency of the swallow, each rater chose 2 treatment targets from the table and inserted the corresponding score number into their Excel scoring spreadsheet. The order in which they place the scores was irrelevant. This rating bridges the gap between deficits observed and clinical application. This table was designed to comprise oral and pharyngeal aspects of the MBSImP protocol and consolidate them into physiological deficits that would be targeted in clinical therapy.

Table 11

Treatment Target Recommendations

Score	Treatment Targets	Definition
1	Oral bolus formation and control	Opening/anterior containment, posterior containment, lingual bolus formation & propulsion
2	Tongue base retraction	Tongue base contact with posterior pharyngeal wall
3	Velar elevation/closure	Adequacy of closure/presence of nasopharyngeal reflux

4	Laryngeal vestibule closure + superior hyolaryngeal movement	Presence of bolus below laryngeal vestibule/risk of penetration
5	Pharyngeal shortening & contraction/squeezing	Efficiency of bolus transport through the pharynx through pharyngeal shortening, Adequate pharyngeal constriction to support efficient bolus transit through pharynx
6	Upper esophageal sphincter opening extent & duration + anterior hyolaryngeal movement	Sufficiency of UES opening for bolus transit to the esophagus
7	None/Other	N/A

Before beginning the rating process, all raters viewed an instructional video guiding them through the process and explaining each of the scores they would be rating. They were asked to complete the process within 20 days. They were allowed to go at their own pace, with the understanding that they could stop the movies but not rewind. Each rater received a gift card to Target.

Data Analysis

Data was evaluated for the following outcomes: temporal, kinematic, safety & efficiency, overall severity, and treatment recommendations. Specific measures for each outcome are listed in Table 12.

Table 12

Summary of outcome measures addressed in this investigation

Temporal	Kinematic	Severity	Treatment Recommendations
• Pharyngeal delay time • Pharyngeal transit time • Upper esophageal sphincter opening duration	• Hyolaryngeal elevation • UES opening extent	• DIGEST score (Penetration-aspiration and residue)	• Treatment target selection; 2 per study

Statistics

Statistics were performed on all outcome measures. Continuous outcome variables included temporal measures of pharyngeal transit time, pharyngeal delay time, upper esophageal opening duration time, and kinematic measures of upper esophageal opening extent and hyolaryngeal elevation extent. Continuous variables were assessed using a nonparametric repeated measures test (Friedman Test) which rank orders variables within a subject with a 0.05 p value cut off for significance. Post hoc pairwise comparisons were performed for statistically significant measures with a 0.025 p value cut off for significance. Kendell's Tau was performed for analysis of correlation across the panel of experts, where anything below 0.4 is considered low correlation, 0.5-0.7 is moderate correlation, and .7-1 is high correlation.

Panel data included ordinal measures of safety, efficiency, and severity. Concordance was determined for each rater-pair per each treatment target. The number of times that both of the raters selected the goal was divided by the number of times at least one of the raters selected the goal. This answers the question of concordance: if one rater selected that particular goal, how likely is it that the other rater selected it as well?

Chapter 4

Results

Temporal Measures

The impact of frame rate on temporal analysis was assessed by measuring PTT, PDT and upper esophageal sphincter opening duration UESOD in thin liquid and pudding/puree swallows.

PTT

Table 13 contains individual PTT data for all participants across both bolus viscosities and three frame rates. Of the 60 swallows, four were removed from the PTT data analysis due to either poor image quality or absent swallow trigger. For the remaining 56 swallows, 22 (39%) showed an increased duration of 100 ms or more from 30 to 5 frames per second (FPS), seven of which were thin viscosity. Six of the 56 swallows (11%) showed a decreased duration of 100 ms or more from 30 to 5 FPS, five of which were thin viscosity.

Table 13

*Summary of individual temporal data in milliseconds for PTT across three frame rate conditions. PTT with an increase of more than 100 milliseconds (ms) as frame rate decreased is in **green;** PTT with a decrease of more than 100 ms as frame rate decreased is in **blue**.*

	Thin	Puree

Patient ID	30 FPS	15 FPS	5 FPS	30 FPS	15 FPS	5 FPS
FR01	1000	1067	1000	1967	1933	2000
FR02	**1100**	**1200**	**1200**	**633**	**733**	**800**
FR03	**1900**	**2000**	**2000**	733	733	800
FR04	833	867	800			
FR05	**1100**	**1133**	**1200**	**1100**	**1133**	**1200**
FR06	**633**	**667**	**800**	**1000**	**1000**	**1200**
FR41	433	400	400	3267	3267	3200
FR42	567	533	600			
FR43	**700**	**733**	**800**	567	533	600
FR44	400	400	400	**500**	**533**	**600**
FR45	**667**	**667**	**800**	1200	1200	1200
FR46	**1333**	**1333**	**1200**	**1267**	**1267**	**1400**
FR51	400	333	400	**400**	**533**	**600**
FR52	**567**	**533**	**400**	**467**	**467**	**600**
FR53	2367	2400	2400	**900**	**933**	**1000**

FR54	600	667	600	**7000**	**7067**	**7200**
FR55	800	800	800			
FR56	1433	1400	1400	1200	1133	1200
FR61	467	400	400	400	400	400
FR62	333	333	400	**500**	**467**	**600**
FR63	**600**	**600**	**400**	1433	1467	1400
FR64	600	600	600	**3867**	**3867**	**4000**
FR65	**1567**	**1600**	**1400**	5967	6000	6000
FR66				**433**	**467**	**600**
FR71	1000	1000	1000	367	333	400
FR72	600	600	600	**833**	**800**	**1000**
FR73	**433**	**467**	**600**	**433**	**400**	**600**
FR74	600	533	600	**433**	**467**	**600**
FR75	**500**	**400**	**400**	**500**	**467**	**400**
FR76	567	600	600	833	800	800

Frame rate significantly altered the duration of PTT ($p=.002$, chi-square(2)=12.246). Post hoc analysis included pairwise comparison for the three frame rates. Pairwise comparisons showed significant different between 30 FPS and 5 FPS ($p=.001$), and between 15 FPS and 5 FPS ($p=.001$).

Analysis of the impact of consistency across the three frame rates revealed that frame rate did not significantly alter the measurement of PTT for thin liquid swallows ($p=0.705$, chi-square(2)=.700). Frame rate did statistically alter the measurement of PTT for pudding/puree swallows ($p<0.05$, chi-square(2)=17.956). Figure 3 displays the normalized temporal area for all three frames rates across the two bolus consistencies. Differences in measures of duration from 30 FPS to 15 and 5 FPS are depicted in Figure 4 (thin liquid swallows) and Figure 5 (pudding/puree swallows), and demonstrate increased variability in PTT duration with decreased temporal resolution**.**

Figure 3

Percent of maximal pharyngeal transit time for all three frame rates across the two bolus consistencies

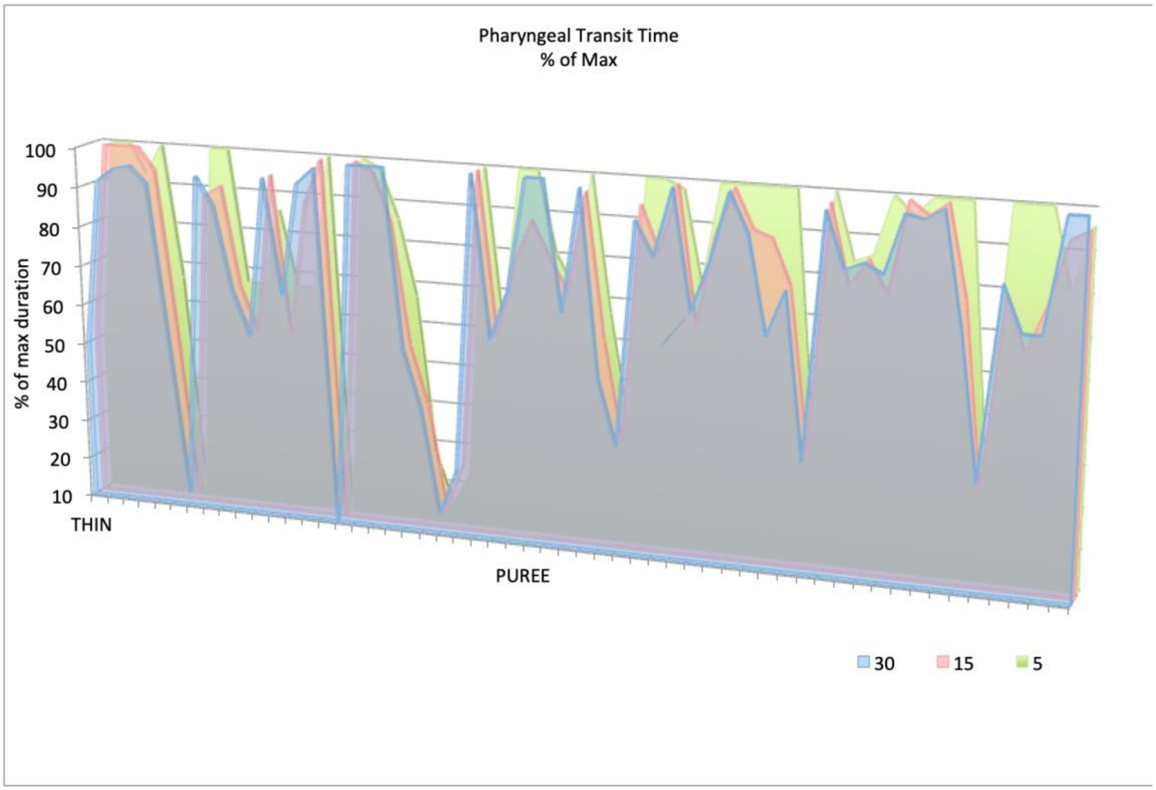
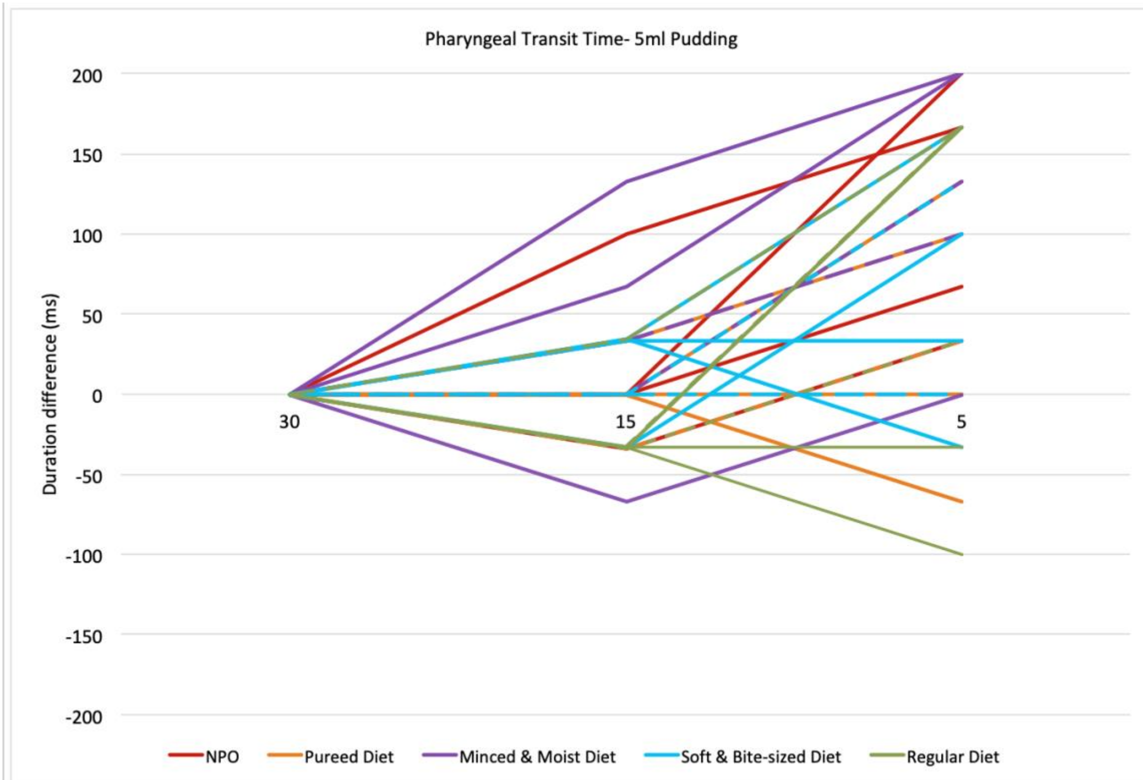


