RESONATING SWALLOWING SOUNDS: UNLOCKING-THE ENIGMA THROUGH A SYSTEMATIC DIAGNOSTIC EXPEDITION

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Abstract:
Objective: Swallowing sounds are transient signals generated by multiple events in the swallowing mechanism and can provide information about normal or abnormal functioning and coordination of swallowing structures. In recent years, there has been an increasing interest in digital signal processing of swallowing sounds in various food and liquid volumes and consistencies. Therefore, this systematic review focuses on the identification of discrete acoustic features associated with different bolus consistencies to provide a differential diagnosis of swallow sounds in healthy adults across food and liquid viscosities.

Methods: Research articles were retrieved after completing a systematic review using multiple search engines such as IEEE Xplore, SpringerLink, Wiley Online Library, ResearchGate, SAGE Journals, SciELO, Academia.edu, PubMed, and Google Scholar. The search terms used were related to the acoustic analysis of swallowing sounds. The study required analysis of swallow sounds across many bolus consistencies in healthy subjects using any method such as cervical auscultation, Accelerometer, Doppler, Cepstrum analysis, or algorithm-based analysis. The quality and relevance of the included studies were assessed according to the PRISMA guidelines.

Results: A total of 50 unique articles were found. After applying inclusion and exclusion criteria, ten publications were selected for systematic review. The average duration of acoustic swallowing (DAS) ranged from 400 to 600 ms, with DAS for soft > honey > puree > thin, but food flow properties rather than viscosity versus duration, yielded more reliable results. Peak intensity (PI) ranges from 40 to 65 dB, with lower viscosities having higher amplitudes. The maximum frequency range is up to 5900 Hz, with thinner liquids producing much higher peak frequencies (PF) than mechanically softer viscosities.

Conclusion: According to the results of this study, the duration and amplitude of swallowing sounds varied significantly between different food and liquid samples. In addition, DAS and PI variables are considered to be more clinically important in the differential diagnosis of swallowing sounds, with the most noticeable differences occurring between 400 and 1000 Hz. In addition, bolus dynamic viscoelasticity, viscosity, and yield stress values elucidate the physical properties that influence the characteristics of swallowing sounds and vice versa. However, further studies are needed to clarify the potential clinical responsibility of bolus consistency and acoustic properties and the relationship between the physiological mechanisms of swallowing and swallowing sounds.

Keywords: Swallowing sounds, cervical auscultation, acoustical analysis of swallowing sounds, swallowing sounds, and bolus consistency, Swallowing assessment.

INTRODUCTION:

Swallowing Physiology and correlation with Swallowing sound:

The act of swallowing involves passing a bolus of food or liquid from the mouth into the oesophagus and then the stomach. A complicated set of interdependent, tightly linked voluntary and involuntary behaviours are used to achieve this. The bolus is first pushed to the back of the mouth by the tongue. The bolus is then inserted into the pharynx. In order to stop the bolus from entering the lungs at this point, the vocal folds close, the larynx elevates, and the epiglottis covers and shields the larynx (Esling et al., 2019) [1]. The soft palate also raises, sealing off the nasal cavities and making nasal airflow (and therefore breathing) impossible. The bolus eventually travels to the oesophagus, where it is then forced into the stomach by muscle contractions.

These intricate actions that take place from the oral phase to the oesophageal phase result in a range of noises being produced during the biomechanical processes of swallowing. These sounds frequently have a significantly lower strength than speech sounds, are undetectable or feeble signals, and are dynamic and transient noises. Three typical audio elements were identified by Morinière et al. (2008) [2] as occurring during swallowing: Laryngeal ascendance sound, upper sphincter opening sound, and laryngeal release sound are the first three sounds. The laryngeal rising sound is heard as gentle since it is weak. All of their recordings contained the sound of the bolus travelling down the pharynx, which is equivalent to the "gulping" sound that is most usually connected with swallowing. It lasts an average of 185 milliseconds in their data. The laryngeal release sound is modest and irregular, much like the ascent sound. The laryngeal ascendance and release sounds are brief (on average 106ms and 72ms, respectively), click-like sounds that are shorter. And according to Vice et al. (1990) [3], the opening of the cricopharyngeal sphincter during the pharyngeal phase is thought to be a contributing factor to the so-called initial discrete sounds (IDS), which are the most distinctive features of swallowing sounds. When a bolus is transmitted into the oesophagus during the pharyngeal phase, gurgling sounds known as bolus transmission sounds (BTS) are produced. BTS are then followed by the final discrete sounds (FDS), which are produced during the oesophageal phase.

