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Effects of Liquid Viscosity and Food Texture on Swallowing Sounds

Chun Feng
University of Nebraska Medical Center

EFFECTS OF LIQUID VISCOSITY AND FOOD TEXTURE ON SWALLOWING SOUNDS

by

Chun Feng

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Advisory Committee:

Ka-Chun Siu, PhD. Kathleen G. Volkman, PT, MS.

Cheryl Wagoner, MS, CCC-SLP, BCS-S.

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ABSTRACT

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Chun Feng, M.S.

University of Nebraska Medical Center, 2020

Supervisor: Ka-Chun Siu, Ph.D.

Cervical auscultation (CA) is a technique of monitoring swallowing performance according to swallowing acoustic signals utilizing a stethoscope or other measurement devices such as a microphone and an accelerometer. In the past few years, doctors have utilized the stethoscope to identify the swallowing sounds, which resulted in an inability to accurately diagnose the aspiration/penetration in patients with dysphagia when compared to the gold standard. A digital CA assessment records swallowing acoustic signals and extracts the specific features from the recordings. It has been proven that digital CA as a promising portable and low-cost tool can be used for identifying patients at risk of aspiration. However, further research is required with regards to effects of liquid viscosity, food texture, and demographic and anthropologic features of healthy people before long-term swallowing monitoring among patients with dysphagia. Chapter 1 includes the literature review that discussed history of CA technique development, effects of different boluses and characteristics of participants, effects of head and neck positions, and data analysis of swallowing acoustic signals. In the following chapters, more detailed effects on swallowing acoustic signals will also be presented. Chapter 2 focused on the effects of liquid viscosity and food texture on swallowing performance. Chapter 3 further explored the influences of neck circumference on the swallowing

acoustic signals. Chapter 4 provided a summary of overall finding of this thesis and general research limitations and future directions. All references were included in chapter 5 bibliography. Chapter 6 appendices included basic information questionnaire, healthy subject data sheet and consent form.

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LIST OF ABBREVIATIONS

BMI: body mass index

CA: cervical auscultation

CP: cricopharyngeal

DAS: duration of acoustic signals

DPI: duration to peak intensity

FEES: Fiberoptic Endoscope Evaluation of Swallowing

HMM: hidden Markov model

HRCA: high-resolution cervical auscultation

IDDSI: International Dysphagia Diet Standardisation Initiative

LAS: laryngeal ascension sound

LP: laryngeal prominence

NC: neck circumference

PF: peak frequency

PI: peak intensity

Prog: progressive

Reg: regular

RMS: root mean square

RQA: Recurrence quantification analysis

SC1: the first sound component

SC2: the second sound component

SC3: the third sound component

SNR: signal-to-noise ratio

UES: upper esophagus sphincter

VFSS: Videofluorography Swallowing Study

Chapter 1 SWALLOWING ACOUSTIC SIGNALS: A LITERATURE REVIEW

I. Abstract

Cervical auscultation (CA) is a technique of monitoring swallowing performance according to swallowing acoustic signals utilizing a stethoscope or other measurement devices such as a microphone or an accelerometer. CA as a promising portable and low-cost tool can be used for identifying patients at risk of aspiration. However, further research is required with regards to effects of liquid viscosity, food texture, and demographic and anthropologic features of healthy individuals before applying long-term swallowing monitoring among patients with dysphagia. This literature review discussed the history of CA technique development, effects of different boluses and characteristics of participants, effects of head and neck positions, and data analysis of swallowing acoustic signals.

II. Introduction

Swallowing as an indispensable daily behavior happens on average 585 times per day (range from 203 to 1008) (C. S. Lear et al., 1965). There are 4 stages of swallowing: Oral Preparatory Stage, Oral Transport Stage, Pharyngeal (throat) Stage and Esophageal Stage. Any event that disturbs any of these four swallowing stages can potentially contribute to dysphagia. Dysphagia is an increased age-related health concern, which can result from over 100 different kinds of disease or injury. Neurological diseases or damage such as amyotrophic lateral sclerosis, gravis myasthenia, Parkinson’s disease, multiple sclerosis and tardive dyskinesia commonly affecting swallowing performance. Even 50% patients suffer from dysphagia after the first week of the stroke (Marin et al., 2018). Prevalence of dysphagia is also higher among elderly populations especially in those staying in nursing homes (Aslam & Vaezi, 2013). A swallowing screening is typically the first step in assessing swallowing abnormalities. A more detailed examination is required if a person is suspected to have a swallowing disorder. Cervical auscultation (CA) is one of the non-invasive and inexpensive screening methods. It involves monitoring the sound and vibration signals generated from the throat during pharyngeal stage swallowing. The stethoscope, as the most traditional device for CA, has been utilized for centuries and is still available during bedside screening for patients with pharyngeal swallowing-impairment in clinical settings (S. Hamlet et al., 1994; Zenner et al., 1995).

Several attempts have been made to identify the physiological causes of swallowing sounds. One theory, known as cardiac analogy hypothesis, links the physiological cause of swallowing sounds and heart sounds. There is speculation that an analogy exists between the generation of heart sounds and swallowing sounds. Based on the existence of several valves and pumps in the pharynx, it has analogous functions to the valves and pumps in the heart (J. A. Cichero & Murdoch, 1998). A digital CA assessment applies a microphone or an accelerometer to record swallowing acoustic signals, which was first introduced by Stott and Russell in the 1950s (Russell, 1956; Stott, 1953). Hammoudi et al. stated that the first component (SC1) of swallowing sound was associated with the rise of the larynx, the second (SC2) with the passage of the bolus through the upper esophageal sphincter (UES), and the third (SC3) occurred during the descent and the opening of the larynx (Figure 1-1). Hamlet et al. suggested the "first click" and "second click" were the closure and release of the epiglottis, respectively (Figure 1-2). Hammoudi et al. and Hamlet et al. all agreed that the interval between "first click" and "second click" was the sound of food being transported through the throat. The nonuniformity of the swallowing sound physiology they qualified might be due to the different 'gold standard devices' they utilized to investigate. Hammoudi et al. used the Videofluorography Swallowing Study (VFSS) to analyze laryngeal movement in a lateral-side view, while Hamlet et al. applied the Fiberoptic Endoscope Evaluation of Swallowing (FEES) which provided a view of the epiglottis' movement during swallowing. They made a certain association between what they observed and what they heard (S.

L. Hamlet et al., 1992; Hammoudi et al., 2014). However, Leslie et al. suggested that there was no evidence of a causal connection between swallowing sounds and the physiological event. Thus, the physiology of swallowing sound has not been clearly understood (Leslie et al., 2007).

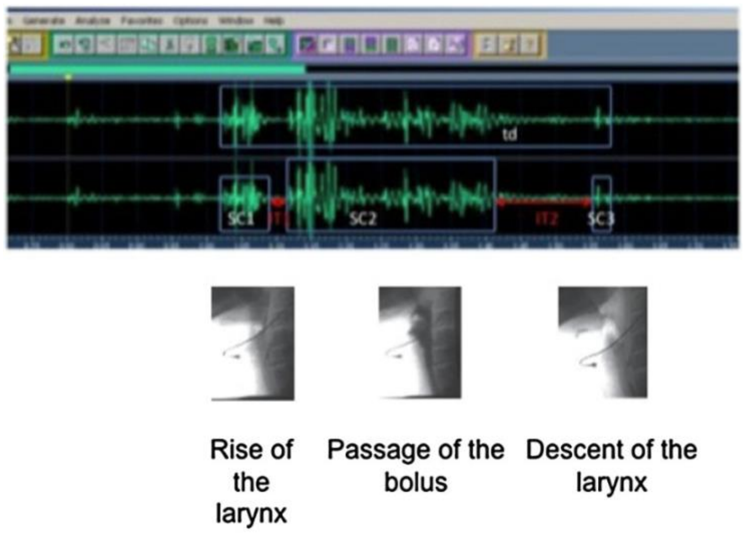

Figure 1-1 Hammoudi et al. stated that the first component (SC1) of swallowing sound was associated with the rise of the larynx, the second (SC2) with the passage of the bolus through the upper esophageal sphincter (UES), and the third (SC3) occurred during the descent and the opening of the larynx. SC = sound component, td = total duration of the sound, IT = interval (Hammoudi et al., 2014)

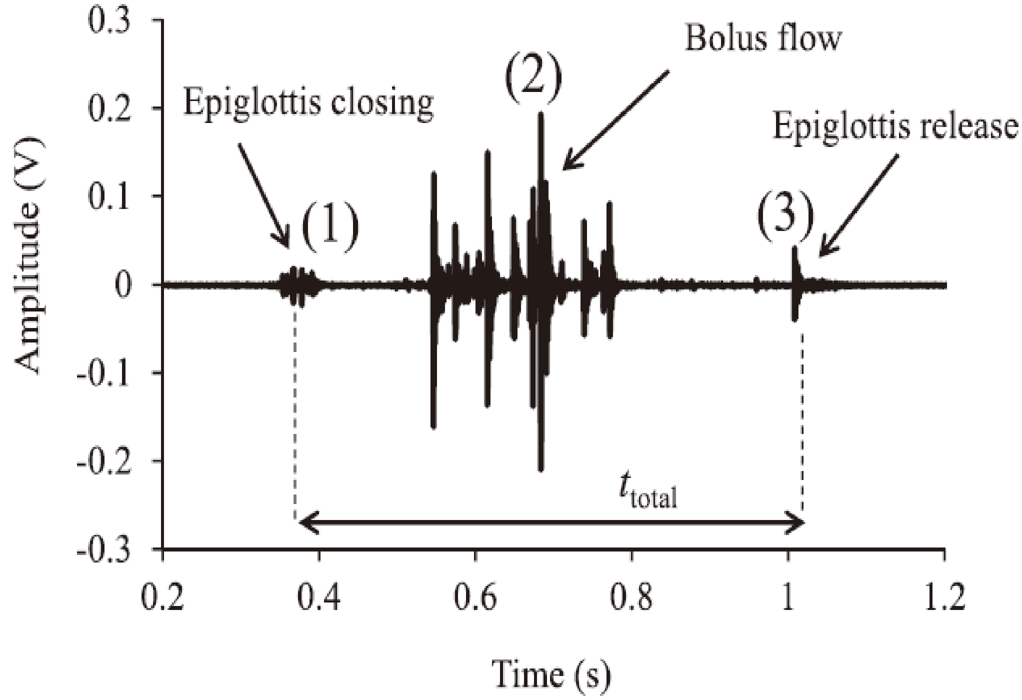

Figure 1-2 Normal swallowing sounds are divided into (1) epiglottis closing, (2) bolus flow and (3) epiglottis release (S. L. Hamlet et al., 1990, 1992; Taniwaki et al., 2013)

Dysphagia occurs when the normal process of swallowing does not work as intended. CA analysis identifies abnormal swallowing based on swallowing acoustic signals. Researchers describe abnormal swallowing sounds among oropharyngeal dysphagia patients with reduction of laryngeal elevation and adduction, delayed triggering of the swallowing reflex, aspiration/penetration as well as reduced pharyngeal 'peristalsis' or cricopharyngeal dysfunction. Most CA screening criteria for dysphagia are based on the swallowing sound during the pharyngeal swallowing phase. Voice and airway sounds are considered as other criteria to differentiate the swallowing performance during pre and post-swallowing phases. The following symptoms or signs are common to screen for aspiration in dysphagic patients: abnormal duration and magnitude of swallowing sounds; abnormal sound properties (i.e., bubbling sound); a shorter or longer swallowing duration a longer post-swallowing apnea (Santamato et al., 2009) and post-swallowing sounds like immediate respiration sounds, and wet voice and/or repeating throat clearing after swallowing.

Over the past half-century, there has been increased attention to effects of demographic, liquid/food viscosity, and volume on swallowing acoustic signals. Researchers have attempted to identify the normal acoustic profile of swallowing acoustic signals across different viscous liquids and texture foods in order to screen for dysphagia under different conditions. However, the swallowing sounds and vibrations related to swallowing physiology and pathology are not clearly understood. There is a diversity of validity and reliability of CA in the diagnosis of dysphagia among adults and children. However, CA might be a more superior method than other non-invasive methods, not only to early screen for aspiration/penetration in patients with dysphagia, but also for long-term diet monitoring (Ferrucci et al., 2013; Jiang et al., 2016; Zenner et al., 1995). The following manuscript attempts to discuss the history, techniques, and clinical applications of CA. The effects of influential factor on swallowing acoustic signals will also be examined.

III. History of Cervical Auscultation

Modified technique with CA began in the 1950s when Stott and Russell (Russell, 1956; Stott, 1953) first evaluated pharyngeal swallowing and the presence of bubbly secretion in adults with bulbar poliomyelitis by utilizing binaural microphone. In the 1960s, Truby & Lind recorded crying and feeding sounds among infants with cleft palates and displayed the sounds with the sonography (Truby & Lind, 1965). Mackowiak et al. and Logan et al. described the acoustic profile of normal adult pharyngeal swallowing with sonography (Logan et al., 1967; Mackowiak et al., 1967). In the 1970s, Bosma et al. distinguished swallowing sounds between dysphagia and non-dysphagia individuals with CA (Bosma, 1976). In 1990s, CA has been recommended as a promising and useful clinical tool for investigation of feeding and swallowing problems related to subtler neurological impairment and preterm birth by evaluating suckle feeding among newborn infants (Vice et al., 1990). In the midst of these modern early CA studies, Zenner et al. proved CA was valid for swallowing disorder screenings with the support of VFSS. They suggested that CA with stethoscope was a method with a high sensitivity and specificity that could determine a specified diet for long-term care (Zenner et al., 1995). In 2002, Stroud et al. evaluated the inter- and intra-rater reliability of CA to detect aspiration in patients with dysphagia. They found there was high agreement when aspiration occurred, but non-aspiration swallows were also over-detected among speech-language pathologists with experience of CA utilization (Stroud et al., 2002).

Researchers not only focused on the swallowing performance by evaluating normal and abnormal swallowing acoustic signals. At the same time, they also applied a microphone to monitor the frequency of swallowing events in adults during 24-hr periods through the pressure of thyroid cartilage movement (C. S. Lear et al., 1965) as well as temporal relationships between chewing and swallowing sounds (Hollshwandner et al., 1975).

Despite these previous studies, there was also a detractor for validity in CA. Leslie et al. evaluated the reliability and validity of CA and suggested that CA was reliable but might not be appropriate as a standalone tool to diagnose dysphagia (Leslie et al., 2004). However, compared to other less invasive methods, including electromyography (Vaiman, 2007), pulse oximetry (Sherman et al., 1999; Wang et al., 2005), a simple questionnaire or a water swallow screening (Bours et al., 2009), CA has exhibited acceptable sensitivity and specificity and proven to be a reliable screening tool. Audible cues provided by CA can act as an early warning sign for identifying patients with a high risk of aspiration/penetration (Borr et al., 2007).

Currently, researchers have applied a wide array of methods and features to characterize signals ranging from simply counting the swallowing events that occur over a period of time (Afkari, 2007; Boiron et al., 1997; C. S. C. Lear et al., 1965) to analyzing various descriptive features in the duration (Santamato et al., 2009), intensity (Santamato et al., 2009; Youmans &

Stierwalt, 2005, 2011), frequency, phase space (M. Aboofazeli & Moussavi, 2005) and entropy (Olubanjo & Ghovanloo, 2014). Recently, investigators have paid more attention to the coordination between swallowing and breathing to screen for dysphagia (Santamato et al., 2009), which was considered more preciously to detect the swallowing sounds (Mohammad Aboofazeli & Moussavi, 2008).

These objective criteria and the digital data obtained by microphones or accelerometers could be useful to develop more sensitive and clinically useful methods for swallowing research. Additionally, the approach of human beings' segmentation is limited to a small sample size, time consuming and human auditory fatigue. Machine segmentation and neural network analysis of swallowing sounds have been explored to substitute human beings' segmentation. Larger volumes of accelerometry and sound data sources necessitate an automatic method to mitigate human error due to fatigue or oversight, which ensures consistent criteria of segmentation.

With the development of CA techniques, bolus viscosity, volume, age, gender and their potential for interaction have been addressed to effects on swallowing acoustic signals for screening swallowing difficulties. Meanwhile, CA also has been developed to calculate the frequency of swallowing events among healthy adults to better understand the etiology of obesity (J. A. Cichero & Murdoch, 2002; Taniwaki et al., 2013; Youmans & Stierwalt, 2011). Researchers investigated the human behavioral pattern of food consumption and energy intake for monitoring ingestive behavior (MIB) through a microphone or acceleratory device by counts of chewing and swallowing events (O. Amft et al., 2009; E. Sazonov et al., 2008; E. S. Sazonov et al., 2010; Edward S. Sazonov et al., 2009).