Figure 4

Differences between PTT duration measured from 30 FPS and the remaining lower temporal resolution frame rates (15 FPS, 5 FPS) for thin liquid swallows

Figure 5

Differences between PTT duration measured from 30 FPS and the remaining lower temporal resolution frame rates (15 FPS, 5 FPS) for pudding/puree swallows



PDT

Table 14 contains pharyngeal delay times (PDT) for all participants across both bolus viscosities and three frame rates. Of the 60 swallows, two were removed from the PDT data analysis due to either poor image quality or absent trigger. Of the 58 swallows evaluated for PDT, 19 (33%) showed an increase of 100 ms or more from 30 to 5 FPS, seven of which were thin viscosity. Five of the 58 swallows (9%) showed a PDT decrease of 100 ms or more from 30 to 5 FPS, all of which were thin viscosity.

Table 14

Summary of individual temporal data in milliseconds for PDT across 3 frame rate conditions. PDT with an increase of more than 100 ms as frame rate decreased is in ***green****; PDT with a decrease of more than 100 ms as frame rate decreased is in* ***blue****.*

	Thin			Pudding/Puree		
Patient ID	30	15	5	30	15	5
FR01	267	267	200	**967**	**1000**	**1200**
FR02	367	400	400	0	0	0
FR03	**967**	**933**	**1200**	0	0	0
FR04	67	133	0	-33	0	0
FR05	**733**	**733**	**600**	533	467	600
FR06	**133**	**200**	**400**	367	400	400
FR41	33	67	0	2833	2933	2800
FR42	**-100**	**-133**	**0**			
FR43	167	200	200	**33**	**67**	**200**
FR44	33	67	0	**0**	**67**	**200**
FR45	**67**	**67**	**200**	**467**	**467**	**600**

FR46	**700**	**733**	**600**	633	667	600
FR51	0	0	0	**-100**	**0**	**0**
FR52	**-67**	**-67**	**200**	**-100**	**-67**	**0**
FR53	**1833**	**1867**	**2000**	400	400	400
FR54	-67	0	0	433	533	400
FR55	167	200	200	0	0	0
FR56	933	933	1000	767	800	800
FR61	**-100**	**-67**	**-200**	-67	-67	0
FR62	**0**	**0**	**200**	-33	0	0
FR63	-67	-67	-200	1067	1067	1000
FR64	833	867	800	**-133**	**-133**	**0**
FR65	**-33**	**-67**	**-200**	**300**	**333**	**400**
FR66				**-100**	**-67**	**0**
FR71	0	0	0	**33**	**67**	**200**
FR72	**67**	**67**	**200**	**400**	**333**	**600**
FR73	133	133	200	**0**	**0**	**200**
FR74	0	0	0	0	0	0

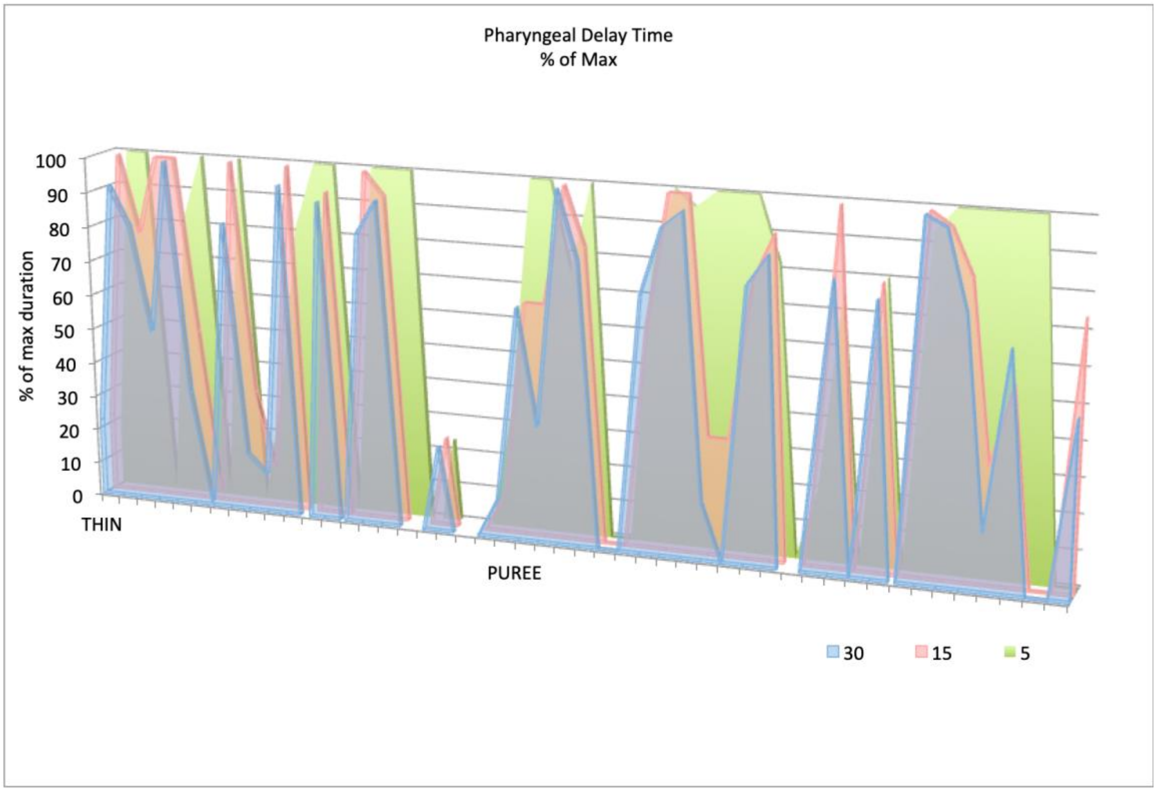
FR75	**67**	**133**	**200**	0	0	0
FR76	267	267	200	133	200	0

Frame rate statistically altered the measurement of PDT across all swallows (p=.002, chi-square(2)=12.705). Pairwise comparison of pudding/puree swallows across frame rates revealed statistic difference between 30 and 5 FPS (.006).

Analysis of the impact of frame rate as a function of bolus viscosity revealed that PDT for thin swallows was not significant (p=.177, chi-square(2)=3.467). PDT for pudding/puree swallows was statistically significant (p=.003, chi-square(2)-11.590). Figure 6 displays the normalized temporal area for all three frames rates across the two bolus consistencies**.** Figure 7 and Figure 8 demonstrate differences in PDT when comparing measures from 30 FPS to other frame rates, and show increased variability in PDT duration with decreased temporal resolution

Figure 6

Percent of maximal pharyngeal delay time for all three frame rates across the two bolus consistencies



Pharyngeal Delay Time
% of Max
% of max duration
100
90
80
70
60
50
40
30
20
10
0
THIN
PUREE
30
15
5

Figure 7

Differences between PDT duration measured from 30 FPS and the remaining lower temporal resolution frame rates (15 FPS, 5 FPS) for thin liquid swallows