As a result, the hyoid bone, larynx, and epiglottis movements, as well as the action of the upper airways during breathing and the sudden changes in the corresponding muscles during the pharyngeal phase of swallowing, are all described as sound components that contribute to the swallowing acoustic signal. The frequency, length, and amplitude of the sound waves can be used to analyse the acoustic signature of these swallowing sounds. Dysphagia is a frequent result of impairments affecting these deglutition structures and functions. As a result, changes in the characteristics of these swallowing sounds must take place, changing the acoustical characteristics in accordance with the problem in a particular phase, or structure, or due to any other comorbidities affecting the anatomy and physiology.

Clinical evaluation of swallowing disorder and management:

Numerous non-invasive screening techniques have been developed in order to be able to distinguish when such an abnormal occurrence occurs without the direct aid of video fluoroscopy. For instance, by employing accelerometers, the doppler sonar technique, and cervical auscultation, after which the acoustic data and vibrations are processed using digital processing algorithms. Stethoscopes and microphones are placed on the surface of the neck to listen to swallowing sounds (Bosma 1976; Hamlet, Penney, and Formolo 1994; Lefton-Grief and Loughlin 1996; Vice and Bosma 1994) [4,5,6,7]. Cervical auscultation is the practise in question. Studies have shown that the acoustic and perceptual examination of swallowing sounds, as identified by the CA approach, can differentiate between patients with and without dysphagia (Bosma, 1976; Mackowiak, Brenman, & Friedman, 1967) [8]. A non-invasive method for monitoring treatment as biofeedback is sonar doppler of the larynx, which is helpful in the evaluation of functional swallowing. Accelerometers detect the neck's vibration pattern that occurs while swallowing.

Further if we see one of the mainstays of clinical practice for treating dysphagia is the use of foods with altered textures and liquids that have been thickened. This widespread practise is based on the idea that altering the characteristics of typical foods and liquids will make them safer and simpler to swallow. But a variety of food consistencies can also impact swallowing sounds in addition to variations in anatomy and physiology. Additionally, using foods with modified textures and thicker liquids is a vital part of therapeutic practice for treating dysphagia. This common practise is founded on the notion that changing the properties of common foods and drinks will make them safer and easier to swallow. Reimers-Neils et al. (1994) [9] discovered that there was a significant increase in the total duration of adult swallowing muscle activity from liquid (e.g., water) to thin paste (e.g., pudding) and from thin paste to thick paste consistencies (e.g., cheese spread), as measured by the time from the onset to the cessation of submental and infrahyoid EMG activity during swallowing.

But studies on how varying food consistency impacts swallowing sounds, however, have been dispersed and fragmented. This thorough systematic review analysis's goal was to correlate various bolus physical parameters with various swallowing sound characteristics. It also identifies the specific acoustic traits to diagnose for despite various bolus consistencies to distinguish abnormal sounds, allowing us to use this information to differentiate between dysphagic swallowing sounds when they fluctuate with different bolus consistencies during a clinical swallowing evaluation.

METHODOLOGY:

Study Identification and Selection:

Multiple search engines were used to conduct a complete literature search to uncover prospective research articles for this systemic review, including IEEE Xplore, SpringerLink, Wiley Online Library, ResearchGate, SAGE Journals, SciELO, Academia.edu, PubMed, and Google Scholar. The search terms were swallowing sounds, clinical swallowing evaluation, cervical auscultation, swallowing sounds and bolus consistency, acoustic characteristics of swallowing sounds, acoustic analysis of dysphagia, non-invasive swallowing evaluation. In the pre-selection phase, articles with work on non-invasive clinical evaluation of swallowing and swallowing sounds were found by screening by their title and abstract. Any differences among the writers were handled by discussion and referral.