IV. Acoustic Profile of Swallowing Acoustic Signals

It is necessary to first acoustically characterize swallowing sounds among normal healthy individuals before reliably detecting aspiration/penetration among patients with swallowing disorders. However, to date, the existing literature provides divergent descriptions of normal swallowing acoustics. Although the pharyngeal movement associated with the swallowing sound was first studied in the 1950s, studies determined the original sources of swallowing sounds in 1990s. Hamlet et al. reported only bolus passing through the cricopharyngeal opening related to swallowing sounds (S. L. Hamlet et al., 1990). In addition, Vice et al. came up with initial discrete and final discrete sounds separated by a bolus transit sound in newborn infants when describing patterns of pharyngeal swallowing and respiratory sounds (Vice et al., 1990). Selley et al. also acknowledged that 'two clicks' were separated by a faint sound which was caused by the bolus transfer. They reported that the first 'click' was caused by the elevation of the larynx and the epiglottis moving down. However, they cannot explain the origin of the second 'click' since they found the movements of the epiglottis and hyoid occurred after the second sound (Selley et al., 1994). Considering the largest peak of swallowing sounds[1], Tsuyoshi Honda et al. divided the swallowing sound into three swallowing sound wave (SSW) parts. They then selected a representative videofluoscopy for each SSW period (Honda et al., 2016). Yagi et al. also addressed laryngeal motion to separate sounds into three parts *(*Sound I[2], Sound II[3], Sound III) in the Figure 1-3. However, they indicated that food transport occurred across both Sound II and Sound III (Yagi et al., 2016). Researchers argued the origin of swallowing sounds might not totally match physiological events (Leslie et al., 2007; Selley et al., 1994). The difficulty to synchronize VFSS images with the swallowing sound seemed to be a major problem in identifying the physiological sources of swallowing sounds. Morinière et al. first synchronized the swallowing sound and the radiologic frame to develop a numeric acoustic-radiologic acquisition. They identified and quantified three sound components: laryngeal ascension sound

[1] The first SSW is defined as the period from the beginning of the swallowing wave to the beginning of the following large peaks. The beginning of the first SSW is tongue making a contact to the palate; the second SSW is the period from the beginning of the large peak to the beginning of the large peak to the third peak. Bolus transport is happening during this stage; the third SSW is the period from the beginning of the third peak to the offset of the swallowing wave. At the beginning of the third SSW, the bolus completely enters the esophagus, and the hyoid bone and larynx resume their baseline positions, the epiglottis reopens.

[2] Sound I correspond to the closure of the nasopharynx

[3] Sound II associates with the opening of UES and food transport through the oropharyngeal

(LAS)[4], upper sphincter opening sound[5], laryngeal release sound[6] and two intervals, which was shown in the Figure 1-4 (Morinière et al., 2008).

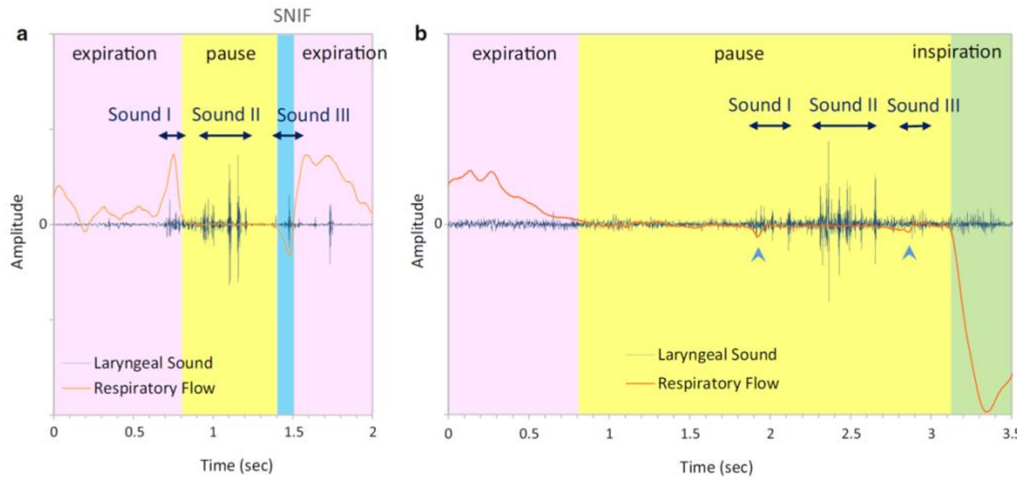

Figure 1-3 Representative swallow-respiratory coordination patterns are together with swallowing sounds ***(Sound I, II and III)***. ***Light pink zone:*** expiratory phase ***light yellow zone:*** pause phase ***light green zone:*** inspiratory phase. ***Blue zone:*** swallow non-inspiratory flow ***(SNIF)***. a. Expiration-swallow-expiration pattern. b. Expiration-swallow-inspiration pattern. Note that swallow negative pressures (arrowheads) are recorded coincident with swallowing sound components (Yagi et al., 2016).

4 Laryngeal ascension sound (LAS) when the sound component occurred during the ascension of the hyoid bone when the bolus was located in the oropharynx and/or hypopharynx

5 The upper sphincter opening sound when the sound component occurred during the opening of the upper sphincter and the bolus was going through the sphincter

6 The laryngeal release sound when the sound component occurred during the descent and the opening of the pharynx and the larynx and the bolus was located in the esophagus

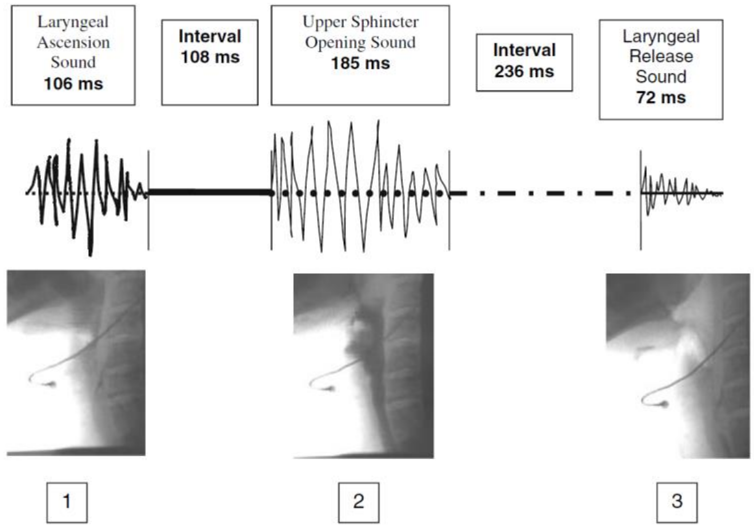

Figure 1-4 Moriniere et al. discussed the origin of the sound components during pharyngeal swallowing via VFSS and determined the laryngeal ascension sound, upper sphincter opening sound, laryngeal release sound and two intervals. Their study analyzed the origin of the three main sound components of the pharyngeal swallowing sound in relation to movements in anatomic structure (Morinière et al., 2008)

Researchers also suggested considering post-swallowing to define breathing-swallowing patterns. Mackowiak et al. divided dry and wet swallowing sounds into three parts: first (α), second (β), and third (γ) component, with a silent interval between each component. They reported dry swallowing sounds showed higher peak energy and a shorter duration than wet swallowing but the third (γ) component was absent in dry swallowing (Mackowiak et al., 1967). Cichero et al. addressed the acoustic evidence of the third (γ) component, which was a release of subglottal air in the post-swallow phase in non-dysphagia individuals. They indicated that the presence of a glottal release sound provided an indication of ability to achieve adequate airway protection during swallowing (J. a. Y. Cichero & Murdoch, 2003).

Researchers built on these normal swallowing studies to understand swallowing acoustics among patients with swallowing difficulties. Yagi et al. reported dysfunction of the pharyngeal phase of swallowing might contribute to the delayed onset of Sound II[7] of the pharyngeal swallow (Yagi et al., 2016). Boiron et al. classified three swallowing patterns into a regular, progressive and irregular pattern by the interval between each swallow. They suggested a good coordination of the pharygo-esophageous movement could indicate the proficiency of swallowing performance that be used to further diagnose swallowing disorders (Boiron et al., 1997). A combination of respiratory flow was also considered by Santamato et al. They evaluated the duration of swallowing sounds and post-swallowing-respiration to approach the acoustic pattern of neurological patients with dysphagia after assessing normal and abnormal swallowing sounds (Santamato et al., 2009).

Based on previous studies, researchers suggested although a "normal" sound profile and the origin of sounds were not well established, however, digital CA could be a promising non-invasive screening to early screening for aspiration/penetration in patients with dysphagia (Leslie et al., 2007; Selley et al., 1994). Dysphagic and non-dysphagic post-swallowing glottal release sounds and swallowing-breathing patterns could be considered in the profile of swallowing acoustic signals to improve the reliability. In recent years, along with the emergence of deep learning, high-resolution cervical auscultation (HRCA)[8] has been utilized to assess the swallowing kinematic events which could potentially provide the association between safe swallowing and hyoid bone displacement (He et al., 2019; Kurosu et al., 2019).

V. Influential Factors on Swallowing Acoustic Signals

1) Demographic Factors

A number of studies have investigated impacts of demographic factors on swallowing acoustics. However, there are divergent findings in previous literature regarding age and gender-related influential factors of CA, which thus fails to provide necessary information for CA

[7] Sound II associates with the opening of UES and food transport through the oropharyngeal

[8] High-resolution cervical auscultation (HRCA): a combined hardware-software system that merges electronic transducers (a microphone and/or accelerometer) with advanced data analysis methods

accuracy and accessibility improvements. An innovative suggestion on identifying influential factors of CA is to take neck circumference (NC) and neck subcutaneous tissue into account. If proved, it can be systematically applied to general patient populations and replace previous demographic factors such as age and gender.

a. Body Mass Index and Neck Circumference

A limited number of studies have considered the effects of body mass index (BMI) and NC on swallowing acoustics. Two studies tried to approach the effects of BMI and NC on swallowing acoustic signals. Considering available standardization of BMI classification and a high correlation between BMI and NC, Sejdić et al. selected BMI rather than NC to address whether anthropometric factors can potentially impact swallowing acoustics. In fact, anthropometric research pointed out NC could better unveil upper body fat distribution than BMI (Abdolahi et al., 2014), and can be independent of BMI (Joshipura et al., 2016). Hanna et al. investigated effects of anthropometric and demographic factors on swallowing vibration signals. They stated no significant linear correlation between signal characteristics and NC in water and saliva swallowing (Hanna et al., 2010), while Sejdić et al. reported participants with a high BMI with longer DAS. However, the two studies mentioned above did not indicate specific volume of intake, which could undermine the reliability of their study.

Even though the effects of age and gender on swallowing acoustics were not conclusive, age and gender are the major factors on tissue difference around the neck. Tissue changes with age have also been documented, including loss of muscular tissues and increased fatty tissues (Palmer & Kirkland, 2016). Meanwhile, there is also the effect of gender on neck tissues, which indicates women usually have more fat tissues and fewer muscle tissues in the necks than men across all races (Li et al., 2014; Whittle et al., 1999). Considering the distribution of the neck tissues, swallowing acoustic signals could potentially be different among different ages and gender. Thus, Youmans et al. suggested that future studies could conduct an assessment of neck tissue in participants to counteract the difference of the age and gender-related neck tissue components (Youmans & Stierwalt, 2011).

The above evidence presented suggests that further research should address whether differences in neck structures certainly affects the acoustic sound received by the accelerometer or microphone.

b. Age

Physiologically, the efficiency of swallowing performance is impacted after the age of 60, which is reflected in longer swallowing duration, more swallows per bolus, increased risk of aspiration, and delayed onset of the esophageal phase (Marik & Kaplan, 2003; Martin et al., 1994; Robbins et al., 1992). Although researchers attempted to address the effect of age on swallowing acoustics, study results achieved a minimal agreement with the age impact on duration, duration to peak intensity (DPI), frequency and peak intensity (PI).

The age effects on the duration of swallowing acoustic signals might be more prominent when comparing young adults with middle-age adults, and young adults with elderly adult populations. Dudik, J. M et al. applied the automated segmentation algorithm supported by a VFSS evaluation to analyze the duration of saliva swallowing. They reported that the duration of saliva swallowing did not demonstrate any notable trends with regard to age in either head-neutral or chin-tuck positions (Dudik et al., 2015a, 2015a). Their results run counter to the past research of Sejdić et al., which might be due to the limited age range of participants (38.9 ± 14.9) in the research of Dudik et al. On the contrary, Sejdić et al. reported older participants exhibited significantly longer swallowing durations than younger participants in dry, wet head-neutral, and wet chin-tuck swallowing (Sejdić et al., 2009). Their other research supported that the age-based differences of swallowing signals only occurred during actual swallows and not during baseline resting and anaerobic conditions (Ervin Sejdić, Komisar, et al., 2010). Hanna et al. also confirmed that age affects water swallowing, however, age does not affect saliva swallowing (Hanna et al., 2010). Cichero et al. emphasized this effect that a shorter DAS was present in the younger group when comparing younger (18-35 years) with middle (36-59 years), and younger (18-35) with older (60+) groups (J. A. Cichero & Murdoch, 2002).

Regarding the DPI, divergent results have also been found. Youmans et al. reported that significantly longer DPI was found in the older group compared to the younger and middle age groups (Youmans & Stierwalt, 2005). Their second study considered that there was an interaction between age and viscosity. They found more viscous boluses demonstrated longer DPIs with increasing age but durations for less viscous boluses were similar across age groups (Youmans & Stierwalt, 2011). One study by Cichero et al. reported DPI was insensitive across age groups. They discussed that the duration at which the swallowing sounds reached PI was an indicator of pharyngeal contraction activity, which was minimally affected by age (J. A. Cichero & Murdoch, 2002).

There were also conflicting findings when addressing age effects on peak frequency (PF). Youmans et al. found that elderly individuals produced higher peak frequencies than younger individuals (Youmans & Stierwalt, 2011). The similar tendency was also found by Santomato et al. (Santamato et al., 2009). However, Dudik et al. reported acoustic frequency did not show any trend in aspect of age (Dudik et al., 2015a).

Researchers disagreed with the impact age had on the intensity of swallowing sounds. Cichero et al. and Santamato et al. both found that there was no difference of sound intensity across age groups (J. A. Cichero & Murdoch, 2002; Santamato et al., 2009). However, Youmans et al. pointed out decreasing intensity of swallowing acoustic signals with age (Youmans & Stierwalt, 2005). In contrast, his other research found that elderly individuals produced higher peak intensities than younger (Youmans & Stierwalt, 2011).

In summary, considering the three dimensions of the acoustic signals (duration, frequency, and intensity), duration is shown to be the most sensitive feature. Regarding the difference of intensity and frequency across age groups, researchers suggest the change of neck tissue might cause the alteration of resonatory characteristics. But this alteration might not be due to higher pressure in the pharyngeal among elderly adults. Cichero et al. pointed out that differences of neck tissues and structures could contribute to variations in swallowing sounds (J. A. Cichero & Murdoch, 2002). Different fat tissues in the neck might have altered the resonatory characteristics of vocal tracts, producing more intense sounding signals (Youmans & Stierwalt, 2011). Researchers suggest future studies should consider an assessment of the tissue in the neck to adjust this relative effect on certain components of acoustic signals.

c. Gender

Physiologically, anatomic differences rather than a consequence of learned behavior might contribute to the variations in key acoustic characteristics extracted from swallowing sounds and vibrations across gender. A relatively small pharynx in females requires a longer and larger duration of UES opening, as well as a longer duration of pharyngeal clearance to accommodate a bolus of equivalent size compared to males (Boiron et al., 1997; Roberto Oliveira Dantas et al., 2009), which is relevant to anatomical structures in the size of the oropharynges (Robbins et al., 1992). However, Dantas et al. confirmed that the swallowing performance was not impressive in older subjects compared to younger subjects in regards with gender (Roberto Oliveira Dantas et al., 2011). Although these anatomic differences might affect the key acoustic characteristics (duration, duration to peak intensity, peak frequency, and peak intensity) of the swallowing sounds among males and females, however, to date, there has been little consistency in the gender effects on swallowing acoustic signals.