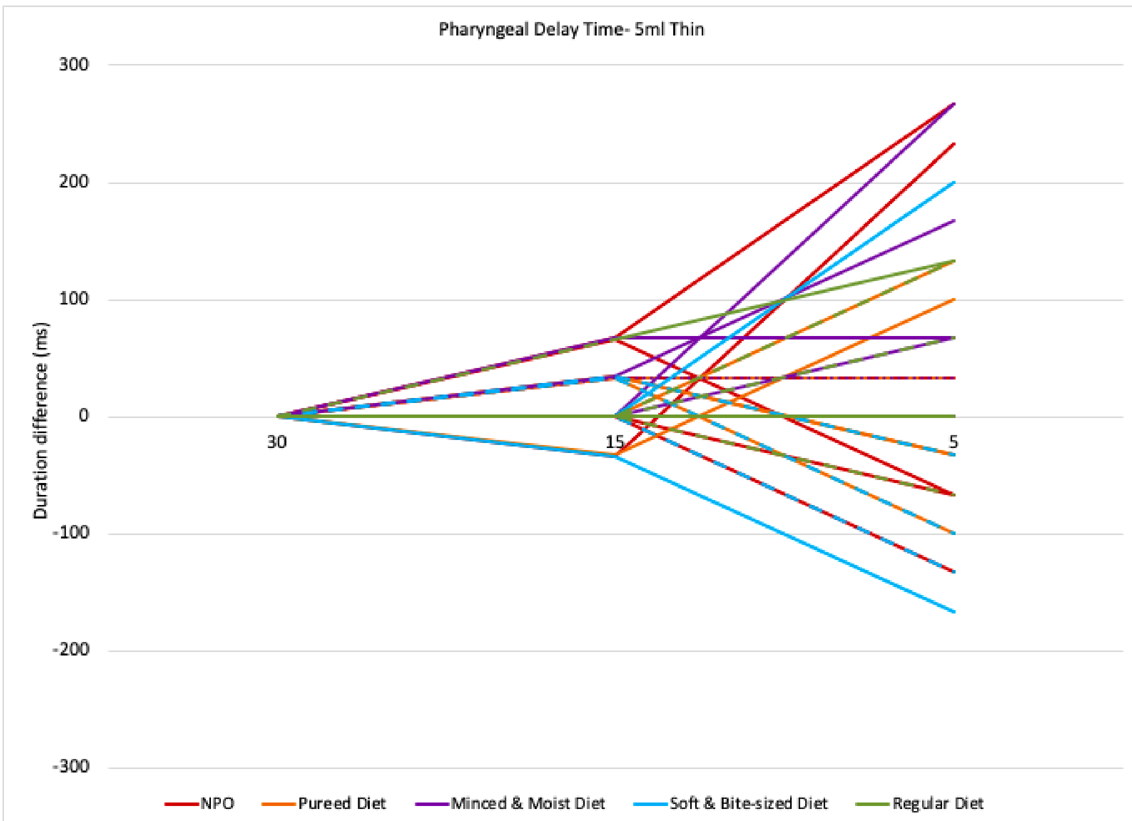
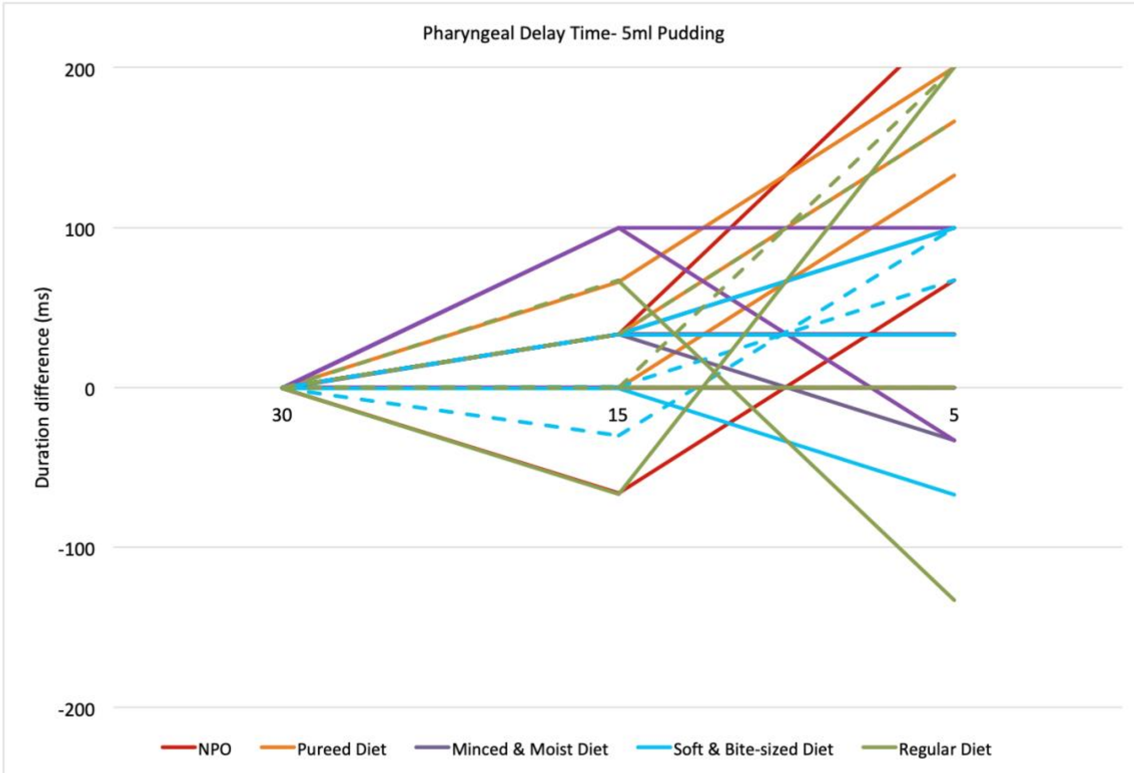


Figure 8

Differences between PDT duration measured from 30 FPS and the remaining lower temporal resolution frame rates (15 FPS, 5 FPS) for pudding/puree swallows



UESOD

Table 15 contains individual UESOD data for all participants across both bolus viscosities and three frame rates. Of the 60 swallows, four were removed from the UESOD data analysis due to either poor image quality or absent trigger. Of the 56 swallows evaluated, 13 (23%) showed an increase of 100 ms or more from 30 to 5 FPS, three of which were thin viscosity. Of the 56 swallows, 13 (23%) showed a UESOD decrease of 100 ms or more from 30 to 5 FPS, seven of which were thin viscosity.

Table 15

Summary of individual temporal data in milliseconds for UESOD across 3 frame rate conditions. UESOD with an increase of more than 100 ms as frame rate decreased is in ***green;*** *UESOD with a decrease of more than 100 ms as frame rate decreased is in* ***blue*****.**

	Thin			Pudding/Puree		
Patient ID	30	15	5	30	15	5
FR01	367	400	400	**733**	**667**	**600**
FR02	**433**	**533**	**600**	**433**	**600**	**600**
FR03	433	600	400	567	600	600
FR04	667	667	600			
FR05	133	200	200	433	400	400
FR06	367	333	400	**333**	**267**	**400**
FR41	233	200	200	267	267	200
FR42	267	267	200			
FR43	400	400	400	**333**	**267**	**200**
FR44	200	200	200	167	267	200
FR45	**500**	**467**	**600**	433	333	400
FR46	433	400	400	400	400	400

FR51	233	200	200	**267**	**400**	**400**
FR52	**367**	**333**	**200**	**300**	**267**	**400**
FR53	267	267	200	**267**	**333**	**400**
FR54	467	533	400	**367**	**400**	**600**
FR55	433	467	400			
FR56	**500**	**467**	**400**	**300**	**200**	**200**
FR61	**267**	**267**	**400**	267	267	200
FR62	233	267	200	**300**	**267**	**400**
FR63	**333**	**333**	**200**	**133**	**133**	**000**
FR64	**333**	**333**	**200**	533	533	600
FR65	**333**	**333**	**200**	333	400	400
FR66				**300**	**333**	**400**
FR71	367	333	400	167	200	200
FR72	467	467	400	333	333	400
FR73	200	200	200	**300**	**267**	**400**
FR74	**367**	**333**	**200**	**233**	**267**	**400**

FR75	400	333	400	**367**	**333**	**200**
FR76	**300**	**267**	**200**	**500**	**467**	**400**

Across all trials frame rate did not statistically alter the overall measurement of UESOD (p=.543), chi-square(2)=1.220). Viscosity specific analysis revealed that frame rate statistically altered the measurement of UESOD for thin liquid swallows (p=0.027, chi-square(2)=7.22). Pairwise comparison showed statistical difference from 30 to 5 FPS for thin liquids(p=.022). Frame rate did not statistically alter the measurement of UESOD for pudding/puree swallows (p=0.515, chi-square(2)=1.326). Figure 9 displays the normalized temporal area for all three frames rates across the two bolus consistencies. Figure 10 and Figure 11 illustrate increased variability in UESOD duration with decreased temporal resolution.

Figure 9

Percent of maximal UES open duration for all three frame rates across the two bolus consistencies

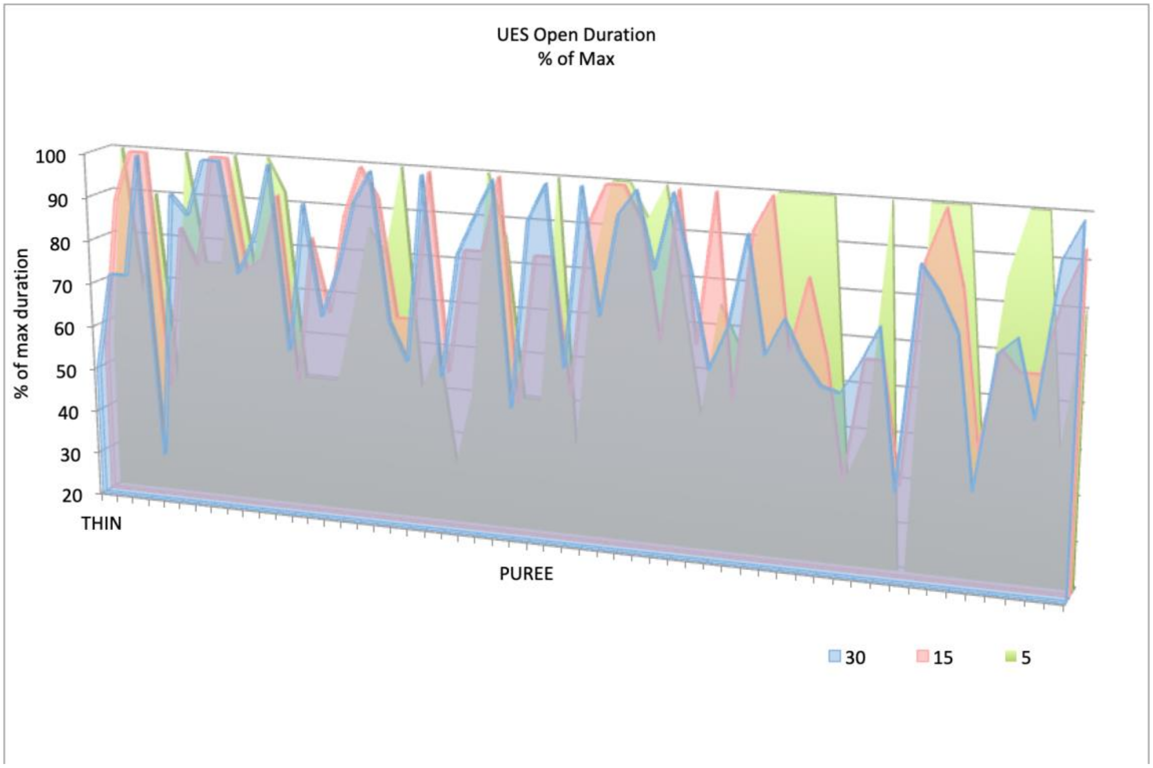

UES Open Duration
% of Max
% of max duration
100
90
80
70
60
50
40
30
20
THIN
PUREE
30
15
5