The authors then established the inclusion and exclusion criteria for the systemic review based on the demand of the study issue and to adhere to the purpose. The whole text of the initial batch of papers was then evaluated, and studies that did not fulfil the eligibility requirements based on the inclusion and exclusion criteria established were excluded. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was utilized to guide the systemic review execution in terms of implementing inclusion and exclusion criteria and expediting the selection of eligible articles.

Inclusion Criteria:

We chose articles that addressed the diagnostic potential of investigating the acoustical characteristics of swallowing sound using various methods, such as cervical auscultation, swallowing accelerometers, doppler sonar, acoustic analysis using Cepstrum analysis, and algorithm-based approaches, and that were used to evaluate swallowing sound in healthy people with no history of dysphagia or neurological disorders. Furthermore, the investigations included swallowing tests with various types of food and liquid consistencies. There were no constraints on age, gender, publication date, or language in the selection criterion.

Exclusion Criteria:

Specifically defined criteria were used to eliminate articles from consideration. First of all, studies using animals as test subjects were excluded from the analysis. Second, studies were rejected if they did not use non-invasive techniques for clinical swallowing evaluation. Thirdly, we did not take into account articles that were only concerned with the acoustic study of swallowing sound in people with dysphagia or other neurological co-morbidities. Additionally, studies that only used a single level of bolus consistency rather than a variety of levels or those that did not involve the use of food or liquid materials during swallowing evaluation were disregarded. Additionally, research that didn't elaborate on how the physical properties of the food and liquids affected swallowing noises were excluded.

Results:

Study selection:

The systematic searches generated 86 non-duplicate articles. During the pre-selection phase, a comprehensive evaluation on 50 abstracts was performed, which had the most relevance to the research topic, and 40 articles were excluded based on the exclusion criteria, leaving 10 articles for full-text reading and inclusion in the qualitative analysis by the authors.

Study characteristics:
The ten investigations that were taken into consideration were carried out between 2003 and 2020. According to the study's population, all of the participants were healthy adults without any form of swallowing disorders. The many methods used to assess and investigate swallowing sounds are outlined in Table 1.

Figure 1. PRISMA flow diagram of the systematic review's search procedure:

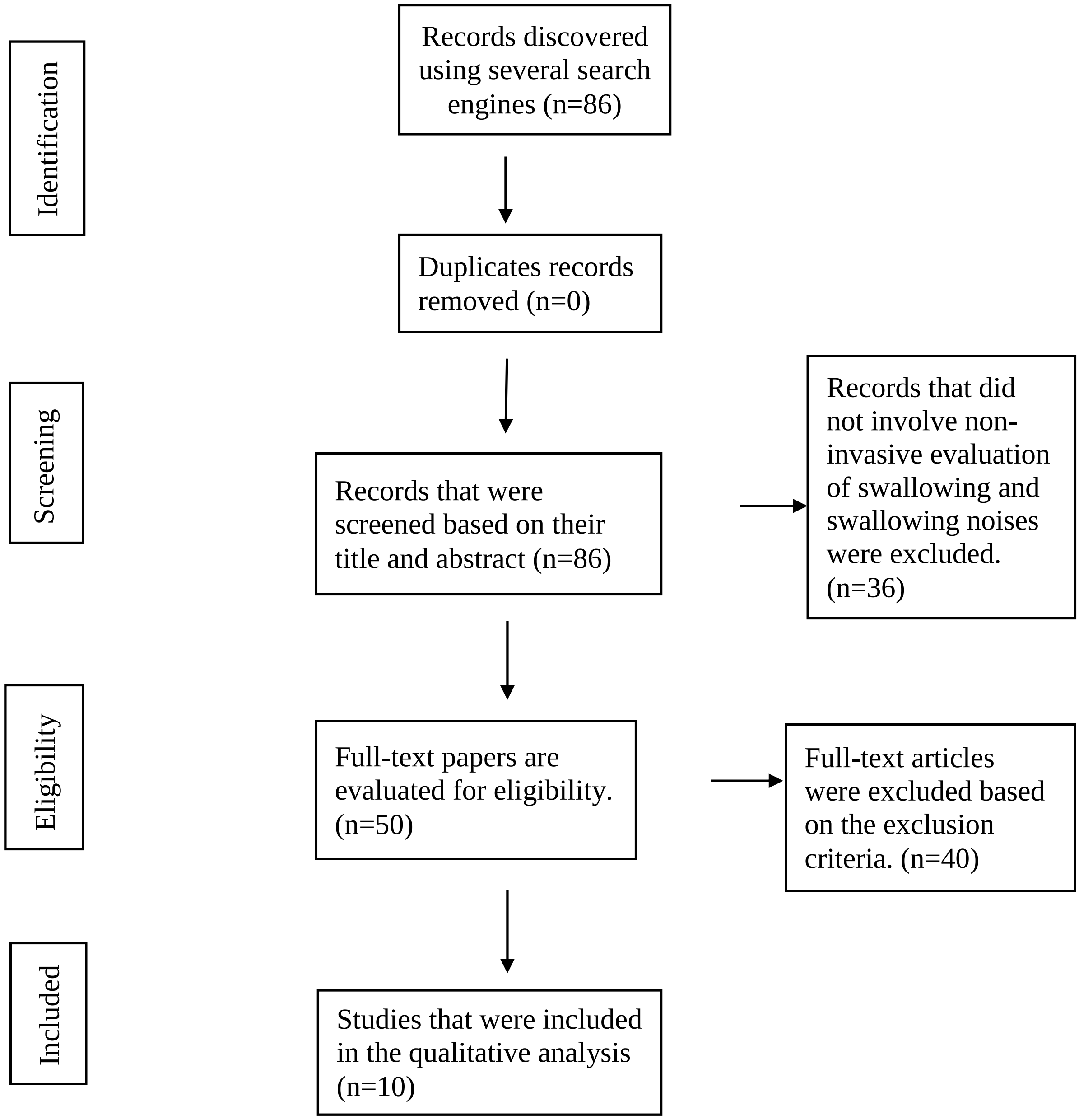

Table 1: Various instrumentation and opted software for acoustical analysis of the recorded swallowing sounds used in the 10 included research papers:

Author	Year	Title	Sample Size	Instrumentation for recording	Acoustical analysis
M. Taniwaki et al. [20]	2013	Acoustic analysis of the swallowing sounds of food with different physical properties using the cervical auscultation method	6 healthy subjects (3 men and 3 female) in their 30s and 40s	A skin-touch controlled piezoelectric microphone (SH-12iK, Nanzu Electric Co. Ltd., Shimoda, Japan) placed at midline of the cricoid cartilage	A data collecting program developed in LabVIEW (National Instruments, Austin, TX)
M. Taniwaki et al. [21]	2012	Fast Fourier transform analysis of sounds made while swallowing various foods	6 healthy subjects (3 men and 3 female) in their 30s and 40s	A skin-touch controlled piezoelectric microphone (SH-12iK, Nanzu Electric Co. Ltd., Shimoda, Japan) placed at midline of the cricoid cartilage	Additional FFT-based frequency analysis program in a data acquisition program developed in LabVIEW (National Instruments, Austin, TX)
Anthony Ki et al. [17]	2020	Acoustic profiling of swallowing sounds of liquid associated with different bolus consistencies	30 healthy adults (15 males and 15 females) between 18 and 30 years	A wireless stethoscope (Model 3200, 3M Littman Electronic Stethoscope, 3M) placed at right lateral neck, on the tracheal lateral border, just below the cricoid cartilage	The software called StethAssist that came with the wireless stethoscope