Results from several studies suggested that the duration of the acoustic signals did not differ regarding difference of gender (Hammoudi et al., 2014; Morinière et al., 2006; Santamato et al., 2009; Youmans & Stierwalt, 2005, 2011), which was supported by the evidence that the neurologic control of swallowing is the same across gender. On the contrary, Sejdić et al. reported males had a significantly longer duration than females in dry and wet swallows (Sejdić et al., 2009). Their other research supported that gender-based differences of swallowing vibration signals were due to anatomical differences between male and female considering similarities of resting and anaerobic baseline conditions (Ervin Sejdić, Komisar, et al., 2010).

A limited number of studies have been investigated to explore the impact of gender on the DPI. These three articles all found that there is no gender effect on DPI (J. A. Cichero & Murdoch, 2002; Youmans & Stierwalt, 2005, 2011). Since DPI might be an indicator of pharyngeal movement (J. A. Cichero & Murdoch, 2002), this could provide support for no difference of pharyngeal contraction activities between gender.

There is also little agreement of gender effects on PF of swallowing acoustic signals. Dudik et al. reported that male participants exhibited greater frequency compared to females both in the chin-tuck and head-neutral positions. They predicted these gender-related diversities might be due to different anatomical size and the position of the laryngeal prominence (Dudik et al., 2015a, 2015b). In contrast, few variations in PF with regard to gender have also been found (Santamato et al., 2009).

Impact of gender on the swallowing sound intensity has also been questioned. Researchers reported that males produced higher peak intensities compared to females in the same age groups (J. A. Cichero & Murdoch, 2002; Lebel et al., 1990; Youmans & Stierwalt, 2011). On the contrary, Cichero et al. and Santamato et al. reported no difference across gender and the intensity of the swallowing sound was stable at 43dB (J. A. Cichero & Murdoch, 2002; Santamato et al., 2009).

In summary, findings concerning effects of gender on swallowing acoustic signals are inconclusive to date. Possible explanations for the divergency are multiple standards for liquid/food viscosity, signal detection equipment and data procession. The controversy about physiological events not totally relevant to the swallowing acoustic signals might also explain this discrepancy in aspect of gender effects (Leslie et al., 2007; Selley et al., 1994).

2) Food Property

A large number of studies have investigated the influences of liquid viscosity, food texture, and bolus volume on swallowing sound and/or vibration signals (S. L. Hamlet et al., 1992). Researchers investigated swallowing sounds among healthy adults across varied bolus viscosity in efforts to build a foundation for the future comparison with dysphagic swallowing acoustic signals (Butler et al., 2009; Taniwaki et al., 2013; Youmans & Stierwalt, 2011). However, inconsistent findings have been noted, which might be due to unavailable standardized worldwide food/liquid preparation criteria.

a. Liquid Viscosity and Food Texture

Liquid viscosity-modified and food texture-modified are the most common approach to manage swallowing issues for long-term dysphagic care (Clavé et al., 2006). The principle behind this practice is that thickened liquids can slow down the velocity of liquids through the UES and allow more reaction time for airway closure, which relies on gravity instead of muscle activities. As a result, higher viscous liquid can decrease risks of aspiration/penetration (Dooley et al., 1988).

Youmans et al. reported thicker liquids produced longer acoustic signals than thin liquids. Soft solids have the longest duration (Youmans & Stierwalt, 2005). Researchers also have divided swallowing acoustic signals into three components (Sound I, Sound II, and Sound III) in order to further explore the effects of liquid viscosity and food texture on each component. Taniwaki et al. investigated sounds while swallowing boluses with different consistencies and texture, including water, yogurt, and konjac jelly. They found no differences with aspects of Sound I and Sound III across three boluses. However, the duration of water transport through the pharynx (Sound II) was longer than the other two viscous boluses (Taniwaki et al., 2013). Hamlet et al. suggested a longer Sound II was due to the generation of turbulent flowing caused by the epiglottis and pyriform sinuses (S. L. Hamlet et al., 1992). It might be the reason for increasing the risk of aspiration/penetration during thin liquid intake. Since evidence supported a shorter total duration of water swallowing acoustic signals than thicker liquid and soft solids (Dooley et al., 1988; Youmans & Stierwalt, 2005), a shorter initial discrete of the swallowing sounds (Sound I) for thin liquid texture can better explain this phenomenon (Mohammad Aboofazeli, 2007).

Regarding the effect of the food consistency on swallowing sounds dependent on muscle activities during swallowing (Clavé et al., 2006; Jestrović et al., 2013; Morinière et al., 2008; Robbins et al., 1992; Tsukada et al., 2009; Youmans & Stierwalt, 2005, 2011), Nakamura et al. divided the swallowing sounds into the high frequency[9] and low frequency components[10]. Their results showed that the harder a bolus was, the smaller was the amplitudes in high frequency components and the larger amplitudes in low frequency components of swallowing sounds (Nakamura et al., 2000). It is apparent that the pharynx moves slowly when intaking harder boluses while liquid boluses are easier to inflow through the pharynx. Researchers not only have investigated different frequency components of swallowing sounds, but also have further achieved agreement on the PF of swallowing sounds across different viscous liquids. Jestrović et al. reported that thicker fluids produced a lower PF with intaking higher viscosity fluids. However, they suggested the difference was more prominent when comparing water to higher viscous liquids (Jestrović et al., 2013). Youmans & Stierwalt reported similar results that thinner liquids produced greater frequency than mechanical soft solids (Youmans & Stierwalt, 2011).

Effects of liquid viscosity on swallowing signal intensity also have been conclusive to date. Youmans & Stierwalt reported thinner liquids produce higher intensity than more viscous liquids (Youmans & Stierwalt, 2011). A similar result showed that paste swallowing has lower amplitude than liquid swallows (S. L. Hamlet et al., 1992). Taniwaki et al. found larger root mean square (RMS) amplitude in water swallowing than the yogurt and konjac jelly (Taniwaki et al., 2013). However, there is a lack of evidence that changing viscosity levels could either continuously or discretely disturb the swallowing acoustic signals.

[9] High frequency component is influenced by liquid/food inflow sound during the pharyngeal phase.
[10] Low frequency component is influenced by the movement of the pharynx.

Overall, most of researchers agree there is a shorter duration, greater frequency, and higher intensity of swallowing acoustic signals during the thinner liquid intake compared to thicker liquids. Although researchers proved thicker liquids could reduce the speed of boluses to minimize the risk of aspiration/penetration, and quite understood characteristics of swallowing acoustic signals, none of the studies have determined safe liquid viscosity for patients with different severities of dysphagia based on their swallowing sound and vibration signals. Santamato et al. suggested consistency of methodology, characteristics under investigation, or terminology was required to achieve high generalization and validity of CA. They pointed out that the inconsistency between their results (Santamato et al., 2009) and Youmans & Stierwalt et al. (Youmans & Stierwalt, 2005) were caused by a different standardization of food.

b. Volume of Liquids/Foods

Although it also has been reported that an increase in bolus volume has no effect on oral and pharyngeal bolus transit time, or the duration of pharyngeal peristaltic waves, however, an increase in bolus volume can cause the prolonged UES opening, laryngeal closure duration, and longer swallowing apnea via VFSS (R. O. Dantas et al., 1990; Lazarus et al., 1993). Lazarus et al. also noted that with increased bolus volume, there was an increase in laryngeal closure duration and cricopharyngeal (CP) opening duration with VFSS (Lazarus et al., 1993).

Given the physiologic changes that occur during swallowing with alterations in bolus volumes, there may also be reasonable volume-related changes to the acoustic profile of the swallow. Cichero et al. found the duration of the swallowing sound was shorter for the 15 ml volume than either 5- or 10- ml volumes (J. A. Cichero & Murdoch, 2002). An explanation for this finding was based on the assumption that the mean flow rate of a liquid would be faster for high-volume (15ml) than low-volume (2ml) passing through the UES (R. O. Dantas et al., 1990). However, most of the studies reported that a larger volume of liquids required a longer duration to safely swallow. Based on the support of VFSS and CA, researchers reported the increased bolus volumes had a longer total duration of swallowing acoustic signals (Hammoudi et al., 2014; Honda et al., 2016; Youmans & Stierwalt, 2011). Dodds et al. also investigated differences in the hyoid bone displacement during different volumes of barium swallows. They reported high volumes of boluses required more hyoid bone movements (Dodds et al., 1988). Cook et al. also reported airway protection and UES opening are related to vertical displacement of hyoid bone during swallowing (Cook et al., 1989). Their findings indicated dysphagic patients who had slow or small vertical hyoid movement were in high risk of aspiration/penetration when intaking high volume liquids. He et al. further investigated the relationship between hyoid bone movement and HRCA acoustic signal features and indicated anterior-posterior signals from accelerometers became more predictable and organized in swallowing with greater vertical hyoid displacement (He et al., 2019). A higher thyroid notch acceleration also presented with an increase in water volume among healthy adults, which required a large laryngeal elevation. Patients with dysphagia had impaired swallowing reflex and weak muscle actions to respond to high volume of boluses, which could result in aspiration/penetration (Greco et al., 2010). Considering these physiological findings, it might be safer for dysphagic patients to intake small volumes of liquids, which is expected to require the shorter duration of UES opening and less hyoid bone movement.

PI and PF of swallowing acoustic signals was less investigated than DAS regarding volume effects. The reason might be that differences in swallowing acoustics are more associated with viscosity rather than volume. Two studies found that participants produced greater PI and PF of the swallowing sound with larger volumes of water (Youmans & Stierwalt, 2005, 2011).

The interactions between bolus volume and other factors have also been explored. Cichero et al. studied the volume-by-gender interaction in frequency ranges and volume-by-age interaction in durations of the swallowing sound. They found that men showed significantly higher frequency range (2,635 Hz) with 5ml water intake than 10ml (2,123 Hz) or 15ml (2,088 Hz), while women’s frequency range were insignificant across 5ml, 10ml and 15ml liquids. They also found that the young age group demonstrated a shorter duration of swallowing sounds than middle- and elderly group when only swallowing 5 ml of water. The middle age group had shorter swallowing sounds when swallowing 15 ml compared to 5 ml or 10 ml of water. The elderly age group exhibited longer swallowing sounds when they swallowed 10 ml or 15 ml (J. A. Cichero & Murdoch, 2002).

Regarding swallowing external liquids, participants were also required to voluntary swallow or swallow their own accumulated saliva. Mackowia et al. explored differences between the wet (saliva) swallowing and dry (non-saliva) swallowing. They found dry swallows were typically longer than wet swallows. This might be due to decreased ability to initiate swallowing reflex to complete the swallowing performance if there was no bolus present. They also illustrated dry swallows could produce less intensity than wet swallows on a spectrogram (Mackowiak et al., 1967). Based on their findings, even though the certain volume of liquids was not determined, a small volume of liquids might be better than no liquid to improve swallowing performance during swallowing training for patients with dysphagia.

Although effects of bolus volume on swallowing acoustic signals have not been fully investigated, a small amount of liquid volume could be considered as a start of feeding trainings for certain type of dysphagic patients with limited hyoid bone displacement. The divergency in the literature requires further studies to prove whether these results can be replicated in the future.

3) Head and Neck Positions

Different head and neck positions, as a postural technique, are commonly used in clinical practice to minimize the risk of aspiration/penetration. The chin-tuck position and the head rotation position are the most common compensatory treatments. The head flexed position, clinically called the chin-tuck position, has been reported to narrow the laryngeal entrance and the posterior shift of the epiglottis (Shanahan et al., 1993), which in turn widens the vallecular space and aids to enhance airway protection (Welch et al., 1993). Patients with dysphagia sometimes have aspiration/penetration when there is impaired innervation, uncoordinated muscle contraction or decreased tissue compliance. Head rotation, however, may divert boluses to the opposite pyriform sinus into the esophagus, bypassing the damaged area and allowing more efficient swallowing among patients with dysphagia. Although head position change techniques are widely accepted by clinicians, the mechanisms underlying the effect of head position on the physiology of swallowing have not been clarified. Alternations of head position change associated with the change of swallowing sounds is also under-explored.

Johnsson et al. investigated the normal oropharyngeal swallowing with the VFSS and manometry in order to evaluate the effects of gravity and body positions on the pharyngeal bolus transport. Their results showed that the horizontal and inverted positions tended to have greater hypopharyngeal intrabolus pressure than the upright position, which resulted in increased maximal sphincter diameters and a shorter duration of sphincter opening as well (Johnsson et al., 1995; J. A. Logemann et al., 1989). However, Johnsson et al. reported that a total swallowing duration, oral and pharyngeal transit time, pharyngeal peristaltic amplitude and duration were unaffected by body positions (Johnsson et al., 1995).

Antunes & Lunet suggested that head and neck positions would influence morphological changes in the bolus pathway during swallowing, which could potentially affect the swallowing acoustic signals. Consequently, it may alter the acoustic characteristics of the swallowing sound (Antunes & Lunet, 2012). Jestrovic et al. found less consistency in features (time domain, frequency domain, time-frequency domain features) comparing head neutral to the chin-tuck head position across swallowing sound and vibration signals. They also indicated that the chin-tuck position has more consistent features and was less affected by the fluid viscosity compared to the head neutral position (Jestrović et al., 2013). Head and neck positions not only changed swallowing sounds during bolus swallows, but also saliva swallow sounds. Sejdić et al. showed the duration of wet swallows in the head neutral position was shorter than the chin-tuck position across all ages, BMI, and gender (E. Sejdić et al., 2009).

Thus, the effect of position on swallowing patterns have not been fully understood yet. The effect of head postures, such as the head flexion or the head rotation, on swallowing sounds should be further investigated to prepare patients with dysphagia progressing to normal food.

In summary, though bolus volumes have an impact on swallowing physiology and swallowing acoustic signals, viscosity of liquid and texture of food might have more contribution on differences of swallowing signals. Even though studies have not fully elucidated safe liquid viscosity and volume for patients with dysphagia based on their swallowing sound and/or vibration signals, they agreed thicker liquids and small volume could reduce the speed of boluses and minimize the risk of aspiration/penetration. however, inconsistency of methodology and food viscosity preparation among research could still be a major stumbling block to clinical application. The strong relationship between the kinematic source of HRCA acoustic signals and several swallow kinematic events such as hyoid bone displacement, UES opening and etc. also indicate HRCA could be a potentially diagnostic and long-term clinical management tool for dysphagia (He et al., 2019; Kurosu et al., 2019).

VI. Technology for Swallowing Sound Detection

1) Acoustic Detector

In previous studies, researchers have been investigating swallowing acoustic signals with various types of acoustic detectors, including a miniature hearing-aid microphone (C. S. C. Lear et al., 1965), contact microphone (Dudik et al., 2015a; Mackowiak et al., 1967; Santamato et al., 2009), piezo-electric type pick-up (including accelerometer) (Boiron et al., 1997; Burke, 1977; Dudik et al., 2015a; S. L. Hamlet et al., 1990, 1992), miniature dynamic earphone (Cunningham & Basmajian, 1969), electret condenser microphone (Honda et al., 2016; Murti et al., 1980), miniature electret microphone (J. A. Y. Cichero & Murdoch, 2002), dynamic microphone (Boiron et al., 1997), throat microphone (Olubanjo & Ghovanloo, 2014; E. Sazonov et al., 2008), piezo-electric sensor, and single-accelerometer (Youmans & Stierwalt, 2005). These devices are also held in place using a variety of approaches, elastic band (Hammoudi et al., 2014; C. S. C. Lear et al., 1965; Morinière et al., 2008), Velcro cuff (or mole skin) (Mackowiak et al., 1967; Youmans & Stierwalt, 2005), hand-held placement (Cunningham & Basmajian, 1969; Logan et al., 1967), a double-sided electrode washer (Vice et al., 1990), single-sided paper surgical tape (J. A. Y. Cichero & Murdoch, 2002; Youmans & Stierwalt, 2005), double-sided tape (Mohammad Aboofazeli & Moussavi, 2008; Dudik et al., 2015a; Honda et al., 2016; E. Sejdić et al., 2009; Ervin Sejdić, Komisar, et al., 2010; Samaneh Sarraf Shirazi et al., 2012), and latex strip (Santamato et al., 2009).

Dudik et al. suggested that swallowing sound and vibration signals provided different information about deglutition (Dudik et al., 2015a). The main differences of gathering signals were that microphones collected airborne sounds rather than accelerometers detected vibrations on the skin surface. Researchers had debates about the superiority between an accelerometer and a microphone. On the one hand, researchers who advocated for accelerometers indicated that three-axis accelerometers might provide additional information since they were able to detect signals from the anterior-posterior, superior-interior, and medial-lateral directions (Movahedi et al., 2016; Ervin Sejdić et al., 2014). On the contrary, researchers advocated for microphones with high signal-to-noise ratio (SNR), which were able to detect respiratory sounds. Since vibration signals are collected in a different way, swallowing vibration signals can be distorted if the integrity of the skin, muscle, or tissue situation have been altered. Additionally, the cost of microphones is cheaper, which is approximately one tenth that of accelerometers.