Figure 10

Differences between UESO duration measured from 30 FPS and the remaining lower temporal resolution frame rates (15 FPS, 5 FPS) for thin liquid swallows

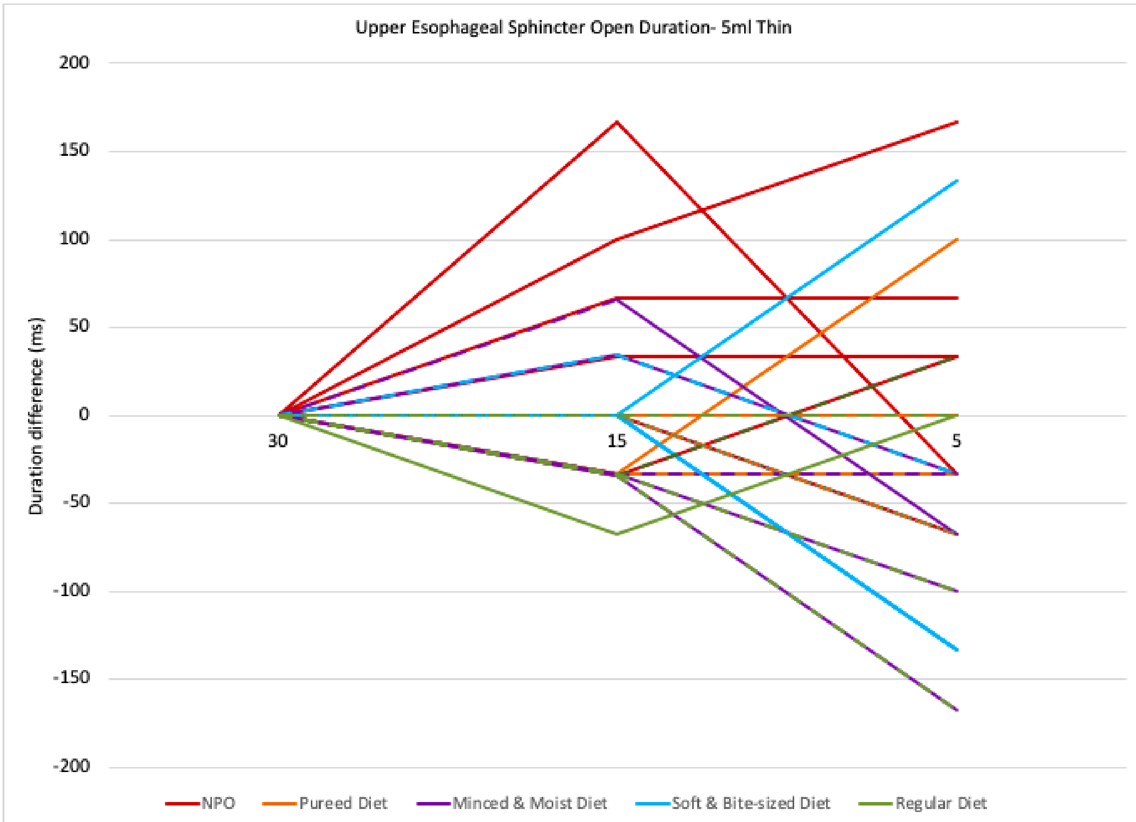
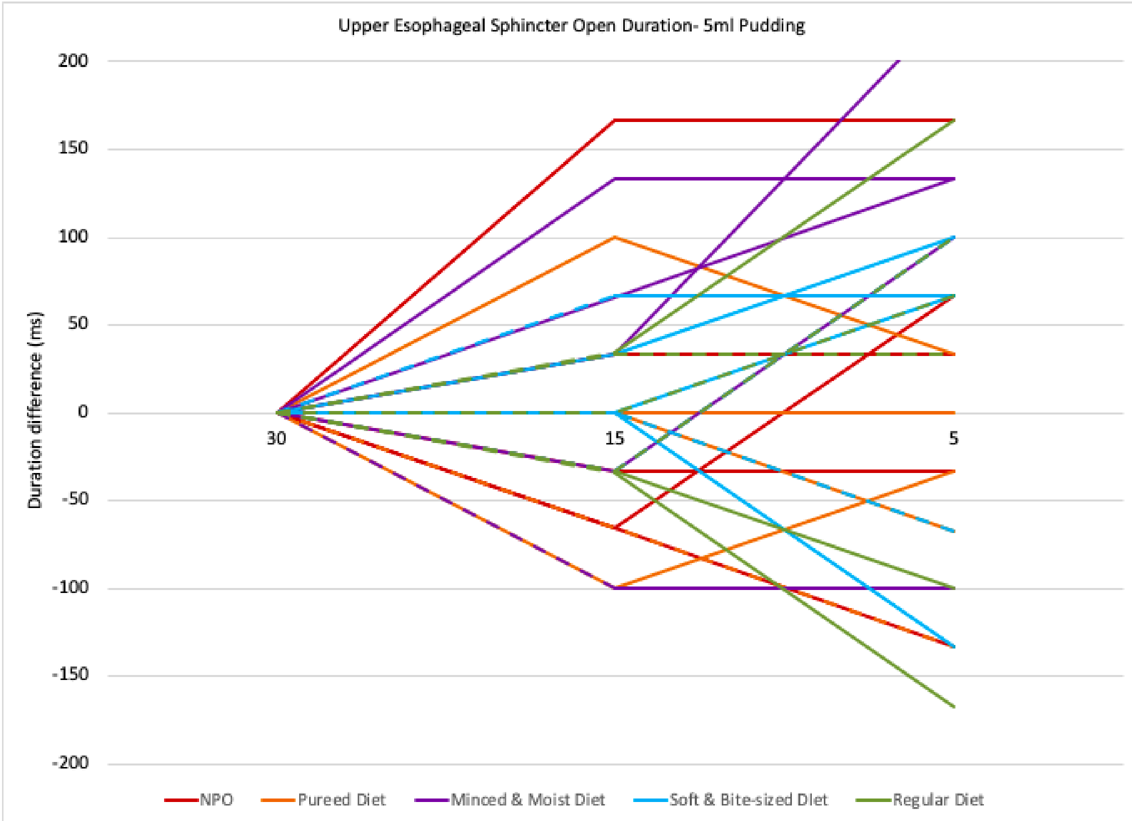


Figure 11

Differences between UESOD duration measured from 30 FPS and the remaining lower temporal resolution frame rates (15 FPS, 5 FPS) for pudding/puree swallows



Kinematic Measures

Impact of frame rate on kinematic analysis of VFES was assessed by measuring the extent of upper esophageal sphincter opening (UESOE) during the swallow and hyolaryngeal elevation (HLE), which was assessed by comparing the hyolaryngeal complex at rest versus at its peak position during the swallow in both thin liquid and pudding/puree swallows.

UESOE

Table 16 contains individual kinematic data for all participants across both bolus viscosities and three frame rates. Of the 60 swallows, five were removed from the UESOE data analysis due to either poor image quality or absent trigger.

Table 16

Summary of UESOE in cervical units across the three frame rate conditions.

	Thin			Pudding/Puree		
Patient ID	30	15	5	30	15	5
FR01	0.262	0.267	0.249	0.341	0.287	0.329
FR02	0.082	0.084	0.084	0.254	0.212	0.221
FR03	0.305	0.334	0.235	0.339	0.355	0.343
FR04	0.398	0.369	0.344	0.205	0.202	0.195
FR05	0.169	0.143	0.069	0.275	0.266	0.214
FR06	0.096	0.102	0.101	0.157	0.141	0.142
FR41	0.117	0.117	0.099	0.252	0.253	0.226
FR42	0.367	0.334	0.350			
FR43	0.060	0.070	0.055	0.099	0.099	0.071
FR44	0.319	0.302	0.292	0.483	0.444	0.479

FR45	0.079	0.085	0.065	0.149	0.151	0.139
FR46	0.245	0.214	0.254	0.260	0.226	0.233
FR51	0.196	0.185	0.192	0.400	0.388	0.359
FR52	0.167	0.150	0.143			
FR53	0.237	0.229	0.231	0.296	0.304	0.275
FR54	0.248	0.244	0.245	0.372	0.357	0.357
FR55	0.439	0.413	0.394			
FR56	0.480	0.498	0.388	0.286	0.299	0.256
FR61	0.223	0.199	0.129	0.370	0.360	0.340
FR62	0.207	0.204	0.225	0.295	0.285	0.292
FR63	0.160	0.129	0.165	0.146	0.143	0.149
FR64	0.212	0.248	0.169			
FR65	0.109	0.112	0.105	0.116	0.110	0.104
FR66				0.226	0.163	0.220
FR71	0.451	0.463	0.427	0.440	0.422	0.420
FR72	0.114	0.109	0.095	0.202	0.192	0.162
FR73	0.133	0.148	0.131	0.186	0.186	0.173

FR74	0.248	0.250	0.241	0.269	0.253	0.239
FR75	0.265	0.271	0.255	0.332	0.316	0.270
FR76	0.118	0.112	0.108	0.214	0.210	0.212

Frame rate statistically altered the measurement of UESOE ($p<0.05$), chi-square(2)=33.107. Pairwise comparison revealed statistical difference between 30 and 5 FPS ($p<.05$), between 30 and 15 FPS ($p=.013$), and between 15 and 5 FPS ($p=.001$).