Hennessey et al., [14]	2017	Developmental changes in pharyngeal swallowing acoustics: a comparison of adults and children	31 healthy children (12 male and 19 female) between 4-5.2 years, 29 healthy adults (14 male and 15 female) between 20.8-28.3 years	An Optimus 33-3013 electret condenser lapel microphone connected to a Sony Hi-MD Walkman MZ-RH1 portable minidisk recorder digitally stereo-recorded placed at participant's throat at a position below the midline of the cricoid cartilage	PRAAT software
Youmans et al. [18]	2005	An acoustic profile of normal swallowing	97 subjects (48 males and 49 females) mean age 48.47 years	Accelerometer (PCB Model 352C22, PCB Piezotronics, Depew, NY, USA); powered by ICP sensor signal conditioner (PCB Model 480E09) set at zero amplification placed at midline of the cricoid cartilage	Computerized Speech Lab (CSL) (model 4400, Kay Elemetrics, Lincoln Park, NJ, USA)
Youmans et al. [19]	2011	Normal swallowing acoustics across age, gender, bolus viscosity, and bolus volume.	96 healthy adults divided into Young aged group (between 20-39) Middle aged group (between 40-59), Older age group (60 and older). All have 32 members each composed of 16 males and 16 females	Accelerometer (model 352C22, PCB Piezotronics, Depew, NY) connected via a thin cable to a signal conditioner (model 480E09, PCB Piezotronics) placed at midline of the cricoid cartilage	Computerized Speech Lab (CSL) (model 4500, Kay/ Pentax, Lincoln Park, NJ)

Huckabee et al. [15]	2005	Repeatability of the acoustic swallowing pattern in normal adults	30 adults divided into 3 age groups: Young adults, between 22-28; Middle aged adults, between 43-48 years; Elder adults, between 61-70 years	Littmann Pediatric stethoscope (KOA 28703) and an omni-directional microphone (Optimus 33-3003) connected at the stethoscope bifurcation placed at right lateral neck, on the tracheal lateral border, just below the cricoid cartilage	KAY Elemetrics CSL-4300B
Cichero et al. [23]	2003	What happens after the swallow? Introducing the glottal release sound	59 non-dysphagic divided into 3 groups: Group 1 (18-35 years); Group 2 (36-59 years); Group 3 (60+ years) each group having 10 males and 10 females except Group 3 having 9 females	Microphone (EK3132 Knowles electret) attached to a preamplifier (prechamp K-5608) placed at midline of the cricoid cartilage	Computerized Speech Laboratory (CSL-4300, Kay Elemetrics)
W. Reynolds et al. [22]	2009	Variability of swallow-associated sounds in adults and infants	20 healthy adults (10 males and 10 females between 26 to 59 years	With a combination of an accelerometer (Vibro-meter Corp., Boston MA, Model 501-FB) and an electret microphone (Optimus [Radio-Shack/Tandy Corp], Fort Worth TX, Model 33–3013) placed at right lateral neck, on the tracheal lateral border, just below the cricoid cartilage	Cool Edit 2000 v1.1 (Syntrillium Software Inc., Phoenix, AZ)
Cagliari	2009	Doppler sonar	90 healthy	Portable ultrasound	VoxMetria

et al. [16]		analysis of swallowing sounds in normal pediatric individuals	individuals divide into 3 groups, 2-5 years; 5-10 years; 10-15 years having 15 males and 15 females each	detector (DF-4001 type from Martec) positioned at right lateral neck, immediately below cricoid cartilage, on the tracheal lateral boundary. The ultrasound detector is connected to a Positivo notebook computer with a Windows XP Professional operating system, an Intel Celeron M360 1.4GHz processor, 240MB of RAM memory, a video card with an integrated graphic accelerator Via Uni Chrome PRO IGP and 64MB of memory, a combo drive (DVD player and CD recorder), and integrated high definition ALC655 audio compatible with AC'97.	software, version 2.8h22

Duration Variables:

Hennessey et al., (2017) [14] administered 2 types of boluses: 4 ml of a normal, thin fluid (fruit cordial, diluted one part cordial to four parts water) in a 200 ml cup, and 4 ml of a smooth, smooth puree consistency food (chocolate yoghurt), given through teaspoons and he derived that in comparison to puree, there was no discernible difference in the (total duration) TD of swallowing with thin fluids. Similar results were also found in other study by Huckabee et al., (2005) [15] who used 10cc of thin liquid swallow (tap water) and 10 cc of commercially produced pudding-consistency yogurt along with dry swallowing of saliva and found no difference in swallowing duration is observed between thin liquid and pudding swallow.