Even though acoustic characteristics extracted from swallowing signals are acquired through those devices, no empirical evidence associated with the effectiveness of the detector unit, as well as the mounting method, has been reported. Since swallowing vibrations and sounds are similar, it appears the date processing is more vital for the swallowing acoustic analysis.

2) Site of Placement

Honda et al. suggested that different placements of sensors around the neck would influence recording signals (Honda et al., 2016). Some studies have suggested that the suprasternal notch was the best placement for the signal detection (M. Aboofazeli & Moussavi, 2006; Mohammad Aboofazeli & Moussavi, 2008; Honda et al., 2016; Samaneh Sarraf Shirazi et al., 2012). However, several studies recorded swallowing acoustic signals over the laryngeal prominence (LP) (Honda et al., 2016; Yagi et al., 2016). It is more suitable for the microphone since the closer to the sound source, the larger the sound pressure. It also brings up another problem for comparisons among different studies if they place their equipment at different sites. In contrast, there is no such concern about accelerometer due to it collecting sound vibrations instead of sound pressure. Most researchers utilized the conclusion made by Takahashi et al. that the greatest peak SNR could be recorded either directly on, immediately inferior to, or immediately lateral to the cricoid cartilage (K. Takahashi et al., 1994) (Figure 1-5). Sarraf Shirazi et al. recorded swallowing acoustic signals in the ear and nose since acquiring signals from the trachea sometimes can be difficult for those with loose skin. They suggested that recording signals in the ear and nose might be a viable alternative when tracheal recording is unavailable (Sarraf-Shirazi et al., 2012).

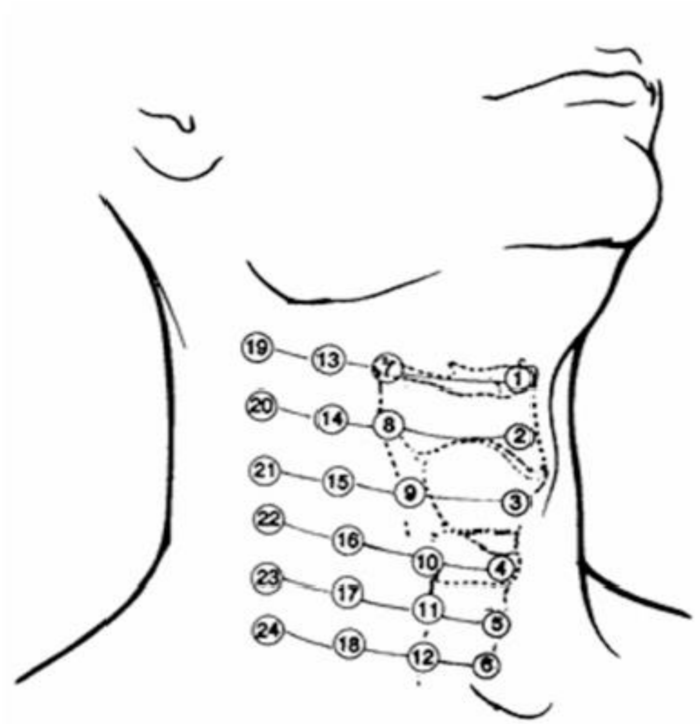

Figure 1-5 Takahashi et al. compared signal-to-noise ratio at 24 sites in the neck and revealed signals with greatest peak signal-to-ratio could be either directly on, immediately inferior to, or immediately lateral to the cricoid cartilage (K. Takahashi et al., 1994)

In summary, the cricoid cartilage is the best anatomic landmark to collect swallowing sound and vibration signals. Alternatively, the LP, ear, and nose can also be utilized to collect swallowing acoustic signals if the anterior neck is not available for collecting sounds.

3) Signal Analysis

a. Data Preprocessing

Utilizing raw transducer signals without the pre-signal processing is common in this field (Borr et al., 2007; J. A. Y. Cichero & Murdoch, 2002; S. L. Hamlet et al., 1992; Hammoudi et al., 2014; Makeyev et al., 2009; Reynolds et al., 2003, 2003; E. S. Sazonov et al., 2010; S. Sarraf Shirazi & Moussavi, 2012; Stroud et al., 2002; K. Takahashi et al., 1994; Taniwaki et al., 2013; Youmans & Stierwalt, 2005, 2011; Zenner et al., 1995). From the standpoint of eliminating background noise, the bandpass filter has been applied. Some studies put the low bandpass as 0.1 Hz in order to maintain "pure" signals (Celeste et al., 2012; Dudik et al., 2015a; Jestrović et al., 2013; J. Lee et al., 2008; Movahedi et al., 2016; E. Sejdić et al., 2009; Ervin Sejdić, Komisar, et al., 2010; Ervin Sejdić et al., 2012), while other researchers utilize the high bandpass as 30 Hz or more to diminish motion artifacts or other low frequency noise (M. Aboofazeli & Moussavi, 2004a; Mohammad Aboofazeli & Moussavi, 2008; Lazareck & Moussavi, 2004b; Sarraf-Shirazi et al., 2012; Samaneh Sarraf Shirazi et al., 2012). Unlike common bandpass filtering techniques to denoise in specific frequency ranges, several researchers also have applied wavelet denoising techniques to reduce both white and colored noise on given signals (Celeste et al., 2012; Dudik et al., 2015a; Jestrović et al., 2013; J. Lee et al., 2008; Joon Lee et al., 2011; Nikjoo et al., 2011; Spadotto et al., 2008; Steele et al., 2013). Additionally, researchers also have attempted to remove the specific unwanted signals such as head or neck motions during swallowing (Celeste et al., 2012; Dudik et al., 2015a; Jestrović et al., 2013; Nikjoo et al., 2011; Ervin Sejdić, Steele, et al., 2010; Ervin Sejdić et al., 2012; Steele et al., 2013). Since each specific transducer has a unique frequency response curve, researchers who used the different devices to record the acoustic or vibration signals also tried to remove noise created by the recording device itself (Dudik et al., 2015a; Jestrović et al., 2013; J. Lee et al., 2008; Nikjoo et al., 2011; Steele et al., 2013). Since the transducers with a flat frequency response will not change the amplitude of recorded signals, most studies suggested complex filtering techniques are deemed unnecessary.

b. Data Processing

The early acoustic analysis of the swallowing mechanism was focused on the duration of swallowing events (S. Hamlet et al., 1994; Leslie et al., 2004). With the development of the techniques, acoustic analysis was expanded to extract other characteristics from swallowing acoustic signals such as PI, PF, DPI and DPF (J. Lee et al., 2008; Sarraf-Shirazi et al., 2012; Youmans & Stierwalt, 2005). Moreover, researchers proposed a method of automatically and accurately segmenting the swallowing sounds and find out the onset and offset of a swallowing event without identification errors of the human ear. The simplest method was the thresholding of time domain signals (J. Lee et al., 2008; Makeyev et al., 2009). Neural network and machine segmentation also have been explored. Aboofazeli et al. applied three automated methods to detect swallowing sounds with non-linear dynamic parameters (Recurrence quantification analysis (RQA)) and hidden Markov model (HMM) (Mohammad Aboofazeli & Moussavi, 2008).

Although the methods of signal analysis involved characterizing swallowing signals through a large number of calculated statistical features, experts in this field have not made an agreement on "key features" in swallowing acoustic signals. In the time domain features, it was common to analyze the overall duration of the swallowing signals (Jestrović et al., 2013; Lazareck & Moussavi, 2004a, 2004b; J. Lee et al., 2008; Joon Lee et al., 2010; Movahedi et al., 2016; Santamato et al., 2009; Ervin Sejdić, Komisar, et al., 2010; Yadollahi & Moussavi, 2007; Youmans & Stierwalt, 2005), and the timing of the different phases of deglutition (Zenner et al., 1995). Many experiments also analyzed the frequency domain features of the signals, such as the average power, PF and so on (M. Aboofazeli & Moussavi, 2004b; Celeste et al., 2012; S. Hamlet et al., 1994; S. L. Hamlet et al., 1992; Jestrović et al., 2013; Lazareck & Moussavi, 2004a, 2004b; Joon Lee et al., 2010, 2011; Movahedi et al., 2016; Prabhu et al., 1994; Santamato et al., 2009; Sarraf-Shirazi et al., 2012; Ervin Sejdić, Komisar, et al., 2010; S. Sarraf Shirazi & Moussavi, 2012; Samaneh Sarraf Shirazi et al., 2012; Smith et al., 1990; Yadollahi & Moussavi, 2007; Youmans & Stierwalt, 2005, 2011).

Even though researchers brought out time domain, frequency domain and time-frequency domain features to describe swallowing acoustic signals, duration of the acoustic signals (DAS, unit: s) and PI were the two most common characteristics. Prolonged swallowing acoustic signals could be evidence of swallowing difficulty, which had a high risk of aspiration/penetration. PI represents the point of highest displacement of the acoustic signal on an energy contour, which may be an indicator of pharyngeal contraction activity (J. A. Cichero & Murdoch, 2002).

VII. Clinical Application of Cervical Auscultation

1) Perspectives

CA is a non-invasive bedside assessment of swallowing performance among patients with pharyngeal swallowing disorders, which can reveal potential differences but not necessarily indicates the presence of dysphagia. The use of digital CA to monitor the swallowing performance has been proposed since the 1950s (C. S. C. Lear et al., 1965; Russell, 1956; Stott, 1953). Although VFSS and FEES assessments are two gold standard assessments to diagnose dysphagia, they are not always portable for bedside assessment due to their requirements for specialized staff as well as the high cost. The short duration of the study and strict protocols utilized during VESS/FEES assessments greatly differs from the conditions of a normal meal, which may affect results for generalizing into natural situations. Compared to VFSS and FEES, swallowing acoustic signals have already contained sufficient information that could be neatly classified by CA analysis (Borr et al., 2007). The recordable CA has advantages of cost-effectiveness, non-invasiveness, recordability and portability that can be applied in daily clinical practices. An acoustic monitoring of swallowing acoustic signals has potential to become a long-term and reproducible clinical procedure and differentiate dysphagic swallowing from normal healthy swallowing patterns.

Currently, much work has been done to develop more sensitive and clinically useful acoustic swallowing sound detection methods to further establish objective criteria and characterize the data obtained with the technique. The reliability and validity of CA have been improved with the support of objective features (Borr et al., 2007; Lazareck & Moussavi, 2004a; Leslie et al., 2004; E. S. Sazonov et al., 2010), especially when considering the coordination between swallowing and respiration (Joon Lee et al., 2011). Compared to other noninvasive and accessible assessments such as bedside Water-Swallow Testing (Brodsky et al., 2016; Jeri A.

Logemann et al., 1999) and Clinical Swallowing Examination (Youmans & Stierwalt, 2011), the digital CA has been reported to have relatively high reliability for screening aspiration.

2) Limitations

Researchers have been trying to replace the VFSS and FEES with CA for a few decades. In 2018, researchers first adapted the term 'High Resolution Cervical Auscultation (HRCA)' to describe a combined hardware-software system that merges electronic transducers (a microphone and/or accelerometer) with advanced data analysis methods such as machine learning (Rebrion et al., 2018).

However, CA technique has not yet been widely accepted in the clinics. There are three things challenging the acceptance of CA: 1) studies have not identified the source of swallowing sounds (S. L. Hamlet et al., 1992; Hammoudi et al., 2014; Leslie et al., 2007); 2) no research has determined both normal swallowing sound patterns and dysphagia swallowing patterns; 3) studies of CA cannot be compared because of a divergence for bolus volume, bolus consistency, and the anthropological effects on swallowing sounds (J. A. Cichero & Murdoch, 2002; Taniwaki et al., 2013; Youmans & Stierwalt, 2005, 2011). Researchers suggest that CA contains enough swallowing acoustic signals for analysis to screen potential aspiration/penetration but cannot be used as a diagnostic tool in clinical practice.

In the past few years, clinical practitioners have utilized the stethoscope to identify the swallowing sounds, which could result in inaccurately identifying the aspiration/penetration among patients with dysphagia when compared to the gold standard. Recently, experts in this field have confirmed that swallowing sounds carry sufficient acoustic evidence. Although some researchers agreed DAS and PI are most reliable features, they have not achieved a consensus on which parameters are crucially related to aspiration/penetration in dysphagia. They also have not identified objective features extracted from the acoustic signals in order to make an exact diagnosis (Borr et al., 2007). Kurosu et al. indicated that acoustic signals from HRCA would predict swallow kinematic events in the future not only for potential diagnosis but also clinical diet management of dysphagia.

There are also inconsistent findings regarding demographic and anthropologic, bolus viscous and volume effects on swallowing acoustic signals in previous investigations (J. A. Cichero & Murdoch, 2002; C. S. Lear et al., 1965). Meanwhile, in previous studies, investigators ignored the neck fat tissue and neck structure, which might affect the swallowing sound detection. Researchers arbitrarily excluded the subjects who had excessive fat in their necks due to swallowing sound detection regions could not easily be palpated. All these reasons mentioned above cut down the comparability among different articles. Thus, detection of the swallowing sound phases without VFSS is still a challenging task .

Secondly, researchers agreed in proposing an acoustic structure for deglutition, but more research is required to quantify the swallowing sound structure. In addition, it is agreed that the acoustic profile of a swallowing act is exclusively determined by physiologic properties of the swallowing tract. However, it has not yet been understood in detail which configurations cause and shape swallowing sounds. Considering each phase of pharyngeal swallowing sounds, researchers proposed the structure involving initial discrete sounds, bolus transit sounds, and final discrete sounds. Coordination of breath-swallowing sound, cough after swallowing, and voice after swallowing is also critical for safely swallowing and should be taken into account for improving sensitivity and specificity of CA.

Moreover, currently available literature is quite divergent for effects of bolus volume, bolus consistency, and characteristics of subjects on swallowing sounds. Articles about food viscosity addressed that more viscous foods or liquids can decrease the aspiration among patients with dysphagia, but researchers only provided the vague conclusion “more viscous” to clinical faculties. They have not quantified viscosity levels, let alone different standardization of food viscosity in various cultures and clinical settings (Steele et al., 2015; T. Takahashi et al., 2002). Complicated equipment such as a *rheometric device* can be utilized for testing dynamic viscoelasticity and viscosity measurements/compression and penetration tests of foods and liquids (T. Takahashi et al., 2002; Taniwaki et al., 2013), however it is not common for clinical application. Although thicker liquids could reduce the speed of boluses and minimize the risk of aspiration/penetration, no studies have determined safe liquid viscosity for patients with dysphagia based on their swallowing sound and/or vibration signals. Progression of different viscous liquid levels is also required for further research. But the lack of standardized terminology regarding food texture and drink thickness is still the major barrier to further research in the dysphagia field.

All of these reasons listed above may be the impediments of directly and widely applying research outcomes to diagnosis or guidance for clinical settings.

VIII. Conclusion

1) Knowledge Gap

Previous studies have reported the ‘external’ effects such as food viscosity (Jestrović et al., 2013), bolus volume (Inagaki et al., 2007; Johnsson et al., 1995) and head and neck positions (Oliver Amft & Troster, 2006), as well as ‘internal’ effects such as age, gender, and etc., could potentially influence swallowing sounds. Researchers have not provided a framework of normal swallowing sounds corresponding to the standardized food, which might help guide speech-language pathologists to identify the right time to progress the patients' liquid/food to a higher level.

Furthermore, different hospitals and health care settings in the same countries have their own adapted classification regarding liquid viscosity and food texture (J. A. Y. Cichero et al., 2013; Steele et al., 2015). In order to address this problem, International Dysphagia Diet Standardisation Initiative (IDDSI) developed globally standardized terminology and definitions for texture-modified foods and thickened liquids for individuals with dysphagia of all ages, in all care settings, and all cultures. In future studies of swallowing sounds, we suggest researchers apply worldwide-accepted food framework IDDSI to prepare food in order to increase comparability of articles between different countries or different study fields.

Youmans & Stierwalt suggested that the within-subjects DAS and PI variable were more suitable to distinguish swallowing sounds under various liquid/food conditions (Youmans & Stierwalt, 2011). But there is still no consensus among experts about which features extracted from swallowing sounds are the most important and the best parameters to identify aspiration. Researchers also pointed out the discoordination between breathing and swallowing to detect an aspiration event and/or predicted the risk of aspiration, which should be further investigated.