Analysis of the role of viscosity on the impact of frame rate revealed statistical difference for both UESOE of thin liquid swallows ($p=.001$), chi-square(2)=14.684 and UESOE of pudding/puree swallows ($p<.05$), chi-square(2)=21.644. Pairwise comparison of pudding/puree swallows across frame rates revealed statistic difference between 30 and 5 FPS ($p<.05$) and between 30 and 15 FPD ($p=.003$). Pairwise comparison of thin liquid swallows across frame rates revealed statistic difference between 30 and 5 FPS ($p<.05$) and between 15 and 5 FPS ($p=.003$). Figure 12 displays the normalized kinematic area for all three frames rates across the two bolus consistencies. Figure 13 (thin liquid swallows) and Figure 14 (pudding/puree swallows) demonstrate increased variability in UESOE with decreased temporal resolution.

Figure 12

Percent of maximum of UES opening for all three frame rates across the two bolus consistencies.

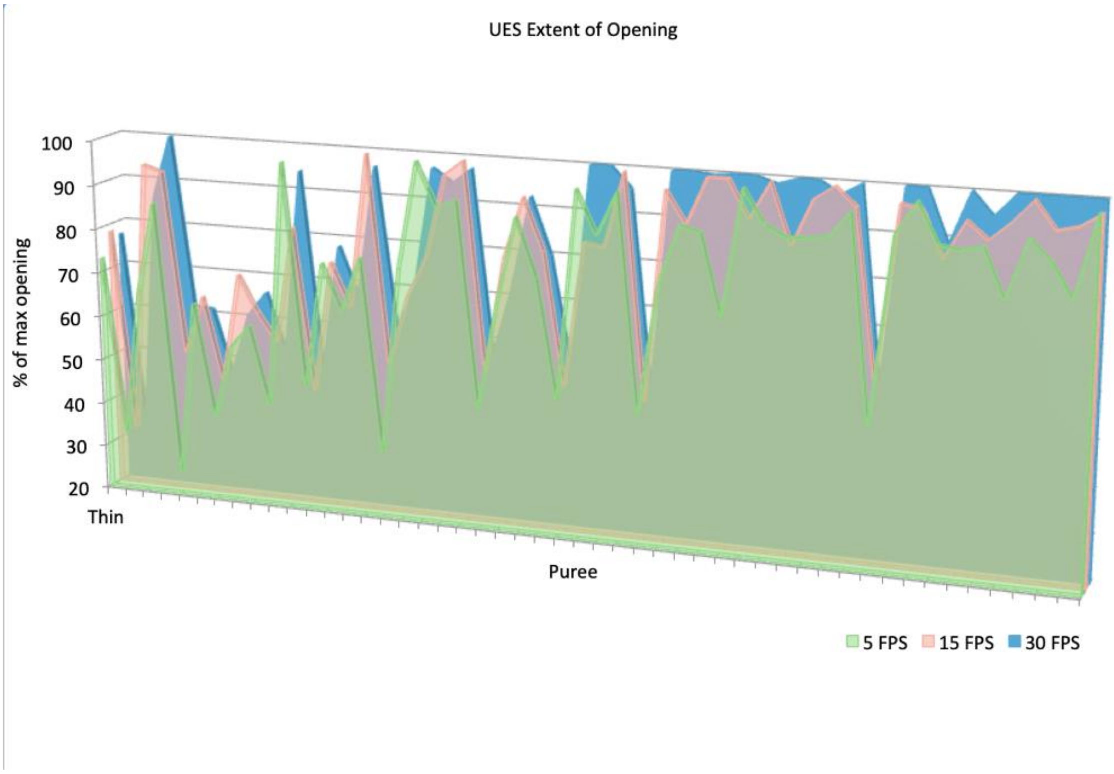


Figure 13

Differences between UESO extent measured from 30 FPS and the remaining lower temporal resolution frame rates (15 FPS, 5 FPS) for thin liquid swallows

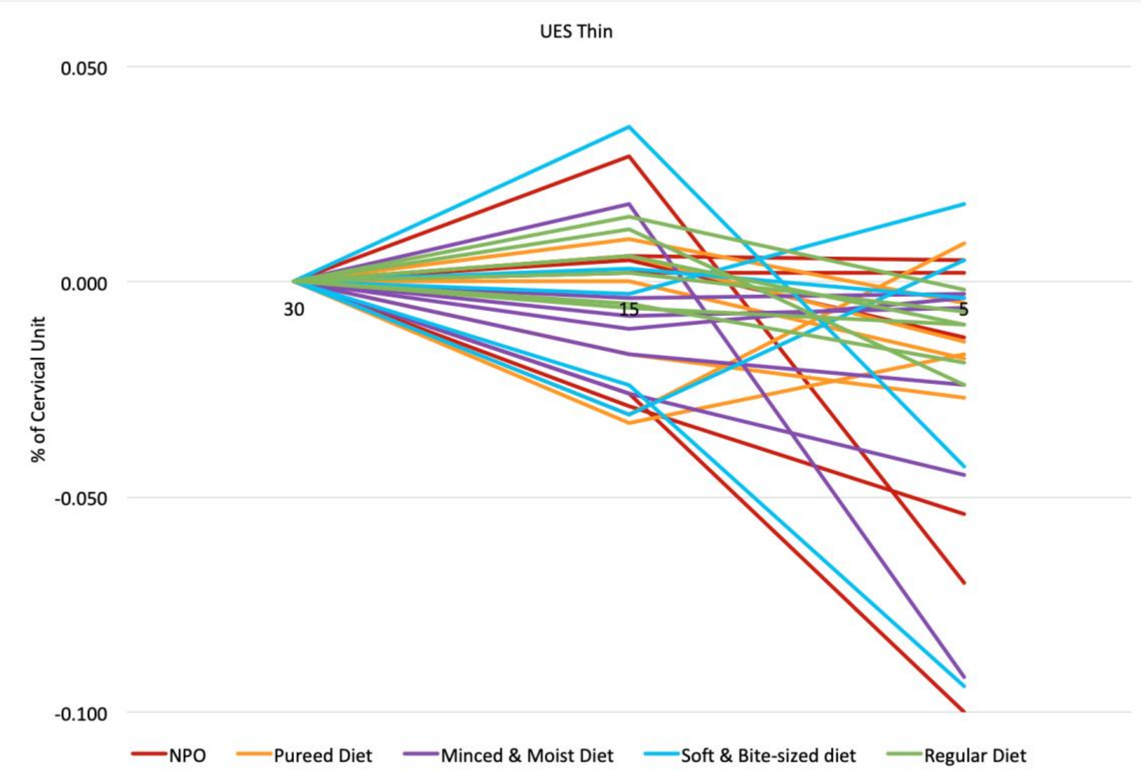
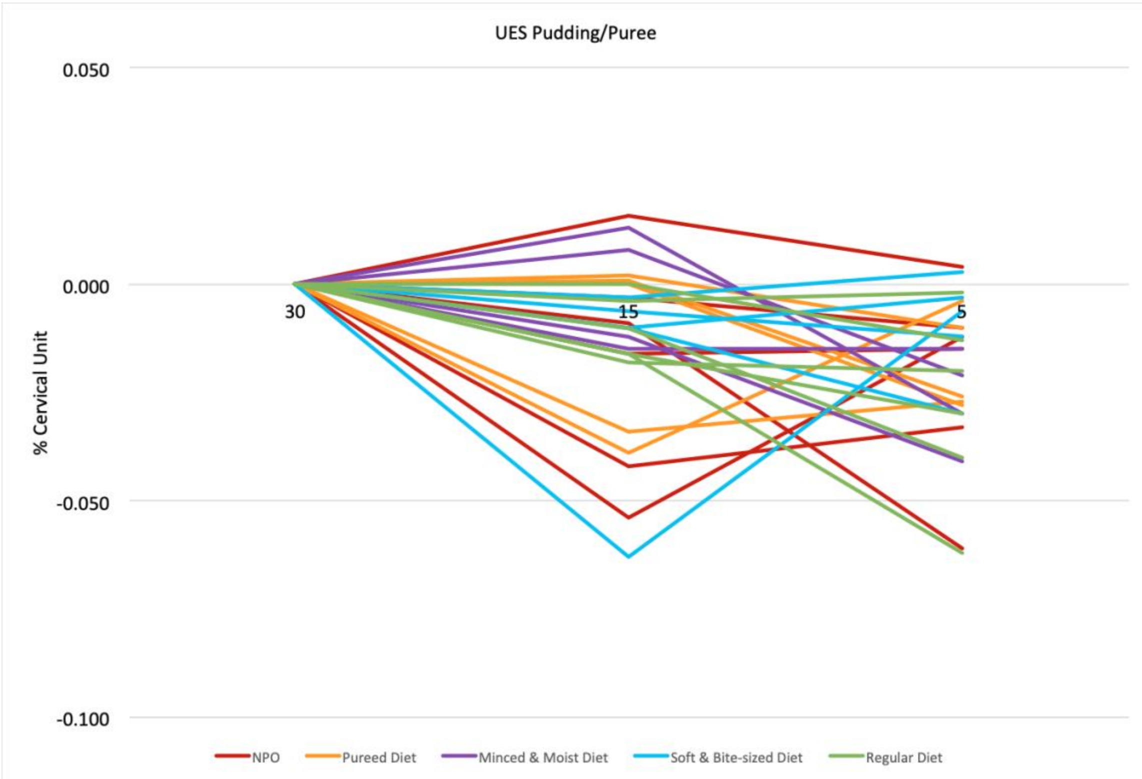


Figure 14

Differences between UESO extent measured from 30 FPS and the remaining lower temporal resolution frame rates (15 FPS, 5 FPS) for pudding/puree swallows



HLE

HLE was determined by the difference in XY coordinates of rest and peak positions of the hyoid during the swallow. Table 17 contains individual HLE data for all participants across both bolus viscosities and three frame rates. Of the 60 swallows, four were removed from the HLE data analysis due to either poor image quality or absent trigger.