Anthony Ki et al., (2020) [17] presented 5 ml of thin, mildly thick, moderately thick and thick liquid. Resource ThickenUp Clear, was used as a thickener, his conclusions differed as he found Average Duration of Swallowing Sound (DAS) was 657ms for thin, 687ms for mild, 767ms for moderate, and 802ms for extra thick consistency specifying that DAS values appeared to increase with the consistency of the liquid consumed, which was supported by W. Reynolds et al., (2009) [22] who by using water, coffee and soft drinks as choice for thin liquid consistency, applesauce for puree consistency and cookie as a solid food where results show signals longer in duration of swallow related sounds with boluses of increasing viscosity. However, Youmans and Stierwalk et al., (2005) [19] used 5- and 10-ml boluses of thin (bottled water), nectar and honey thick liquids (pre-thickened apple juice), and 5 ml boluses of mechanically soft (three sliced canned peaches) and puree (applesauce) consistencies and observed that the mean DAS for thin, soft, honey, and puree was 490ms, 570ms, 550ms, and 530ms, respectively. Again, Youmans and Stierwalk et al., (2011) [18] while using puree consistency (applesauce), honey-thick liquid (apple juice and "Thick-It" brand thickener), thin liquid (tap water), and mechanical soft consistency (four diced canned pear pieces) also concluded increased duration with increased viscosity, here DAS for thin liquid for 5ml was 540ms and for 10ml volume of the same it was 600ms; so, he further inferred with increased volume swallowing gets longer.

In the study by Hennessey et al., (2017) [14] (Duration of peak intensity) DPImean was significantly shorter for thin fluid boluses compared to puree, which is in conjunction with other article which was reviewed, where Anthony Ki et al., (2020) [17] revealed that average DPI of 219ms was found across bolus types, and with 190ms for thin, 214ms for mild, 224ms for moderate, and 246ms for extra bolus consistency. In contrast, Youmans and Stierwalk et al., (2005) [19] found that puree, honey, and soft had average DPIs of 190ms, 230ms, and 220 ms, respectively. He suggested that the intensity of the three clicks determined the DPI variable. Additionally, Youmans and Stierwalk et al., (2011) [18] state that, increased viscosity often resulted in a considerably longer duration from the swallowing onset to the peak intensity.

Results by Hennessey et al., (2017) [14] also showed that in the thin fluid condition compared to the puree, the spectral Mmean and spectral SDmean were much bigger, and the spectral skewnessmean and spectral kurtosismean were significantly reduced. Article which used doppler effect, by Cagliari et al., (2009) [16] conducted investigation using 2.5ml of water as liquid food consistency and 2.5ml of Danoninho (refrigerated yoghurt-like product) as pasty food and saliva swallowing, signification was marked between liquid and paste consistency among frequency and peak intensity variables.

Intensity Variables:

Hennessey et al., (2017) [14] stated (peak intensity) PImean and (standard deviation of intensity) SDImean were found to be significantly greater in swallows of thin fluid compared to puree, the (peak intensity coefficient of variation) PICV was found to be higher for puree than thin fluid. Unlike the above findings, Anthony Ki et al., (2020) [17] discovered that PI values were similar across bolus consistencies and among all bolus types. The mean PI was 88.8 dB collapsed across all consistencies, other study by Youmans and Stierwalk et al., (2005) [19] likewise stated that their PI across consistencies was consistent, however their PI was 60.8 dB, this might be because an accelerometer was utilized instead of a microphone and stethoscope combination. But Youmans and Stierwalk et al., (2011) [18] claimed to the contrary that swallowing thin liquids caused participants to produce a larger auditory swallowing signals than honey-thick liquids or even more viscous boluses (puree or mechanical soft).