2) Purpose of This Study

The purpose of the present study was to identify differences of swallowing acoustic signals across multiple liquids and foods. Furthermore, this study would address the effects of neck circumference (NC) on swallowing sounds among different liquids and food. Our study prepared liquid/food based on IDDSI standards and structuralized the normal pattern of swallowing sounds across various viscous liquids and textured foods in healthy participants for future comparison with patients who have swallowing disorders.

3) Specific Aims and Hypotheses of This Study

Aim 1: To address the effects of different viscous foods or liquids on swallowing sounds across IDDSI. This aimed to identify differences in the duration of acoustic signals and peak intensity of swallowing sounds generated by various viscous foods and liquids through the pharynx among healthy subjects. We hypothesized that different textures of foods and the viscosity of liquids would influence the swallowing sounds. The more viscous liquids and more hardness of foods, the lower PI and the longer DAS of the swallowing sounds were.

Aim 2: To illustrate the effects of NC differences on swallowing sounds across IDDSI. This aimed to identify differences in the duration of acoustic signals and peak intensity of swallowing sounds generated by health people with various NC through the pharynx across 8-level liquids and foods. We hypothesized that different neck circumference would affect the swallowing sounds. The bigger neck circumference, the lower PI and the shorter DAS of the swallowing sounds were.

Chapter 2 THE EFFECTS OF DIFFERENT VISCOUS LIQUID AND SOLID FOOD ON SWALLOWING SPEEDS AND SOUNDS AMONG HEALTHY ADULTS

I. Abstract

Background: Cervical auscultation (CA) is a portable and non-invasive technique to detect swallowing acoustic signals through stethoscope or recordable equipment such as microphone or accelerometry. Digital cervical auscultation has been proposed since 1950s for screening aspiration among patients with dysphagia. Researchers have investigated the 'external' effects such as food viscosity (Jestrović et al., 2013), bolus volume (Inagaki et al., 2007; Johnsson et al., 1995) and head and neck positions (Oliver Amft & Troster, 2006), while the influences of standardized liquid viscosity and food texture on swallowing sounds have not been fully understood due to lacking uniform standardization of bolus preparation. Therefore, this study investigated the effects of 8-level liquids and foods on swallowing sound features based on the International Dysphagia Diet Standardisation Initiative (IDDSI).

Methods: We collected swallowing sounds from 30 healthy subjects ranging in age from 19-60 years old and self-reporting no history of swallowing disorders. Each participant swallowed different consistency liquids and foods with their head-trunk in neutral position. The throat microphone recorded three trials of swallowing each food and liquid at the cricoid cartilage level. All swallowing sound waves were recorded by RavenPro Software and manually identified first visually and then auditorily.

Results: Our results showed that thicker fluids and more solid foods had longer acoustic signals. We found significant difference of duration of acoustic signals (DAS) across different liquids and foods except between swallowing thin liquid (Level 0) and slightly thick liquid (Level 1), and pureed (Level 4) and minced & moist (Level 5). Our results also demonstrated that liquid viscosity significantly impacted the peak intensity (PI) of swallowing sounds. Differences in PI were noted in various liquids $[F\ (3,90) = 5.633; p = 0.001; \text{partial } \eta_2 = 34.400]$, especially between thin (Level 0) and slightly thick liquid (Level 1) $(p = 0.001)$, thin (Level 0) and moderately thick liquid (Level 3) $(p = 0.001)$, and mildly thick (Level 2) and moderately thick liquid (Level 3) $(p = 0.001)$. However, no significant difference was present in PI among different textures of food.

Discussion and Conclusions: As an initial exploration of digital CA across four levels of different liquid viscosity and four levels of food texture according to IDDSI, we established the baseline findings from healthy adults for future comparisons with other study populations or other various consistent liquids/foods. According to these results, we concluded influences of varied fluid consistency and food texture on swallowing sounds. However, more investigations should explore whether changing viscosity levels could either continuously or discretely disturb the swallowing acoustic signals. In this study, we only captured DAS and PI to describe the acoustic features of swallowing sounds. Future research could adapt more physiology-related swallowing acoustic parameters to further describe swallowing acoustic signals. We concluded that acoustic swallowing monitoring could be utilized to develop long-term swallowing behavior detection and clinical management regarding the screening of dysphagia.

Keywords: Swallowing, Swallowing sounds, Viscosity, Signal characteristics

II. Introduction

Difficulty swallowing, referred to as dysphagia, has different symptoms, such as the feeling of food being stuck in the throat, the difficulty in placing and controlling food in the mouth, and the cough after swallowing food Importantly, these symptoms are usually observed in neurological patients, such as patients with stroke or Parkinson’s disease (Roy et al., 2007). A study emphasizes that up to 50% of patients suffer from dysphagia after the first week of a stroke

(González-Fernández et al., 2013). The prevalence of dysphagia is also higher among elderly populations especially among those in nursing homes (Marik & Kaplan, 2003) Therefore, it is crucial to perform early screens of swallowing behaviors in order to prevent patients from developing serious medical issues such as malnutrition, dehydration, or pneumonia (Dziewas et al., 2017).

The gold-standard methods for evaluating swallowing behaviors are a fiberoptic endoscope evaluation of swallowing (FEES) and a videofluoroscopy swallowing study (VFSS) However, these methods are expensive and invasive for patients. VFSS also involves radiation, which may have negative consequences for the health of the patient. Therefore, cervical auscultation (CA) as one of the non-invasive and inexpensive screening methods has been used to investigate swallowing performance since the 1950s (Russell, 1956). The components of CA for evaluating swallowing behaviors are electronic acoustic and vibratory detectors, such as a microphone or an accelerometer, which are placed on the neck of healthy subjects or patients with dysphagia in the region of the larynx to listen or record the swallowing acoustic or vibration signals (Lazareck et al, 2004, Dudik et al, 2015). Furthermore, in order to understand which component is more important than the other (swallowing sound or swallowing vibration), a study investigates 881 swallows from 72 patients with dysphagia by drinking thin liquid (Varibar Thin Liquid with < 5 cp viscosity), nectar-thick liquid (Varibar Nectar with ~ 300 cp viscosity), and a semi-solid pudding (Varibar Pudding with ~ 5000 co viscosity). It concludes that not only the swallowing sound but also the swallowing vibration are crucial because each component represents unique characteristics of swallowing behavior (Movahedi et al., 2017).

He et al. further investigated the relationship between hyoid bone movement and vibration acoustic signal features and indicated anterior-posterior signals from accelerometers became more predictable and organized in swallowing with greater vertical hyoid displacement (He et al., 2019). The duration of swallowing acoustic signals indicates how fast the food/liquid can be consumed. The peak intensity (PI) of swallowing vibration indicates how much energy can be consumed to swallow the liquids/foods (Dudik et al., 2018). However, the above-mentioned studies primarily use liquids as the experimental component. Does swallowing different kinds of solid food alter the duration of swallowing acoustic signals and the PI of swallowing vibration? To date, no investigation of the swallowing acoustics of healthy adults has included food texture.

To fill this knowledge gap, the purpose of this chapter is to identify swallowing sounds among healthy subjects across different viscous foods and liquids. We recorded and measured differences in swallowing acoustic signals by asking participants to swallow eight different types of liquids/foods based on the International Dysphagia Diet Standardisation Initiative (IDDSI). We hypothesized that as the viscosity of liquid/food increased, the duration of swallowing acoustic (DAS) signals and the PI of the swallowing sounds would increase.

III. Methodology

1) Subject Recruitment

Thirty healthy volunteers were enrolled from a local Medical Center in Omaha, NE, and its neighborhoods on a voluntary basis. The inclusion criteria included: 1) age ranging from 19 to 60 years old, 2) no previous history of swallowing, respiratory, speech, or neurologic problems, 3) no major surgery of the head and neck that would impact their swallowing function, 4) currently no swallowing disorders, 5) no cervical spondylosis or having pain or diseases in the throat for example tonsil inflammation. Exclusion criteria: 1) the presence of a prosthesis in the neck (e.g., tracheostomy, vocal cord prosthesis), which may influence the quality of swallowing acoustic signals. This study was approved by the Ethics Committee of the local Medical Center (IRB# 782-16-EP), and informed consent was obtained from all subjects prior to the experiment.

2) Study Design

Liquid/Food Samples

Four kinds of viscous liquids and four kinds of food textures (a pureed solid, and minced & moist solid, known as liquid-solid mixtures, as well as a soft & bite-size solid and an easy to chew/regular solid food, known as solids) were prepared for participants according to the IDDSI (J. A. Y. Cichero et al., 2013), which was indicated in the Figure 2-1. Food samples used in the present study were commercially available and included Nestle ThickenUp, distilled water, rice, bananas, and crackers. In our pilot study, participants reported the liquids and odorless. We added 2-grams of sugar into each liquid sample to improve the taste. The temperature of foods and liquids would be at room temperature and recorded prior to sound collection. Please see Table 2-1 for Liquid/food preparation.

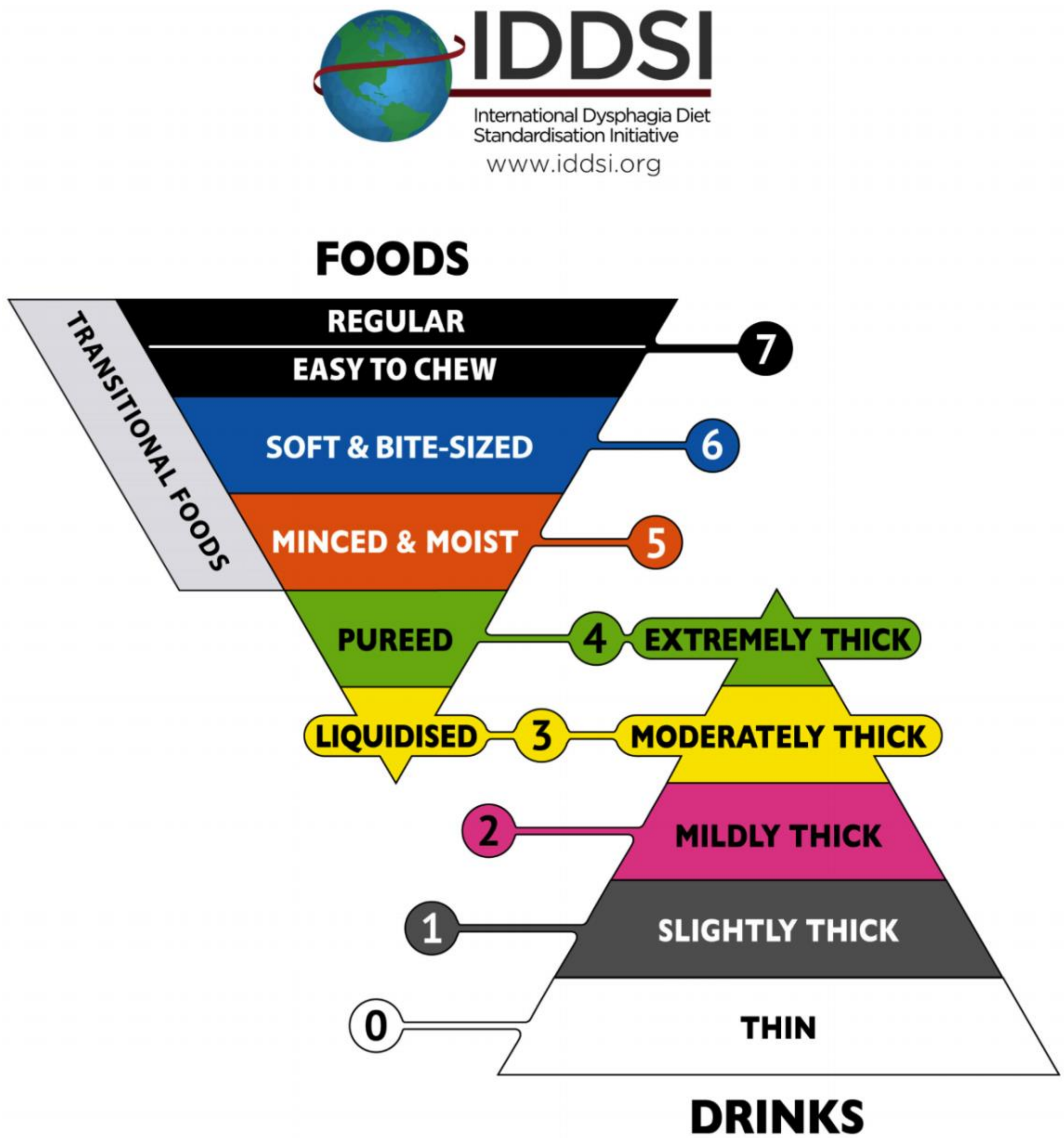

Figure 2-1 Liquid and food preparation based on the International Dysphagia Diet Standardisation Initiative, which is retrieved from https://iddsi.org/framework/

Table 2-1 Liquid/food preparation based on the International Dysphagia Diet Standardisation Initiative (IDDSI)

IDDSI Level	Preparation
Level 0 Thin	0 spoon Thicken-up powder: 4 fl oz de-ionized water
Level 1 Slightly thick	1 spoon Thicken-up powder: 4 fl oz de-ionized water
Level 2 Mildly thick	2 spoon Thicken-up powder: 4 fl oz de-ionized water
Level 3 Moderately thick	4 spoon Thicken-up powder: 4 fl oz de-ionized water
Level 4 Pureed	Applesauce (Mott's applesauce original, US)
Level 5 Minced & Moist	4 mm gruel rice
Level 6 Soft & Bite-sized	15 mm thick bananas
Level 7 Easy to chew/Regular	15 mm thick crackers (Keebler Club Original Crackers, ®, ™, © 2018 Kellogg NA Co.)

Procedure

First, we instructed the participant to be seated in a straight chair, with his/her head and trunk in a neutral position to standardize the same recording procedure. Next, we cleaned the participant's cervical region by using alcohol wipes and secured an elastic band of the microphone to the participant's neck. Third, we used a throat microphone headset (iASUS NT3-R, CA, USA) to record each swallowing trial of all participants. We placed the equipment at the level of the cricoid cartilage at the anterior neck (Figure 2-2), where the average magnitude of the SNR was the highest (K. Takahashi et al., 1994).

Swallowing trials were completed following installation and calibration of above identified equipment. Participants were provided four different viscous liquids (thin, slightly thick, mildly thick, and moderately thick liquid), and then four different textures of solids (pureed, minced & moist, soft & bite-sized, easy to chew/regular) (Table 1). All liquids and solids were provided in the same sequence to all participants. In each trial, three swallowing sounds were recorded. Each trial was a measured to swallow a specific bolus size. At least a 2-minute break was provided between each trial. The swallowing sound detected by the microphone was saved in a password protected laptop (Surface Pro3, Microsoft Corporation, Redmond, WA) using the RavenPro1.5.0 (Bioacoustics Research Program, 2014). The data sampling rate of 44.1 kHz and resolution of 16 Bit was recorded as a monotype in the computer. The duration of the acoustic signals (DAS, unit: second) was defined as the time that elapsed from the beginning to the cessation of the signal. The start and the end of the sound of swallowing were identified by listening to the sound and observing the spectrogram. Peak intensity (PI, unit: dB) represented the point of highest displacement of the acoustic signal on an energy contour.

Figure 2-2 The throat microphone is placed at the level of the cricoid cartilage in the anterolateral neck.

Data Analysis

The resulting signals were bandpass filtered from 30 to 3000 Hz in the MATLAB R2015a (MathWorks, Natick, MA). Acoustic signal selection and variable measurements were also completed in the RavenPro1.5.0 software (Figure 2-3). We manually identified each swallowing sound by first visually identifying the sound waveform and spectrum display, and then by identifying auditorily the swallowing sound by playing them back and forth several times in the software. When multiple swallowing events occurred after a single eating behavior, only the first swallowing sound was considered in the series.

Descriptive statistics were expressed as mean ± standard deviation (M ± SD) and the range of liquid and food swallowing acoustic features (Table 2-2). One-way repeated-measures ANOVA was performed to evaluate differences among various viscous liquids and textures of food. Bonferroni follow-up pairwise comparison measurements were conducted. SPSS 21 (IBM Corp. 2012, SPSS Inc., Chicago, IL) was used for all analyses. An alpha level of 0.05 was set for all analyses.

Table 2-2 The subjects' characteristics and liquid and swallowing acoustic features (M ± SD).