Table 17

Summary of HLE extent in XY pixel difference across the three frame rate conditions

	Thin			Pudding/Puree		
Patient ID	30	15	5	30	15	5
FR01	70.1	59.5	55.1	61.9	56.3	53.6
FR02	21.2	19.4	22.1	53.1	44.6	44.6
FR03	41.9	24.5	30.1	73.8	68.3	58.6
FR04	67.9	82.8	51.0	36.9	43.3	33.5
FR05	37.2	37.2	37.6	33.0	30.6	34.3
FR06	79.1	78.4	82.3	58.7	59.5	60.1
FR41	54.6	55.6	55.6	70.2	67.6	67.6
FR42	26.9	28.3	34.0			

FR43	18.7	18.5	16.8	25.2	24.3	22.9
FR44	38.6	32.4	14.2			
FR45	70.7	71.5	69.1	3.7	-1.7	10.2
FR46	55.1	45.2	41.6	65.5	54.3	56.5
FR51	44.1	41.7	40.3	39.8	38.6	31.7
FR52	52.5	41.0	41.7	106.5	76	79
FR53	82.2	68.6	77.8	1.3	7.5	12.6
FR54	30.1	18.5	19.4	33.3	27.3	35.1
FR55	34.8	31.8	38.6			
FR56	42.9	47.7	51.1	35.2	38.4	36.6
FR61	54.3	58.3	53.3	29.4	24.8	10.5
FR62	83.4	69.5	65.0	87.4	71.4	80.0
FR63	56.9	55.2	51.1	58.1	59.2	40.5
FR64	41.9	38.1	34.3	60.5	38.8	43.1
FR65	68.1	61.1	59.9	55.5	51.1	49.3
FR66				24.7	17.7	17.1

FR71	39.7	45.4	37.6	51.5	55.6	55.6
FR72	59.6	62.0	59.5	37.3	33.3	36.1
FR73	29.0	26.7	30.6	43.2	42.5	27.7
FR74	63.5	64.0	64.0	48.3	49.2	48.4
FR75	31.1	25.4	23.3	64.7	71.0	56.0
FR76	62.8	60.7	60.3	44.5	41.1	41.0

Frame rate statistically altered the measurement of HLE (p=.002), chi-square(2)=12.882. Pairwise comparison revealed statistical difference between 30 and 3 FPS (p<.05) and between 30 and 15 FPS (p=.021).

This was true for HLE of thin liquid swallows (p=.038), chi-square(2)=6.544 and HLE of pudding/puree swallows (p=.042), chi-square(2)=6.340.square(2)=12.882. Pairwise comparison for thin liquid swallows revealed a significant difference between 30 and 5 FPS (p=<.05) and 30 and 15 FPS (.021) but not between 15 and 5 FPS (.238). Pairwise comparison for pudding/puree swallows revealed a significant difference between 30 FPS and 5 FPS (p=.014) but not between 30 and 15 FPS (p=.102) or 15 and 5 FPS (p=.414). Figure 15 displays the normalized kinematic area for all three frames rates across the two bolus consistencies. Figure 16 and Figure 17 illustrate how increased variability in HLE extent with decreased temporal resolution.

Figure 15

Percent of maximal hyolaryngeal elevation for all three frame rates across the two bolus consistencies.

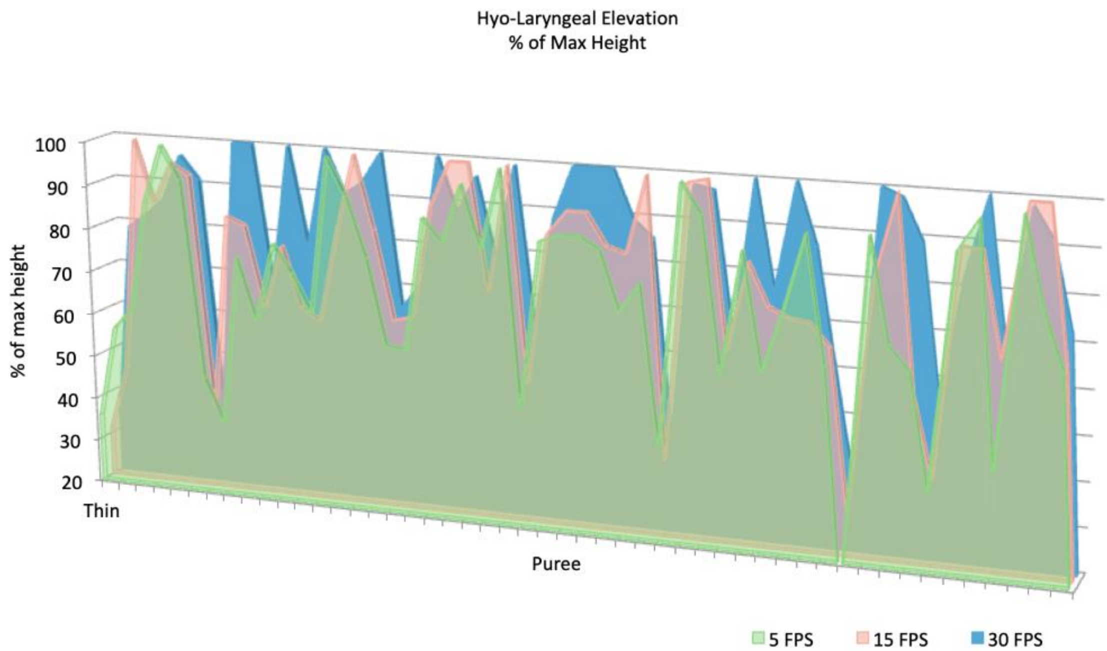

Hyo-Laryngeal Elevation
% of Max Height
% of max height
100
90
80
70
60
50
40
30
20
Thin
Puree
5 FPS
15 FPS
30 FPS

Figure 16

Changes in HLE extent of thin liquid swallows with decreased temporal resolution

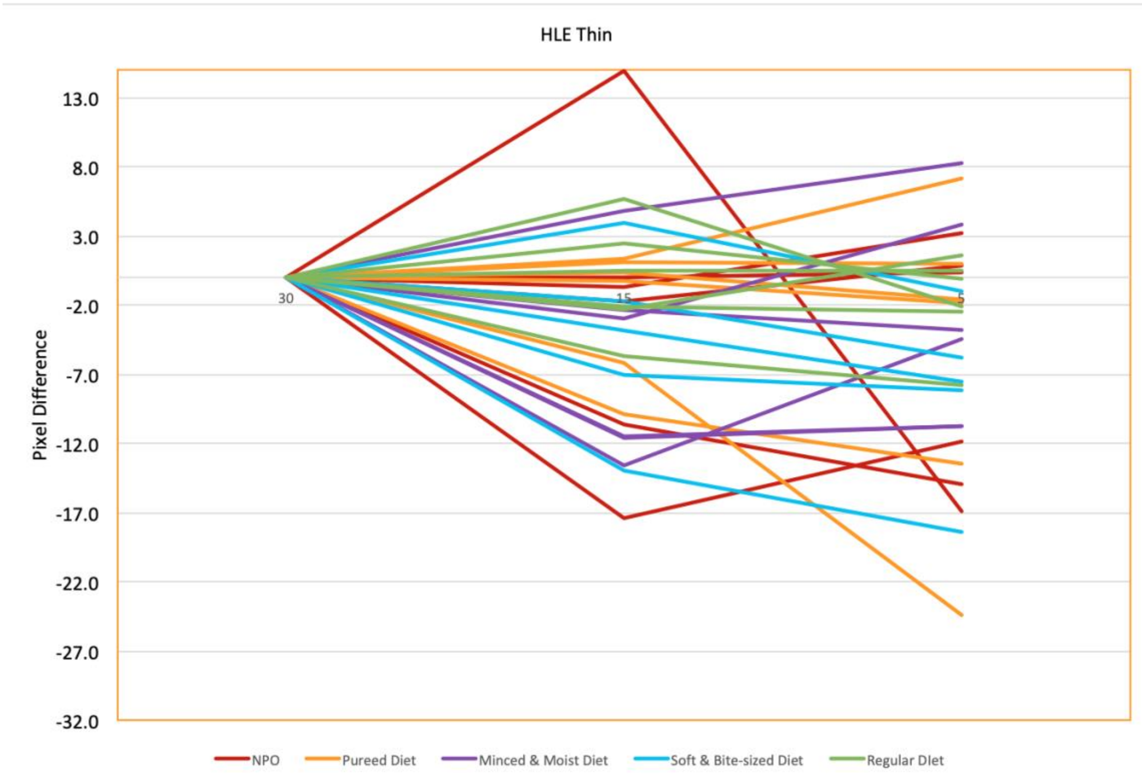
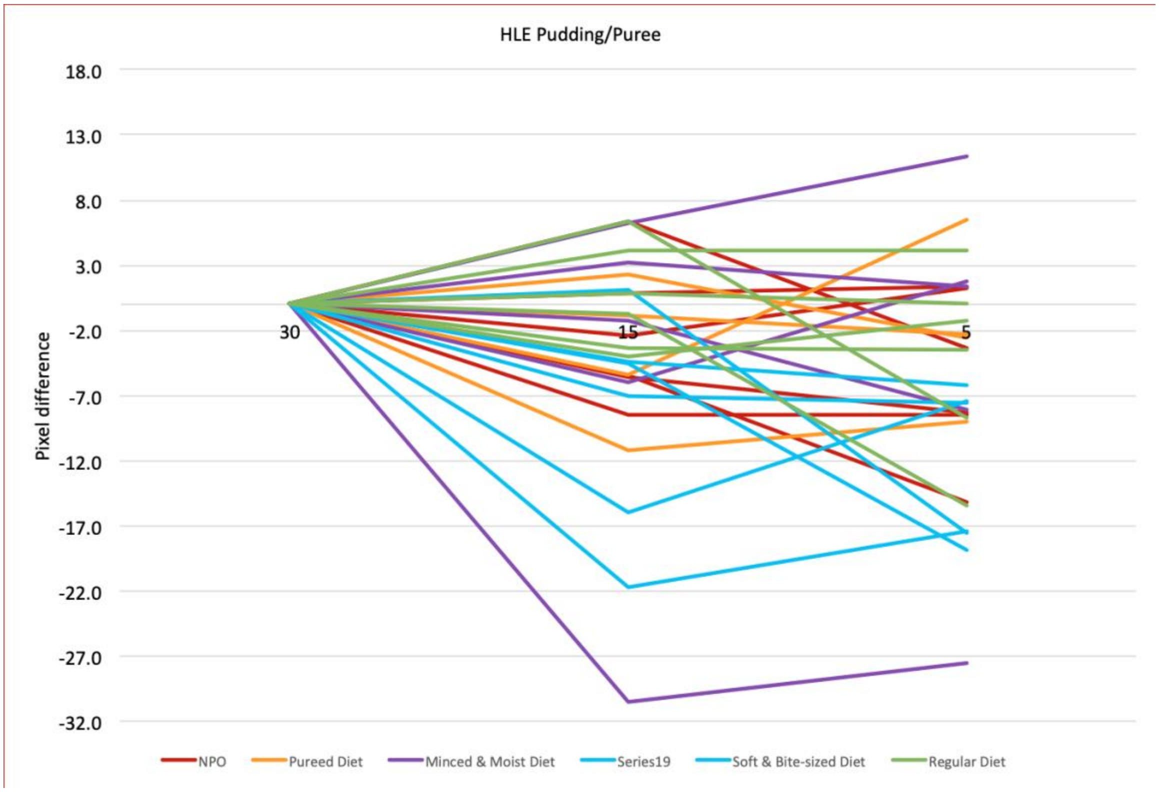


Figure 17

Changes in HLE extent of pudding/puree swallows with decreased temporal resolution



Interrater reliability for continuous measures

Interrater reliability was determined for 15% of each temporal landmark for thin and pudding/puree swallows. Across all landmarks, interrater reliability ranged from 94 to 100%, exceeding the minimum goal of 85%, as demonstrated in Table 18. Interrater reliability was 88% and 85% for HLE and UESOE respectively, which met the minimum requirement of 85% agreement, as demonstrated in Table 19.