Frequency Variables:

Anthony Ki et al., (2020) [17] showed mean (Frequency of Peak Intensity) FPI was 976 Hz with all bolus types used by him and to be specific was 995 Hz for thin, 988 Hz for mild, 962 Hz for moderate, and 957 Hz for extra thick consistency. While Youmans and Stierwalk et al., (2005) [19] indicated that all bolus types averaged 587 Hz for FPI and considering the average peak frequency (PF) for the various bolus consistencies were 2295.34 Hz (puree), 2187.92 Hz (honey), 2322.63 Hz (thin), and 2413.15 Hz (soft), with a PFmean of 2304.76 Hz collapsing across bolus types used by him. And considering the finding of Youmans and

Stierwalk et al., (2011) [18] for PF, thin liquids were ingested at a substantially greater frequency than mechanical soft solids due to the fact that signals in thin liquids with higher intensities preserve more high-frequency information than signals with lower intensities. But according to M. Taniwaki et al., (2012) [21], who took water for liquid, yoghurt for semiliquid, and konjac jelly for solid, the frequency range is most significant between 400 to 1000 Hz and it is varied among the food samples. Lower frequency ranges became more dominant in less viscous boluses, and the amplitude of swallowing sounds in this range was in the order of fluidity: liquid>semiliquid>solid.

M. Taniwaki et al., (2013) [20] again took water for liquid, yoghurt for semiliquid, and konjac jelly for gel found that swallowing sound duration in water lasted longer than yoghurt and konjac jelly: water > konjac jelly > yoghurt, and most importantly he concluded that flow features of food, such as scattering, are more likely to indicate the duration which is determined by Dynamic viscoelasticity, viscosity, and yield stress.

At the end one unique article by Cichero et al., (2003) [23] which had, generated thin fluid consistency with Cottees Diet fruit cup cordial mixed with water. Thickened cordial was made by mixing thin fluid mixture with Ketrol food thickener as the different consistency talked about the characteristics of glottal release sound, which was longer with thin fluid than thick fluid.

DISCUSSION AND CONCLUSION:

This comprehensive review examined various variations in swallowing sounds and acoustical characteristics according to physical characteristics like viscosity, consistency levels, yield stress, and volumes across a variety of food and liquids, which are used not only during clinical swallowing evaluations but also as clinical management of swallowing disorders to compensate for compromised swallowing anatomy and physiology.

The methods used non-invasive digital signal processing of the acoustic data, and this systemic review observed how methodology alters the characteristics of swallowing sounds quantitatively but qualitatively for a range of consistencies, from thin to extra thick or puree.

Out of the included studies 4 studies derived results for all the duration variables, intensity variables and frequency variables which help in understanding every aspect of swallowing. Other studies emphasized on peak intensity and swallowing duration, which is not a much problem because these two factors show the most consistent across studies and food and liquid type and volume. Having less discrepancies qualitatively but quantitively differs due to different age groups of participants, instrumentation and different food types. And one can conclude the few of the difference in data is due to the lack of formal definition of the beginning and end of a swallowing sound.

DAS increases with increase in viscosities. But one unique article stated additionally that viscosity will cause discrepancy in some level of moderate to thick level of consistencies, so RMS of food material and most importantly dynamic viscoelasticity, viscosity, and yield stress collectively decides the duration of swallowing, as high flow characteristics of food and low yield stress will result in shorter duration as they are easy to swallow rather than saying thin viscosity is easy to ingest.

PI is consistent across food types and volumes and for cervical auscultation with microphone and stethoscope is 88.8 dB whereas it gets attenuates using accelerometer 60.8 db.

Considering spectrographic results food samples resulted a frequency range of 400-1000Hz and low viscous bolus dominant the low frequency ranges. The range over 1000 Hz might be affected due to the fundamental resonance of the microphone. And amplitudes are higher for more liquids and least for solids.

These results can somewhat helpful for further researches which are needed to consider a uniform study on an informed definition of particular level of consistencies, to lower the discrepancies and enhance the efficacy of classifying the other variables. But the two variables are helpful to diagnose swallowing disorders along with invasive and radiographic techniques of evaluating swallowing disorders. Also, the review shed light on the main factor of deciding the physical properties of food which dynamic viscoelasticity, viscosity, and yield stress combinedly is the flow characteristics of the material which is very important to keep in mind during management of dysphagia when a specific compensatory level of consistency is given to the patient. Further studies should use these factors in order to explain the physiological correlates to alterations in food and liquid physical properties will be highly encouraged to solve this enigma of swallowing sounds more appropriately.

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