		Total (n=30)	Male (n=15)	Female (n=15)
		Mean ± Std. Deviation		
Age		34.87 ± 11.54	34.87 ± 2.99	34.87 ± 3.08
BMI (kg/m2)		24.23 ± 4.18	25.84 ± 0.57	22.61 ± 1.31
Neck circumference (cm)		37.32 ± 4.48	40.96 ± 0.65	33.70 ± 0.68
Liquid	DAS (s)	0.947 ± 0.247	0.89 ± 0.02	1.01 ± 0.04
	PI (dB)	50.697 ± 1.505	50.69 ± 0.19	50.88 ± 0.18
Food	DAS (s)	1.015 ± 0.325	0.94 ± 0.04	1.06 ± 0.03
	PI (dB)	50.542 ± 1.452	50.40 ± 0.19	50.61 ± 0.20

DAS = Duration of swallowing acoustic signals, in second; PI= Peak intensity, in dB.

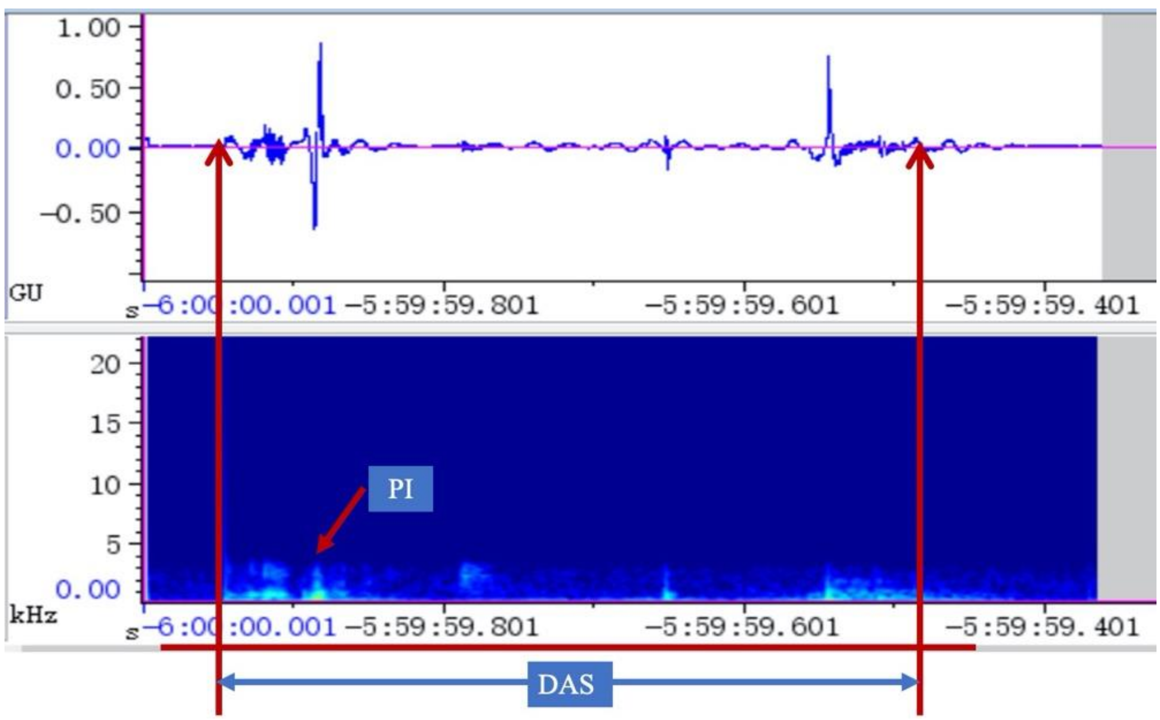

Figure 2-3 Example of acoustic recording analyzed using RavenPro software. Two bursts can be identified. The starting point is the first of the signals and the end point is identified when the signals return to the baseline. Duration of acoustic signal = DAS, Peak intensity = PI

IV. Results

There were significant differences in DAS respectfully when different viscous liquids *[F (3,90) = 14.056; p = 0.001; partial η2 = 1.395]* or different textures of food were taken *[F (3, 90) = 12.194; p = 0.001; partial η2 = 4.016]*. Bonferroni follow-up pairwise comparison of measurements was significantly different except between thin (Level 0) and slightly thick liquids (Level 1), pureed (Level 4) and minced & moist (Level 5) (Figure 2-4).

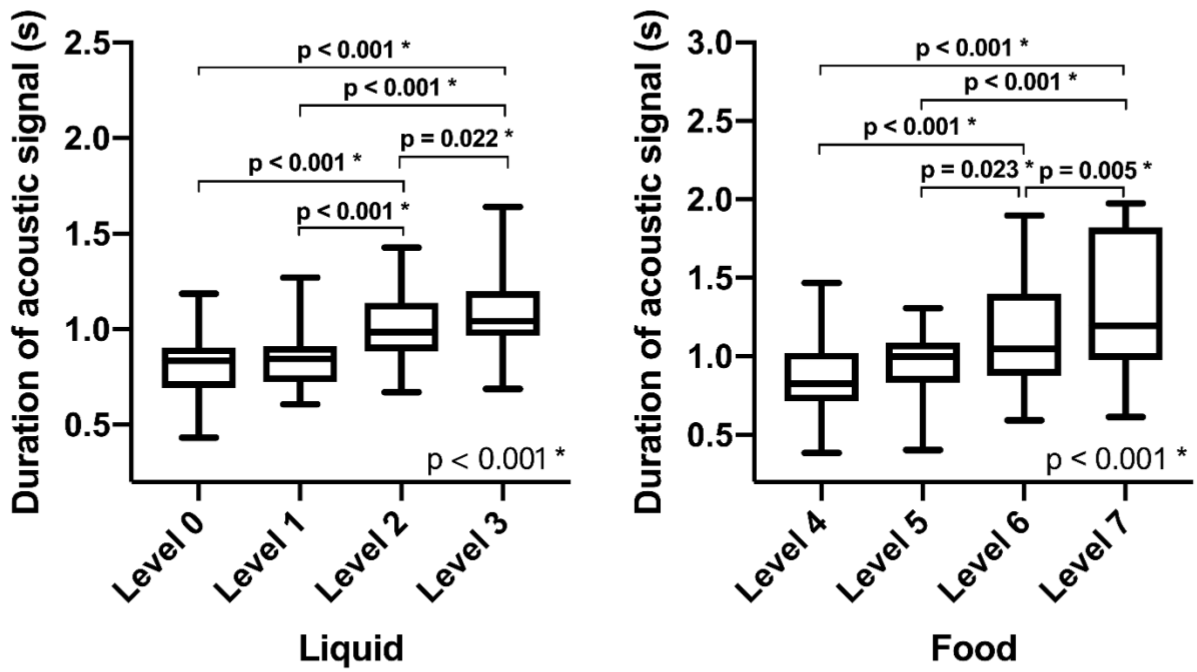

Figure 2-4 Different duration of acoustic signals (DAS) among four levels of liquids and four levels of foods

Differences in PI were also noted in various liquids PI *[F (3,90) = 5.633; p = 0.001; partial η2 =34.400]*, especially between thin (Level 0) and slightly thick liquid (Level 1) *(p = 0.001)*, thin (Level 0) and moderately thick liquid (Level 3) *(p = 0.001)*, and mildly thick (Level 2) and moderately thick liquid (Level 3) *(p = 0.001)*. There were no significant differences in PI among different textures of food (Figure 2-5).

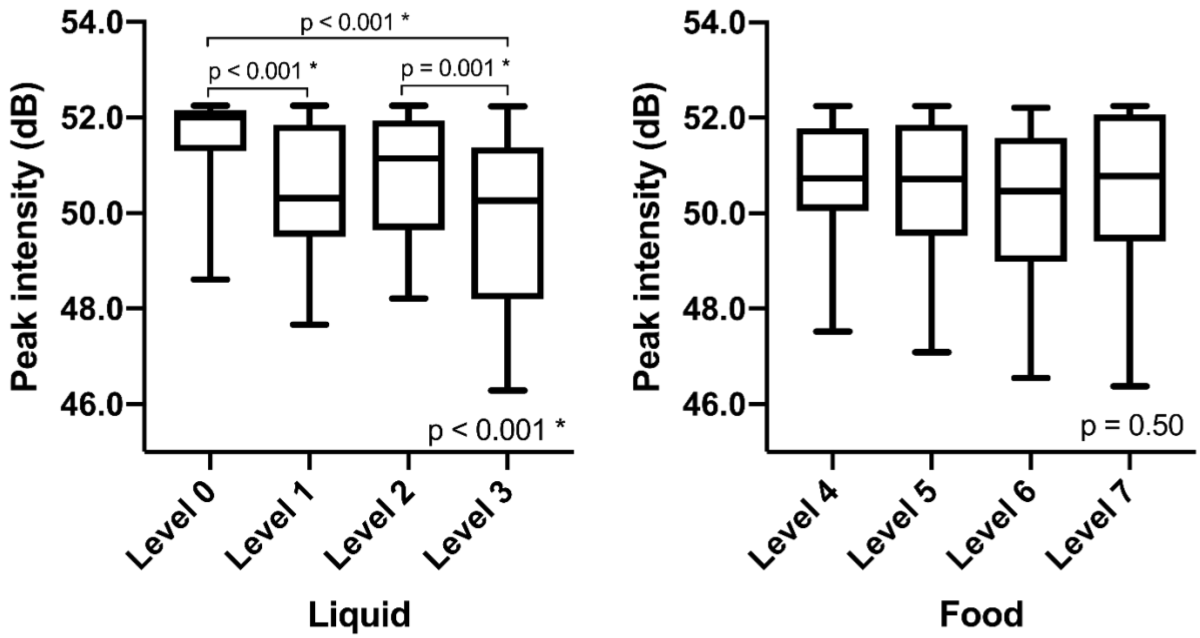

Figure 2-5 Different peak intensity (PI) among four levels of liquids and four levels of foods

V. Discussion

The purpose of the study was to fill the knowledge gap of different viscous foods and liquids based on international standardization. Our results showed as the viscosity of liquid and the hardness of food increased, the duration of swallowing acoustic signals had a tendency to increase, while the inconsistent change of PI between liquid and food was noted. In the current study, CA was utilized to assess swallowing behaviors when drinking four different liquids and eating four different solid foods. The results confirmed previous studies that higher viscous liquid needed longer duration to swallow and less pharyngeal movement (Youmans & Stierwalt, 2011). Longer duration of swallowing sounds was found with increasing hardness of food. Unexpectedly, higher solid food texture did not affect the pharyngeal displacement, which was in line with a longer duration but not amplitude of suprahyoid muscle activity based on electromyographic activity (Tsukada et al., 2009).

Several speculations have been made to identify the physiological causes of swallowing sounds. One theory, known as the cardiac analogy hypothesis, links the physiological cause of swallowing sounds and heart sounds. There is a speculation that the generation of swallowing sounds is similar to the generation of heart sounds. Based on the existence of several valves and pumps in the pharynx, it has analogous functions to the valves and pumps in the heart (J. A. Cichero & Murdoch, 1998). Researchers have suggested that the DAS represented the duration of closing and reopening epiglottis movement, whereas PI only indicated the displacement of the pharyngeal movement (J. A. Cichero & Murdoch, 2002). As a result, the DAS can be more accurate and sensitive to describe whole swallowing performance.

This study served as an initial exploration of CA across eight levels of different liquid viscosity and food texture according to IDDSI, and established the baseline finding from healthy adults for future comparisons with other study populations.

Duration of Swallowing Acoustic Signals (DAS)

We found that as liquid viscosity increased, the duration of swallowing events increased, which were supported by previous studies (Youmans & Stierwalt, 2011). It is possible that thickened liquids can slow down the velocity of liquids through the upper esophageal sphincter (UES), allow more reaction time for airway closure, and rely on gravity instead of muscle contraction activities, which potentially eliminate risks of aspiration/penetration (Dooley et al., 1988; Youmans & Stierwalt, 2005). However, there were no statistical differences in DAS between thin and slightly thick liquids. Although the human esophagus is very sensitive to changes in bolus viscosity (R. O. Dantas et al., 1990), the viscosity of water and slightly thick liquid might be too similar for a person to respond differently and reflect the significant alternations in swallowing duration. On the contrary, Youmans et al. found significant differences between thin and nectar-like liquids, but medium effect size was observed in this previous study (Youmans & Stierwalt, 2011). Unlike the liquid/food preparation in the previous study, we attempted to examine the effects of 8-level liquid and food consistency on swallowing acoustic signals based on IDDSI. Different liquid and food preparations might contribute to the discrepant findings between our study and previous study, which was no significant duration of swallowing between thin and slightly thick liquids in this study. Significant differences were found across other liquids, which were supported by previous studies (Youmans & Stierwalt, 2011).

In addition, our results found that as food hardness and dryness increased, the duration of swallowing events increased. Studies reported harder and dryer bolus required more movement of the pharynx compared to soft solid food (Tsukada et al., 2009). While these changes in DAS were not reflected in swallowing pureed solids (Level 4) and minced & moist solids (Level 5), differences were only noted among other comparisons in food texture (Figure 10). In fact, there was a substantial difference in food texture between swallowing pureed solids (Level 4) and minced & moist solids (Level 5) also known as liquid-solid mixtures and soft & bite-size solids (Level 6) referred to as solid food. Therefore, it was more likely for solid food (Level 6) to form a cohesive bolus before swallowing than liquid-solid mixtures (Level 4 and Level 5). The liquid-solid mixture could be challenging as it has two swallowing phases (liquid and solid phase). In our study, we only considered the first swallowing sounds when multiple swallowing events occurred after a single eating behavior. Therefore, before chewed-dependent food portion arrived at the seal of tongue-palate, the liquid portion is already swallowed.

In the current study, we only captured the first swallowing sound during a single swallowing performance, which might indicate that pureed solids and minced & moist solids were swallowed in the “liquid” phase. We inferred that swallowing behavior had already been triggered by the “liquid” portion of the mixture before the whole cohesive bolus of pureed solids and minced & moist solids arrived at the hypopharynx. As a result, there were no differences of swallowing duration between pureed solids and minced & moist solids, which were considered as ‘liquid’ swallowing pattern. However, for masticating solid food (soft & bite-size solids and easy to chew/regular solids), our results supported that even though different solid foods tended to form a bolus, their bolus still influenced the duration of swallowing sounds. More research is warranted to investigate the association between solid food texture and swallowing durations.

Peak Intensity

Cichero et al. suggested that PI of swallowing sounds was an indicator of pharyngeal contraction movement (J. A. Cichero & Murdoch, 2002). We found that differences in PI were only in various viscous liquids intake especially between Level 0 (thin) and Level 1 (slightly thick), Level 0 (thin) and Level 3 (moderately thick), level 2 (mildly thick) and level 3 (moderately thick) (Figure 11). The results showed that thinner liquids tended to produce higher intensity than more viscous liquids. Similar findings were also observed in other studies (Taniwaki et al., 2013; Youmans & Stierwalt, 2011). Youmans & Stierwalt reported thinner liquids produced higher intensity than more viscous liquids (Youmans & Stierwalt, 2011). A similar study result revealed that paste swallowing produced lower amplitude than liquid swallows (Taniwaki et al., 2013). Taniwaki et al. also found larger root mean square (RMS) amplitude in water swallowing than yogurt or konjac jelly (Taniwaki et al., 2013). Higher viscous liquids relied less on muscular driving force and more on gravity to move through the pharynx, which likely reduced the intensity of the swallowing acoustic signals (Saitoh et al., 2007).

Our study showed difference in PI between Level 0 (thin) and Level 1 (slightly thick), which seemed to contradict the result that no significant differences of DAS was found between them. It could be due to the different measurable characteristics between PI and DAS. Previous studies described DAS as a relatively reliable feature of swallowing sounds, which showed the total swallowing process included elevation of the hyoid bone, liquid transport, and depression of the hyoid bone (Yagi et al., 2016). Meanwhile, PI could indicate the amount of pharyngeal displacement during swallowing (J. A. Cichero & Murdoch, 2002). Since there were no differences in swallowing durations between Level 0 (thin) and Level 1 (slightly thick), we concluded they were the same ‘consistency’ liquids. However, differences in PI were observed between thin liquids and slightly thick liquids. It could be explained that there was a learning effect occurring in the order of liquid swallowed. Participants demonstrated a ‘learning process’ to swallow the ‘thin’ and ‘slightly thick’ liquids since they were considered the same ‘viscosity’ level. After the adaptation process of swallowing thin liquids, the PI of swallowing sounds decreased while swallowing slightly thick liquids. As a result, it takes less pharyngeal movement for subjects to swallow the ‘slightly thick’ liquids. Thus, the PI of swallowing sounds for slightly thick liquids may have decreased due to the learning effects.