Table 18

Interrater reliability for swallow landmarks used in temporal measures

	BPM	HB	UESO	UESC

n	32	32	32	30
n agreement	31	30	32	29
% agreement	97	94	100	97

Table 19

Interrater reliability for kinematic measures

	HLE	UESOE
n	58	54
n agreement	51	46
% agreement	88	85

Safety & Efficiency

A panel of three experts independently watched 90 VFES and scored them for safety and efficiency. Guided by the framework of the Dynamic Imaging Grade of Swallowing Toxicity (DIGEST) scale (**Error! Reference source not found.**), safety was assessed using the panel of expert's scores of the severity, frequency and amount of penetration or aspiration. Efficiency was judged by rating the amount and type of bolus residue.

The impact of frame rate on rater agreement was judged by comparing correlations across raters within a frame rate. Across the three raters, correlations ranged from .4-.6 for 30 FPS, .5 to .8 for 15 FPS, and .5-.7 for 5 FPS (Table 20), showing slightly decreased agreement with higher temporal resolution. Expert agreement on judgments of efficiency ranged from .3-.6 for 30 FPS, .2-.4 for 15 FPS, and .4-.6 for 5 FPS (Table 21).

The impact of frame rate on safety scores was assessed by using the median value across the three panel experts. Overall, frame rate did not significantly alter safety or efficiency ratings (p=.223, chi-square(2)=3.000 and (p=.218, chi-square(2)-3.020, respectively).

Table 20

Correlation across raters for measures of safety

	30-1	30-2	30-3	15-1	15-2	15-3	5-1	5-2	5-3
30-1	1.0	.6*	.4*						
30-2		1.0	.5*						
30-3			1.0						
15-1				1.0	.8*	.5*			
15-2					1.0	.5*			
5-3						1.0			
5-1							1.0	.6*	.7*
5-2								1.0	.5*
5-3									1.0

*p<.05

.

Table 21

Correlation within frame rate across raters for measures of efficiency

	30-1	30-2	30-3	15-1	15-2	15-3	5-1	5-2	5-3
30-1	1.0	.6*	.5*						
30-2		1.0	.3*						
30-3			1.0						
15-1				1.0	.4*	.3			
15-2					1.0	.2			
15-3						1.0			
5-1							1.0	.6*	.4*
5-2								1.0	.4*
5-3									1.0

*p<.05

Severity Ratings

Severity was calculated by combining safety and efficiency ratings given by the panel of raters, according to the DIGEST (Hutcheson, 2017). Agreement of severity as a function of temporal resolution was assessed through correlation. Across the three raters, correlations ranged from .4-.5 for 30 FPS, .4 to .6 for 15 FPS, and .3-.5 for 5 FPS as seen in Table 22. Statistics revealed that temporal resolution did not statistically impact overall severity ratings (p=.199), chi-square(2)=3.231.

Table 22

Correlation across raters for measures of severity

	30-1	30-2	30-3	15-1	15-2	15-3	5-1	5-2	5-3
30-1	1.0	.5*	.4*						
30-2		1.0	.4*						
30-3			1.0						
15-1				1.0	.6*	.4*			
15-2					1.0	.5*			
15-3						1.0			
5-1							1.0	.5*	.3
5-2								1.0	.3*
5-3									1.0

*p<.05

Treatment Targets

Based on VFES, panel experts selected two treatment targets from a list of seven targets for each swallow study. Within a frame rate, raters showed low to fair concordance across targets, demonstrating that overall agreement was limited regardless of frame rate. However, 8/18 (44%) of concordance measures were systematically reduced as frame rate decreased. This is compared to 5/18 (27%) of concordance measures which stayed the same throughout frame rates, and another 5/18 (27%) that showed an increase in agreement as frame rates decreased. Table 23 demonstrates the concordance for each rater pair per treatment target. Table 24 demonstrates the changes in mean concordance between rater pairs across changes in temporal resolution, where we see a slight decreasing trend. Within rater reliability was 0.50, 0.63, and 0.64, indicating moderate to high consistency across changes in temporal resolution.

Table 23

Treatment target concordance between raters across frame rates

Target #	R1-R2			R1-R3			R2-R3		
	30	15	5	30	15	5	30	15	5
1	.69	.40	.44	.13	.17	.08	.17	.40	.19
2	.21	.14	.20	.28	.35	.29	.38	.17	.09
4	.40	.37	.56	.44	.50	.43	.60	.33	.27
5	.37	.35	.44	.36	.24	.27	.25	.30	.21
6	.33	.25	.29	.06	.15	.21	.17	.40	.25
7	.46	.19	.23	.25	0	.17	.25	0	.33

Table 24

Mean concordance between rater pairs across frame rates

Rater Pair	Frame Rate		
	30	15	5
R1 x R2	0.41	0.28	0.36
R1 x R3	0.25	0.23	0.24
R2 x R3	0.30	0.27	0.22

Chapter 5

Discussion

The purpose of this thesis was to investigate the impact of temporal resolution on clinical decision-making for individuals with dysphagia. It explored the effects of changes in frame rate on (a) temporal measures, (b) kinematic measures, (c) ratings of swallow safety, efficiency, and severity, and (d) treatment target selection for the swallow studies of 30 individuals across five levels of diet recommendations.

Temporal Measures

A common approach to understanding swallow deficit is to consider the movement of the bolus through the swallow system. In this investigation we chose PTT, PDT and UESOD as key temporal measures to reflect swallow deficit. Because swallowing is a time-sensitive action, a longer transit time or a longer pharyngeal delay time implies decreased efficiency and potentially greater risk. In our investigation, reductions in temporal resolution (i.e., frame rate) had a tendency to increase measures of transit time and delay time. For delay time this effect was more pronounced during the puree consistency. Yet the effect of losing temporal resolution is asystematic. Increases or decreases of greater than 100 ms were noted in 46% of swallows at the lower resolution. This is in agreement with the investigation performed by Bonilha et al, (2013), which found differences in the timing of the initiation of the pharyngeal swallow between 30 and 15 FPS. The clinical implication of increased values is that a speech-language pathologist may interpret more severe findings when assessing individuals using lower temporal resolution. This may result in inaccurate diagnosis or unnecessary treatment plans. Alternatively, decreased values may influence a clinician to interpret a swallow as faster, and thereby safer than it is in reality. This means they could miss a deficit and fail to implement treatment when necessary, putting the individual at heightened risk for aspiration and its associated sequelae.

In a healthy swallow, the upper esophageal sphincter (UES) stays open long enough to allow for complete bolus passage, then closes quickly to encourage downward driving pressure towards the stomach. If a bolus is headed towards the UES but adequate distension does not last long enough for the bolus to pass through, this may result in pooling in the pyriform sinus which may consequently spill over into the airway. Conversely, if the UES remains open longer than necessary for bolus passage, then esophageal pressure may be insufficient to guide the bolus toward the gut and may lead to backflow into the pharynx risking penetration into the airway entrance. For these reasons, the ideal length of UESOD is a delicate balance between *too long*, and *not long enough*. In this investigation, although UESOD across consistencies was not statistically significant, for pureed consistency there was a strong tendency for the duration to be altered with changes in temporal resolution. Similar to the other temporal measures assessed, there was no systematic impact of reduced temporal resolution on duration. Rather, the reduced frame rate was noted to both increase and decrease with decreased temporal resolution. Another potential effect is that treatment choices may be misguided with inaccurate estimates of duration. For example, if PDT is presumed longer than it is, one might focus on sensory deficits when none exist. If PTT is inaccurately presumed longer, a clinician may waste time focusing on aspects of driving pressure such as oral bolus control and tongue base retraction.

The temporal data findings in this investigation indicate that precision of perceived duration is lost with reductions in temporal resolution. Because the changes are not systematic, low temporal resolution can result in either neglecting treatment when warranted or implementing treatment when there is not truly a deficit. In essence, temporal swallow measures are altered with reductions in temporal resolution. One might argue that if we could systematically anticipate the impact of reductions in frame rate on temporal measures, we could account for those discrepancies and make accurate calculations based on that data. However, because changes in temporal resolution impact both specificity and sensitivity of the temporal swallow measures, the direction of the impact cannot be calculated, and this would not be a justifiable risk when making safety-based decisions that could impact mortality. Mulheren et al. (2019), who also found temporal data to change across frame rates, stated that "Judgement of timing and clinical measures requires consideration of each frame as part of the dynamic process of swallowing rather than as an isolated slice", arguing that seemingly insignificant temporal details may be greater than the sum of their parts when viewed within the context of the whole swallow.