Increased DAS in mildly thick liquid swallowing sounds led us to believe there was a significant viscosity change between slight thick liquids and mildly thick liquids, however, we found no significant difference of PI between them. Possibly, after learning the adaption process of swallowing thin liquids for more than three times, subjects were able to utilize less pharyngeal contraction, which may have led to a similar amount of the pharyngeal displacement to swallow thick liquids.

We did not find any differences in PI across diverse textures of food. Even though we applied four different textures of food, food requires fully chewing to make similar size boluses before initiating the pharyngeal movement of swallowing process. It was reasonable that there were no differences in PI, which reflected the displacement of the pharynx. However, the DAS showed the differences among various textures of food since duration of total swallowing reflected the total duration of epiglottis closing and reopening as well as the speed of bolus transport though the UES.

Nonetheless, there is still a need for additional research in swallowing acoustics. Researchers have proved thicker liquids could reduce the speed of boluses to minimize the risk of aspiration/penetration, and quite understood the characteristics of swallowing acoustic signals, however, none of the studies have determined safe liquid viscosity, liquid-food mixtures and food texture for patients with dysphagia based on their swallowing sounds and vibration signals. The progression of different viscous liquid levels in dysphagic patients is an area that requires for further research regarding long-term feeding care. In addition, the currently available literature cannot agree on the effects of bolus volume, bolus consistency, and characteristics of subjects on swallowing sounds. Studies regarding food viscosity found that more viscous foods or liquids can decrease aspiration among patients with dysphagia, but researchers only provided the vague conclusion “more viscous” to clinical practitioners. They rarely used viscous liquids and foods based on standardization of food viscosity let alone in various cultures and clinical settings (J. A. Y. Cichero et al., 2013). Santamato et al. suggested that consistency of methodology (e.g. IDDSI), characteristics under investigation, or terminology was required to achieve high generalization and validity of CA. They pointed out that the discrepancy between their results (Santamato et al., 2009) and Youmans & Stierwalt et al. (Youmans & Stierwalt, 2011) were caused by different standardization of food. Complicated equipment such as a rheometric device has also been considered to be utilized for testing dynamic viscoelasticity and viscosity measurements/compression and penetration tests of foods and liquids (T. Takahashi et al., 2002). However, those devices are not common for clinical application. As a result, the lack of standardized terminology regarding food texture and liquid thickness are still the major barriers to further expanding the swallowing research. Our study serves as a pilot study to tackle those barriers and explore the effect of food/liquid samples prepared according to the IDDSI on swallowing sounds for future comparison (J. A. Y. Cichero et al., 2013). However, there is a lack of evidence that changing viscosity levels could either continuously or discretely disturb the swallowing acoustic signals.

Furthermore, based on our results and previous studies, DAS and PI variables as two main features of swallowing acoustic signals were suitable to distinguish swallowing sounds under various liquid/food conditions (J. A. Cichero & Murdoch, 2002; Youmans & Stierwalt, 2011). However, there is still no consensus among experts which features extracted from swallowing sounds are the most important and the best parameters to identify aspiration. Additional exploration regarding other features should narrow the path to accurately describe swallowing acoustics. Further investigation will also determine if these differences are also found in people with dysphagia.

VI. Conclusion

Researchers have been trying to replace the VFSS and FEES with CA for a few decades. However, CA has not yet widely been accepted in clinics. There are three things challenges of the acceptance of CA: 1) studies have not fully identified the source of swallowing sounds (Leslie et al., 2007); 2) no research has determined both normal swallowing sound patterns and dysphagia swallowing patterns; 3) studies of CA cannot be compared because of a divergence for bolus volume, bolus consistency, and anthropological effects on swallowing sounds (J. A. Y. Cichero et al., 2013; Santamato et al., 2009).

Our preliminary contribution to this field is a systematic investigation of swallowing sounds across 8-level liquids and foods based on IDDSI. We find swallowing acoustic signal features among healthy adults are different among various viscous liquids and foods. Increased DAS is associated with increased consistency of liquids and increased hardness of food. Increased viscosity of liquids is also related to decreased PI. It might indicate that acoustic swallowing monitoring can be used for clinical screening of dysphagia, which will provide a basis for the development of long-term swallowing behavior detection and clinical management.

Chapter 3 EFFECTS OF NECK CIRCUMFERENCE ON SWALLOWING ACOUSTIC SIGNALS ACROSS DIFFERENT VISCOUS LIQUIDS AND FOOD INTAKE

I. Abstract

Background The benefits of cervical auscultation (CA) for swallowing performance detection has been explored. However, conflicting results regarding the effects of gender and age on swallowing acoustic signals have impeded the development of CA. In order to solve this contradiction, researchers have suggested to investigating the influences of neck structures rather than separately considering gender and age. Thus, this study investigated the influence of NC on swallowing acoustic signals during various viscous liquids/foods intake.

Methods Thirty healthy individuals participated in this study, ranging in age from 21 to 58 years old. Each participant wore a throat microphone at the level of the cricoid cartilage of at the anterior neck and recorded eight conditions of swallowing sounds. Participants swallowed four different viscous liquids (water, nectar-like, honey-like, pudding-like liquid) and four different textures of foods (applesauce, gruel rice, banana, and crackers). Swallowing acoustic features, including the duration of acoustic signals (DAS) and the peak intensity (PI), were extracted from the recordings.

Results DAS were different across the four liquids *($p = 0.016$)* and the four textures of foods *($p < 0.001$)*. Differences of PI were also found across various viscous liquids *($p < 0.0001$)*. Individuals with larger NC exhibited shorter DAS in swallowing pudding *($r = -0.46, p < 0.001$)* and applesauce *($r = -0.29, p = 0.02$)*. Larger NC had lower PI while swallowing honey *($r = -0.66, p < 0.001$)* and pudding *($r = 0.-49, p < 0.001$)*. Interestingly, swallowing acoustic signals during food intake were not affected by NC.

Discussions and Conclusions Both liquid viscosity and food texture had effects on swallowing acoustic signals. We noted that influences of NC were more prominent on swallowing acoustic signals for thickened liquids intake. Swallowing more viscous liquids tended to produce more intense signals. The thickened liquids were mainly relied on the gravity to move through the throat rather than depending on pharyngeal musculature movement. Relatively big NC produced more intense signals, which might be due to the alteration of the resonatory characteristics in the vocal tract. Future investigations of CA could account for NC to further understand the effects of neck structures on swallowing acoustic signals rather than separately considering age and gender.

Keywords: Cervical auscultation, Swallowing acoustic signals, Neck circumference, Liquid/Food viscosity

II. Introduction

Cervical auscultation (CA) is a non-invasive bedside assessment of swallowing performance among patients with pharyngeal swallowing disorders. A digital CA assessment utilizes a microphone or an accelerometer to record swallowing acoustic signals, which was first introduced by Stott and Russell in the 1950s (Russell, 1956; Stott, 1953). However, most health professionals prefer to evaluate swallowing efficiency among patients with dysphagia using stethoscopes (Nozue et al., 2017). Some researchers and health professionals have suggested utilizing CA as a substitute method of videofluoroscopy/video fluorography swallowing study and fiberoptic endoscope evaluation of swallowing performance. However, CA is still not widely accepted because the sources of normal swallowing sounds are poorly identified, thus a standardized comparable model is not available (S. L. Hamlet et al., 1992; Hammoudi et al., 2014; Leslie et al., 2007).

A number of studies have evaluated impacts of different factors on swallowing acoustics. However, inconsistent results were found regarding effects of age and gender on swallowing acoustic signals. Researchers agreed as age increases, duration of swallowing acoustic signals

(DAS) increases (J. A. Cichero & Murdoch, 2002; Youmans & Stierwalt, 2011). However, conflicting findings of peak intensity (PI), peak frequencies (PF) and duration to peak intensity (DPI) with respect to effects of age were noted. Youmans et al. found that elderly individuals produced higher PF than younger (Youmans & Stierwalt, 2011). The similar tendency was also found by Santomato et al. (Santamato et al., 2009). However, Dudik et al. reported PF did not show any notable trend with aspect of age (Dudik et al., 2015a). Cichero et al. and Santamato et al. both reported there was no difference of sound PI across different ages (J. A. Cichero & Murdoch, 2002; Santamato et al., 2009). However, Youmans et al. pointed out PI decreased with increased age (Youmans & Stierwalt, 2005). In contrast, his other research found that elderly individuals produced higher PI than younger individuals (Youmans & Stierwalt, 2011).

Gender impact on the DAS, PF and PI of swallowing acoustic signals also has been questioned. Physiologically, a relatively small pharynx in females should require a longer duration of upper esophagus sphincter (UES) to accommodate a bolus of equivalent size compared to males (Boiron et al., 1997; Roberto Oliveira Dantas et al., 2009). In contrast, several researchers reported that the DAS was not different between gender (Hammoudi et al., 2014; Youmans & Stierwalt, 2005, 2011), while Sejdic et al. reported males had a significantly longer DAS than females in both dry and wet swallows (E. Sejdić et al., 2009). The effect of gender also has little agreement on PF. Dudik et al. reported male participants exhibited greater frequency compared to females both in the chin-tuck and head-neutral positions (Dudik et al., 2015a, 2015b). However, few variations in PF regarding gender effect also have been reported (Santamato et al., 2009). Contradicting results were not only noted in DAS and PF, but the results in PI. Researchers reported males produced higher PI compared to females in the same age group (J. A. Cichero & Murdoch, 2002; Lebel et al., 1990; Youmans & Stierwalt, 2011). On the contrary, Cichero et al. and Santamato et al. reported the gender had little impact on swallowing sound intensity and was stable at 43dB across gender (J. A. Cichero & Murdoch, 2002; Santamato et al., 2009).

With the inconsistent findings in the literature regarding age and gender-related effects on CA, they failed to provide necessary information for CA accuracy and accessibility improvements. An innovative suggestion for identifying CA influential factors was taking the neck circumference (NC) and neck subcutaneous tissue into account. If proved, it can be systematically applied to the general population and replace previous conflicting contributing factors such as age and gender. However, differences of NC-related neck subcutaneous adipose tissues in swallowing have not been routinely investigated in the literature.

To address this knowledge gap, we measured differences in swallowing acoustic signals among participants with different NC, by consuming eight different types of liquids/foods based on the International Dysphagia Diet Standardisation Initiative (IDDSI). We hypothesized those who with larger NCs would attenuate the swallowing sound amplitude and change the duration of swallowing acoustic signals.

III. Methodology

1) Subject Recruitment

Thirty healthy volunteers were enrolled from the local Medical Center and its neighborhoods on a voluntary basis. The inclusion criteria included: 1) age ranging from 19 to 60 years old, 2) no previous history of swallowing, respiratory, speech, or neurologic problems, 3) no major surgery of the head and neck that would impact their swallowing function, 4) currently no swallowing disorders, 5) no cervical spondylosis or having pain or diseases in the throat for example tonsil inflammation. Exclusion criteria: 1) the presence of a prosthesis in the neck (e.g., tracheostomy, vocal cord prosthesis), which may influence the quality of swallowing acoustic signals. This study was approved by the Ethics Committee of the local Medical Center (IRB #782-16-EP), and informed consent was obtained from all subjects prior to the experiment. The clinical trial number is NCT03024333.

2) Study Design

Neck Circumference

Clinical practice and scientific research have proven that NC can serve as an indicator of upper-body adipose tissue distribution and has been generally used in prediction of cardiometabolic diseases, intubation difficulties, and obstructive sleep apnea (Ben-Noun et al., 2001; Davies & others, 1990; Gonzalez et al., 2008). Therefore, we chose NC as an indicator of upper body adipose tissues in our study to quantitatively approach the effect of neck fat on the swallowing performance by exploiting CA (Ben-Noun et al., 2001; Li et al., 2014).

Liquid/Food Samples

We prepared four kinds of various viscous liquids and four kinds of different textures of food according to the IDDSI (J. A. Y. Cichero et al., 2013). Food samples used in this study were commercially available and included Nestle ThickenUp, distilled water, rice, bananas, and crackers. In our pilot study, participants reported the liquids tasted tasteless and odorless. We added 2-grams of sugar into each liquid sample to improve the taste.

Liquid/Food Preparation

According to the IDDSI guidelines, we decided to use the following powder-liquid ratio to prepare the different viscous liquids and chose four different textures of foods (Table 3-1). All liquid and food samples were stored at room temperature (approximately 25℃) prior to the swallowing process.

Table 3-1 Liquid/food preparation based on the International Dysphagia Diet Standardisation Initiative (IDDSI)

IDDSI Level	Preparation
Level 0 Thin	0 spoon Thicken-up powder: 4 fl oz de-ionized water
Level 1 Slightly thick	1 spoon Thicken-up powder: 4 fl oz de-ionized water
Level 2 Mildly thick	2 spoon Thicken-up powder: 4 fl oz de-ionized water
Level 3 Moderately thick	4 spoon Thicken-up powder: 4 fl oz de-ionized water
Level 4 Pureed	Applesauce (Mott's applesauce original, US)
Level 5 Minced & Moist	4 mm gruel rice
Level 6 Soft & Bite-sized	15 mm thick bananas
Level 7 Easy to chew/Regular	15 mm thick crackers (Keebler Club Original Crackers, ®, ™, © 2018 Kellogg NA Co.)

Procedure

Prior to the swallowing trials, we measured each participant's weight and height to calculate BMI (unit: kg/m_2). Neck circumference (NC, unit: cm) was also measured at the level of the cricoid cartilage with a tape measure.

First, we instructed the participant to be seated in a straight chair, with his/her head and trunk in a neutral position. Next, we cleaned the participant's cervical region by using alcohol wipes and secured an elastic band of the microphone to the participant's neck. Third, we used a throat microphone headset (iASUS NT3-R, CA, USA) to record each swallowing trial of all participants. We placed the equipment at the level of the cricoid cartilage at the anterior neck, where the average magnitude of the signal-to-noise ratio was the highest (J. A. Y. Cichero & Murdoch, 2002; K. Takahashi et al., 1994).

Three swallowing trials were completed following installation and calibration of above identified equipment. Participants were provided our different viscous liquids (water, nectar-like liquid, honey-like liquid, and pudding-like liquid), and then four different textures of food (apple sauce, gruel rice, banana, crackers). All liquids and foods were provided in the same sequence to all participants. In each trial, three swallowing sounds were recorded. Each presentation was a measured and specific bolus size. At least a 2-minute break was provided between each trial. The swallowing sound detected by the mic was saved in a password protected laptop (SurfacePro3, Microsoft Corporation. Redmond, WA) using RavenPro1.5.0 (Bioacoustics Research Program, 2014). The data sampling rate of 44.1 kHz (Borr et al., 2007; J. A. Cichero & Murdoch, 2002) and resolution of 16 Bit was recorded as a monotype in the computer. The duration of the acoustic signals (DAS, unit: second) was defined as the time that elapsed from the beginning to the cessation of the signal. The start and the end of the sound of swallowing were identified by listening to the sound and observing the spectrogram. Peak intensity (PI, unit: dB) represented the point of highest displacement of the acoustic signal on an energy contour, which might be an indicator of pharyngeal contraction activity (J. A. Cichero & Murdoch, 2002).

Data analysis

The resulting acoustic signals were bandpass filtered from 30 to 3000 Hz in the MATLAB R2015a (MathWorks, Natick, MA). We manually identified each swallowing sound by first visually identifying the sound waveform and spectrum display, and then by identifying auditorily the swallowing sound by playing them back and forth several times in RavenPro1.5.0 software. When multiple swallowing events occurred after a single eating behavior, only the first swallowing sound was considered in the series. Acoustic signal selection and variable measurements were also completed in RavenPro1.5.0.

Descriptive statistics were expressed as mean ± standard deviation (M ± SD) and the range of liquid and food swallowing acoustic features (Table 3-2). A simple linear regression model was performed to evaluate the relationships between NC and swallowing acoustic features in various liquids and foods. SPSS 21 (IBM Corp. 2012, SPSS Inc., Chicago, IL) was used for all analyses. An alpha level of 0.05 was set for all analyses.

Table 3-2 The mean values and standard deviation for the participants' information (M ± SD).