Kinematic Measures

Kinematic measures allow us to assess movement of structures during the swallow. If movement is reduced, the bolus may lack adequate driving pressure for a safe and efficient swallow. In this investigation we measured the extent of opening of the upper esophageal sphincter (UESOE) during bolus passage and the difference in the hyolaryngeal position at rest and peak associated with the swallow. More distension and displacement is typically associated with a safer and more efficient swallow. To elaborate, adequate movement of the hyolaryngeal complex is imperative for a healthy swallow as it (a) moves the airway out of the bolus pathway, and (b) assists in UES opening through passive stretch. Similarly, the UES must be open wide enough to allow the full bolus to pass through in an efficient fashion. In our investigation, reductions in temporal resolution had a significant effect on kinematic measures in both thin and pudding/puree swallows. Unlike temporal measures, reductions in temporal resolution had a systematic impact on kinematic measures. In general, as temporal resolution decreased, kinematic measures were reduced. In the case of the extent of UES opening, this means that adequate opening may be perceived as inadequate, which can be associated with pharyngeal pooling. Furthermore, if a clinician observes minimal hyolaryngeal displacement during the swallow, their concern for the swallow's safety would likely increase. In these cases, the clinician may implement incorrect treatment targets.

The potential for perceived reduction in extent of kinematic measures as temporal resolution decreases may have an effect on the clinician's goal writing and treatment planning. Because a more severe deficit may be interested as a result of decreased extent of movement, this may result in a protracted treatment duration and unnecessary sacrifices of the patient's quality of life.

Safety, Efficiency, and Severity

A panel of experts was recruited to assess the impact of temporal resolution on rater agreement as well as the impact of frame rate on the measures themselves. For each swallow study, safety and efficiency scores were taken from the panel of expert raters. The primary investigator combined these scores into one severity score for each frame rate, as out lined in the DIGEST (Hutcheson, 2017).

The first question asked with regard to measures of swallow safety, efficiency, and severity was whether or not frame rate altered correlation of scores across the panel of experts. Rater agreement on these measures was not greatly impacted by reductions in temporal resolution. One exception was noted for safety, where rater agreement improved with reductions in temporal resolution. On initial consideration, this is counterintuitive. How does reduced temporal resolution improve rater agreement? One hypothesis is that lower temporal resolution requires review of fewer images. When less frames are provided, there is less room for disagreement in selection. Generally, however, we saw correlation linger around medium to high agreement for each frame rate. Based on these findings, clinicians' agreement on measures of safety and efficiency are unlikely to be significantly altered with changes in temporal resolution.

The second question regarding swallow safety, efficiency, and severity was whether or not the median rating changed across frame rate. In most cases, this was the scored selected by 2/3 or 3/3 of the raters. In some cases of zero agreement across raters (10% of severity ratings, 13% of efficiency ratings, and 16% of safety ratings), the median was the middle score chosen. Statistical analysis showed that median ratings of safety, efficiency, and severity were not significantly altered by frame rate. This information implies that generally, perceptions of these three measures will remain statistically consistent despite losing temporal resolution.

These findings contradict Cohen's study on severity perception (2009), which found that the most severe instance of penetration-aspiration was only visible in one frame for seven out of 10 swallow studies, indicating that severity ratings would change with a decrease in temporal resolution However, the findings of this thesis were aligned with the 2019 study conducted by Mulheren, et al., which saw no difference in PAS scores as temporal resolution decreased from 30 to 15 FPS, and the study by Layle et al. (2019), which evaluated individuals from four months to 16 years, found consistent PAS interpretations from 30 to 15 FPS. Despite a consistency of severity, both studies maintained that 30 FPS is still not ideal due to other quantitative measures that are affected and could potentially affect the path of treatment going forward. It is important to make the distinction that both Mulheren et al. and Laylu et al. assessed a minimum of 15 FPS, whereas this thesis investigation explored 5 FPS as well.

One might wonder: if the perceived safety or severity of the swallow did not change with reductions in frame rate, then why are we worried about losing temporal resolution? It is important to remember that VFES are not conducted solely to make a severity diagnosis. The goal is to identify the deficits as well as the impact of those deficits on safety and efficiency. Therefore, although safety is a key concern, it is not the only concern. One requires a thorough understanding of the swallow physiology to adequately prioritize a successful treatment plan.

Treatment Targets

If frame rate impacts treatment target selection, it may be observed in several ways. First, within an individual rater, they could alter their selection as temporal resolution is reduced. Second, across raters and within a given frame rate, rater agreement could be changed as a result of temporal resolution. While the panel of raters showed moderate to high correlation for quantifiable measures of safety and efficiency, they had low to moderate concordance for treatment targets. Because this treatment selection agreement across raters was limited at all frame rates, our interpretation of the impact of temporal resolution on treatment target selections (and thus, clinical application) is limited. Concordance asks: out of all the instances when a treatment target was selected, how many times was it selected by both members of a rater pair? There was a slight trend in decreasing concordance as frame rate was altered. However, the raters did not have high concordance for treatment target selection from the beginning. Interestingly, these findings indicate that two clinicians may rate safety, efficiency, and severity with moderate to high agreement, yet still choose different physiological targets to fix a problem.

This introduces an interesting discussion within the field of speech-language pathology that is outside the scope of this investigation. If raters agree on quantifiable variables, where is the disagreement occurring that influences a different choice in treatment targets? It's possible that years of experience with a particular population may influence a clinician's tendency towards a specific target. It is also possible that more information could have streamlined their selections. In this project, the raters were only allowed to view the swallow studies twice---with no frame by frame analysis.

Furthermore, in the typical clinical setting, the clinician would receive a case history that may help guide decision-making. This additional information may have influenced higher concordance across raters.

Regardless, the bottom line is that based on this data, changes in treatment plan were not linked to temporal resolution. This contradicts the investigation of Bonilha et al., (2013), which found that the difference in MBSImP scores across frame rates influenced a difference in treatment recommendations. While there are concerns regarding the low rater agreement for treatment selection, the observation that frame rate does not influence treatment selection is in line with the research done by Mulheren, Azola, and González-Fernández (2018). Due to the overall low agreement across raters in our investigation and lack of interrater reliability, interpretation of the impact of frame rate on treatment selections is guarded at best.

Limitations

Internal Validity

Although 85%-100% interrater reliability was upheld, the primary investigator who did the ratings for temporal and kinematic measures is a graduate student without prior clinical experience reading VFES. While completing this investigation, she passed the MBSImP ™ standardized training and reliability testing offered by Northern Speech Services, Inc. The fact remains that anatomy and video quality varies with each study, therefore accurately and confidently reading swallow studies is a skill that can be obtained only through clinical experience.

Because this was a retrospective study, only existing swallow studies were used for analysis. This study strived to standardize data by including the same four viscosities per study. However, some swallow studies did not contain all four viscosities and were still included in the data set. Some studies had visual issues such as shoulder covering up the UES during the swallow. In this case, if a measure could not be made with confidence, it was excluded from the data set.

Correlations were made across raters but not within raters; the raters were not presented with the same swallow study at a given frame rate more than once. This means that within rater reliability was not determined for the panel of experts.

30 swallow studies across five diet types were used for this investigation in order to equal representation of all swallow severities. However, when the panel of expert's ratings were translated into DIGEST scores, they indicated primarily mild, moderate and severe with only one "life-threatening" rating. This indicates that a different system might be considered in future investigations to ensure equal representation of disorder severities for the sample population.

External Validity

It is typically wise to conduct an investigation on a normative sample first. This study was not done on a normative sample first for three main reasons. First of all, normative data for temporal and kinematic swallow measures exists in literature (Steele, 2019). Second, VFES are not often conducted on people with healthy swallows, and getting IRB approval to radiate people who are not at risk for dysphagia is not warranted. Finally, normal healthy swallows do typically show as much change across frame rate because a healthy swallow occurs in a quick and concise manner. It is important for us to look at the disordered population where VFES is used, therefore this study intentionally looked at the effects across five diet types, ranging from nil per os (NPO), or nothing by mouth, to mechanical soft/regular.

Future Directions

Although this investigation was conducted on a wide range of disordered swallows, all participants were adults. These findings do not apply to pediatric swallows studies due to the difference in physiology and susceptibility to radiation. Further research is necessary to determine the impact of temporal resolution on interpretation of swallow studies for the pediatric population.

The low concordance across raters for treatment target selection at each frame rate suggests a need for further investigation into the decision-making process of clinicians who diagnose and treat dysphagia.

Conclusion

This investigation brings up a series of further questions for research and clinical considerations. Because decreasing frame rate generally did not show a *significant* impact on swallow scores until 5 FPS was reached, one potential thought is that VFES could initially be conducted at 15 frames per second, cutting radiation exposure in half. If low safety and efficiency scores warrant further assessment, the clinician could decide if VFES at a higher frame rate is necessary to decipher the cause of problems. However, the problem remains that variations in visual perception take generally unpredictable routes, and it may be hard to make the decision of when further videofluoroscopic assessment is warranted. If it is done at 15 and then 30 FPS, then we would be radiating an individual at one and a half times the necessary amount--albeit cutting it in half for others.

This investigation into the impact of temporal resolution on clinical decision-making for individuals with dysphagia found that some areas were impacted more than others. All kinematic and temporal measures were significantly impacted by a change in frame rate. The majority of the time, the significant change occurred when temporal resolution was reduced to five frames per second. However, safety, efficiency, and severity ratings were not significantly altered by reduction in frame rate. Based on this information, a clinician may be able to determine overall swallow severity by gauging penetration and aspiration and residue at a lower frame rate but they may have difficulty in deciphering specifically where the breakdown in swallow mechanics is occurring to cause the deficit. Based on the results of this investigation, it is unclear if lower temporal resolution alters treatment selection such that treatment target selection showed variability within each frame rate as well. Further investigation is warranted.

It is easy to get caught up in small discrepancies of milliseconds and pixels, but it is imperative that, when considering the implications of investigations, we keep in mind the reason we do it: for the patients' wellbeing. This means taking not only the statistical evidence into account but also the physical, emotional, and economical impact of our decisions. An unnecessary treatment plan—which could be implemented if a clinician perceives deficits where there are none—will be a waste an individual's finances, time, and peace of mind. Because healthcare is often far from affordable all three of these aspects must be considered. Alternatively, if a clinician fails to recognize an existing deficit, the patient is at risk of untreated physiological problems which, could eventually have an even larger impact on quality of life and finances than if initially treated. To summarize: more than a scientific curiosity of temporal resolution, this is a matter of preserving and promoting one of the few universal pleasures that exists in a world of increasing unpredictability and disparity.

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