		Total (n=30)	Male (n=15)	Female (n=15)
		Mean ± Std. Deviation		
Age		34.87 ± 11.54	34.87 ± 2.99	34.87 ± 3.08
BMI (kg/m_2)		24.23 ± 4.18	25.84 ± 0.57	22.61 ± 1.31
Neck circumference (cm)		37.32 ± 4.48	40.96 ± 0.65	33.70 ± 0.68
Liquid	DAS (s)	0.947 ± 0.247	0.89 ± 0.02	1.01 ± 0.04
	PI (dB)	50.697 ± 1.505	50.69 ± 0.19	50.88 ± 0.18
Food	DAS (s)	1.015 ± 0.325	0.94 ± 0.04	1.06 ± 0.03
	PI (dB)	50.542 ± 1.452	50.40 ± 0.19	50.61 ± 0.20

DAS = Duration of swallowing acoustic signals, in second; PI= Peak intensity, in dB.

V. Results

Although BMI and NC had a strong positive correlation *($r = 0.74, p < 0.001$)*, NC was chosen for further discussion because it is better to reflect the upper body adipose tissues(Ben-Noun et al., 2001; Davies & others, 1990; Gonzalez et al., 2008; Li et al., 2014). There were significant differences in DAS when various viscous liquids *($F (3, 28) = 6.679, p = 0.016$, partial $\eta_2 = 0.103$)* or when different textures of food were taken *($F (3, 28) = 46.018, p < 0.0001$, partial $\eta_2 = 0.442$).*

Effects of the Neck Circumference on Swallowing Acoustic Signals

NC was negatively associated with DAS in Level 3 (pudding-like) *($r = -0.46, p < 0.001$)* and Level 4 (apple sauce) *($r = -0.29, p = 0.002$)*. The association between NC and PI of food/liquid was more evident during Level 2 ($r = -0.66$, honey-like) *($p <0.001$) and* Level 3 (pudding-like liquid) (r = 0.-49, $p < 0.001$). Interestingly, swallowing acoustic signals during food intake were not affected by the NC.

The associations between NC-DAS and NC-PI across 8-level liquid/foods were presented in Figure 3-1 and Figure 3-2 respectively.

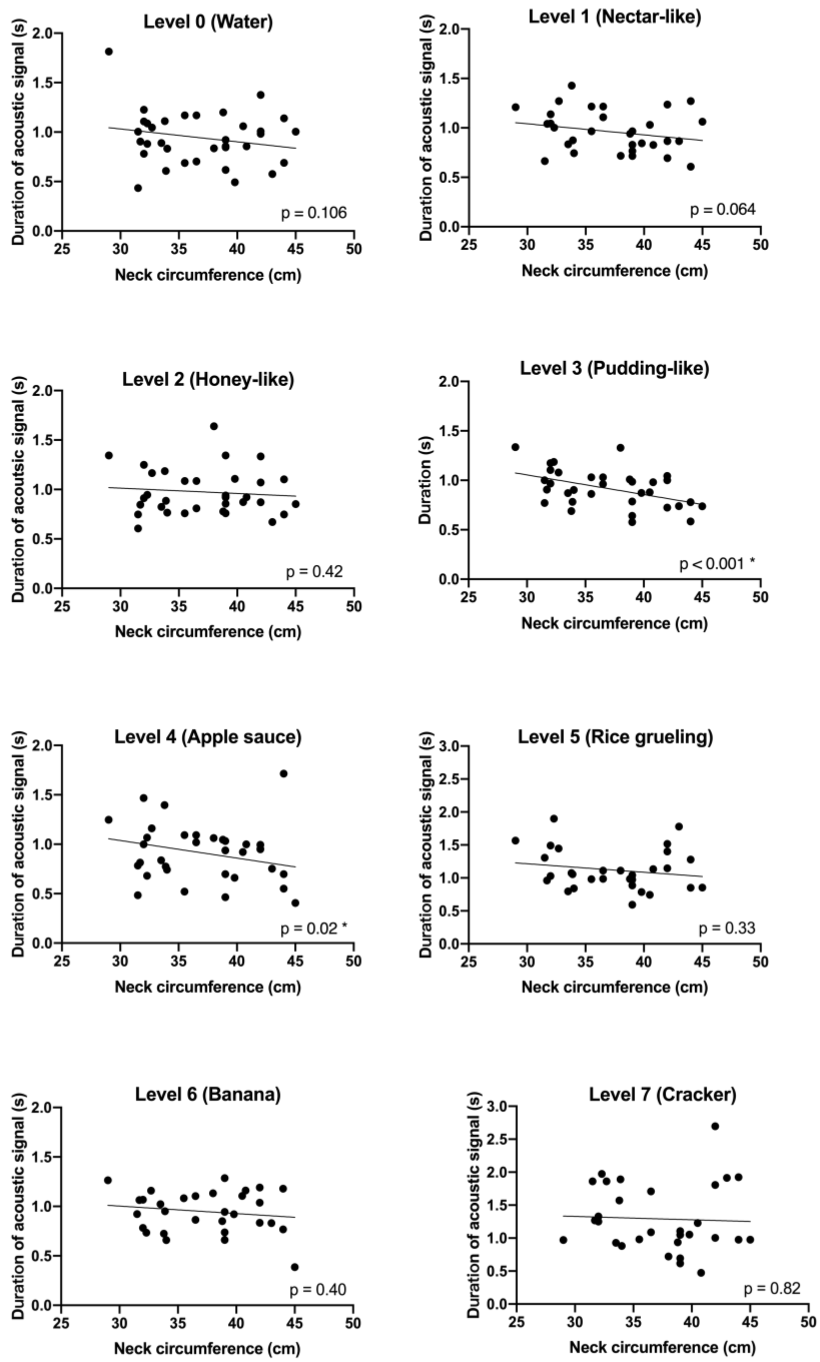

Figure 3-1 Correlations between neck circumference and duration of acoustic signals among different liquids/foods

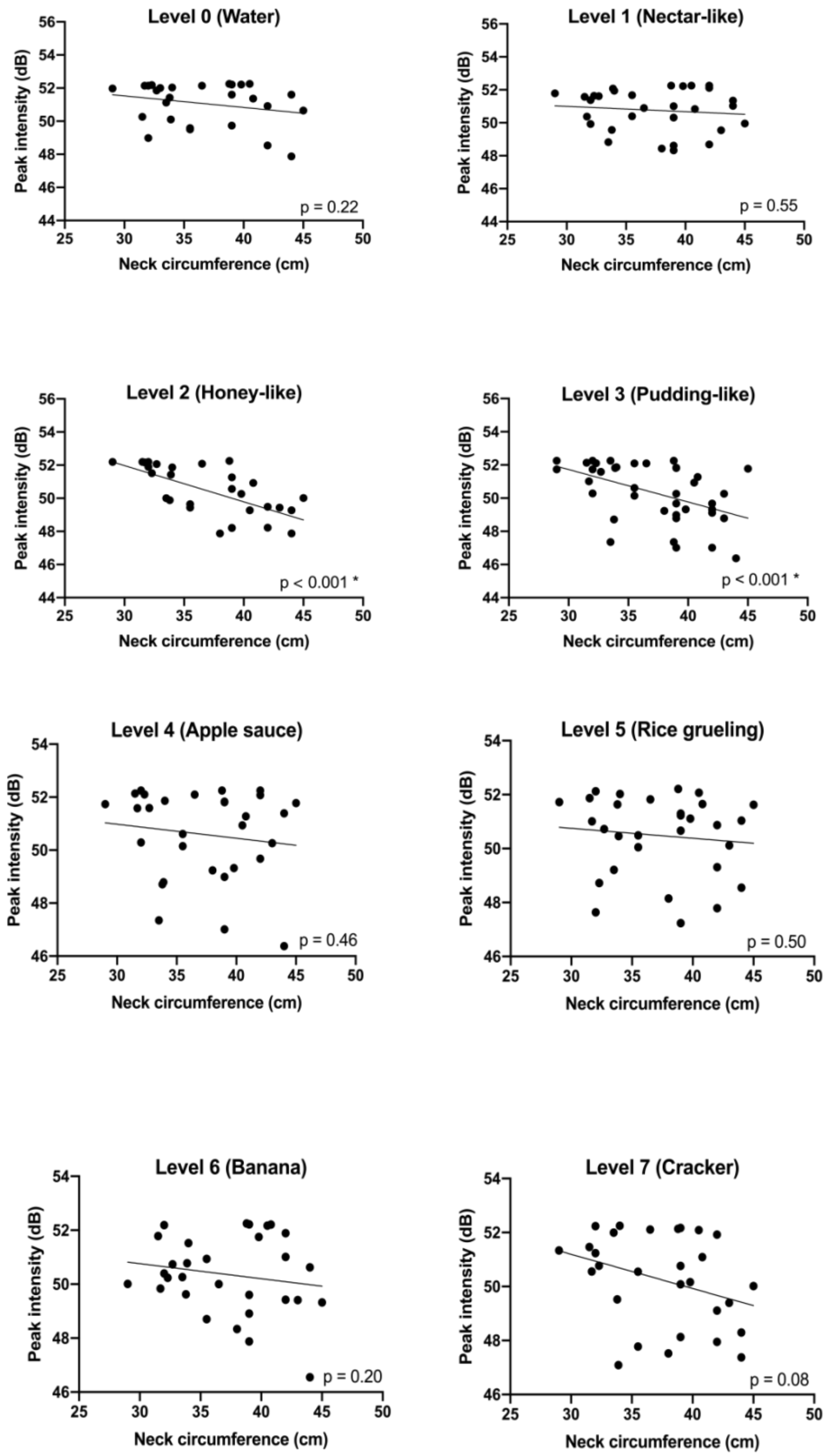

Figure 3-2 Correlations between neck circumference and peak intensity among different liquids/foods

VI. Discussion

The purpose of our study was to measure differences in swallowing acoustic signals among participants with different NC based on the IDDSI. Since the swallowing performance is evaluated by CA analysis, the preparation of different viscous liquid and texture modified foods is a crucial aspect for researchers in this field. Researchers have explored thickened liquids and different texture boluses such as “thin”, “nectar-like”, “honey-like”, “puree”, “coffee”, “juice”, “yogurt” and “konjac jelly” to investigate their effects on swallowing acoustic signals. However, it can cause confusion in different cultures settings, which might have different standardizations and classifications for viscosity and texture (Steele et al., 2015; T. Takahashi et al., 2002). Even though researchers have tried to quantify the food consistency and texture with a *rheometric device*, this technique might not be available or practical for the clinical setting (T. Takahashi et al., 2002; Taniwaki et al., 2013). A major dilemma to prevent further replication in the CA field is lacking standardized terminologies and definitions in aspects of food texture and drink thickness. Our current study, as a preliminary trial of CA across eight levels of different liquid/food viscosity and texture according to IDDSI, investigated swallowing acoustic signals for future comparisons.

Associations between neck circumference and swallowing acoustic signals

Since we found differences in swallowing acoustic signals across liquid and food intake, we respectively investigated the effect of NC on each liquid and food. Our results showed as NC increased, DAS only decreased in Level 3 (pudding-like liquid) and Level 4 (applesauce). Although fat tissue can attenuate sound intensity, the distribution of sound spread would have greater speed with increasing fat concentration compared to air. We noted that influences of NC were more prominent on swallowing acoustic signals for thickened liquids intake. The tendency also showed that larger NC had lower PI in level 2 (honey-like liquid) and level 3 (pudding-like liquid) intake. Fat tissues in the neck might alter resonatory characteristics of their vocal tracts and change the sound intensity. Larger NC might indicate more fat distribution in the neck but not loss of muscular tissues among normal healthy subjects. The increased adipose tissue in the neck may result in an attenuation of the signal amplitude and producing softer swallowing sounds. Since thicker liquids have higher acoustic regularity and predictability (Jestrović et al., 2013), it explained that effects of NC on DAS and PI were notable only in more viscous liquids.

NC as a better index of the upper-body adipose tissue distribution than BMI might contain more acoustic information than BMI (Ben-Noun et al., 2001; Davies & others, 1990; Gonzalez et al., 2008; Li et al., 2014). Although we chose NC as main effects, it is necessary to note that the neck structure and neck adipose tissues should be investigated in future research. More precise measurements of subcutaneous tissues and standardizing the neck structure can improve the swallowing sound analysis. Standardized assessment of neck fat tissue, such as Computed tomography and Magnetic Resonance Imaging can be conducted to systematically explore NC effect on swallowing acoustic signals.

Although our conclusion might be limited by our sample size, we gave a glimpse and unveiled the effects of eight varied boluses on swallowing acoustic signals. Based on this study, we also suggest standardizing the preparation of liquids/foods according to IDDSI, which will be beneficial for future CA studies.

VII. Conclusion

In conclusion, swallowing acoustic signal features among healthy adults are different among various viscous liquids and foods. Increased DAS was associated with increased consistency of liquids and increased hardness of food. Increased viscosity of liquids was also related to decreased PI. We also found that swallowing acoustics were related to NC. A smaller NC produces louder swallowing sounds and requires more time to swallow thickened liquids. Based on impacts of viscosity of liquids and different texture of foods on the swallowing performance, more viscous liquids such as level 3, level 4 and level 5 in the IDDSI might be the best choice for research related to neck circumference effects on the swallowing acoustic signals and swallowing performance.

CHAPTER 4 GENERAL CONCLUSIONS

I. Summary

Our preliminary contribution to this field is a systematic investigation of swallowing sounds across 8 levels of liquids and foods based on the IDDSI. The two parameters describing the swallowing acoustic signals were DAS and PI which were suggested as two relatively reliable physiologically related parameters. Researchers have suggested that the DAS represents the duration of closing and reopening epiglottis movement, whereas PI indicates displacement of the pharyngeal movement (J. A. Cichero & Murdoch, 2002).

In Chapter 2, we found swallowing acoustic signal features among healthy adults were different regarding intaking various viscous liquids and foods, which was in line with our hypothesis. We found there was a tendency that longer DAS was associated with increased consistency of liquids and increased hardness of foods. However, there were no statistical differences in DAS between thin and slightly thick liquids. One possible explanation is that viscosity of water and slightly thick liquid might be too similar even for a healthy person to respond differently and do not reflect significant alternations in swallowing duration. It also brought up another question of whether changing viscosity levels could either continuously or discretely disturb the swallowing acoustic signals, which would provide rich opportunities for future research.

We also found that there were effects of food hardness and dryness on the duration of swallowing events. In contrast to our hypothesis, these changes in DAS were not reflected between swallowing pureed solids (Level 4) and minced & moist solids (Level 5). The different food texture between them and solid food (Level 6) could explain this phenomenon. Two swallowing phases (liquid and solid phase) were required to be able to safely swallow Level 4 and Level 5 bolus. However, in our study, we captured the first swallowing sounds when multiple swallowing events occurred, which might indicate we only considered the liquid swallowing phase. As a result, there were no differences in swallowing duration between pureed solids and minced & moist solids, which were considered as a 'liquid' swallowing pattern. The researchers also suggest the chewed-dependent food portion reduces the seal of the tongue-palate, which may increase the risk of aspiration due to potentially allowing the liquid to spill into the pharynx for liquid-solid mixtures (Saitoh et al., 2007). Future research will be the most productive if considering varied food texture combined with different levels of analysis.

Our study revealed that differences of PI were in 4 levels of viscous liquids intake especially between Level 0 (thin) and Level 1 (slightly thick), Level 0 (thin) and Level 3 (moderately thick), and level 2 (mildly thick) and level 3 (moderately thick). However, we did not find a significant difference of DAS between Level 0 (thin) and Level 1 (slightly thick), which led us to reconsider the underlying dissimilarity between DAS and PI as well as the sequence of swallowing trials. In previous studies, researchers defined DAS to include the whole pharyngeal movement and suggested it as a reliable characteristic to describe total swallowing performance, while PI was considered as a parameter to describe pharyngeal displacement. We concluded Level 0 (thin) and Level 1 (slightly thick) were the same 'consistency' liquids based on no statistical difference between them. However, we did notice the changes of PI in Level 1 (slightly thick) liquid swallowing after intaking Level 0 (thin) liquid. This phenomenon might be explained by a learning effect since the subjects repeatedly swallowed increasingly viscous liquids three times and adjusted their swallowing according to changes in 'viscosity'. This adjustment led subjects to swallow both Level 1 (slightly thick) and Level 0 (thin) liquids with the different PI. As a result, the subjects utilized less pharyngeal movement to swallow the 'slightly thick' liquids compared to the predicted value. Thus, decreased PI of swallowing sounds could result from the learning. We did not find differences between Level 1 (slightly thick) and level 2 (mildly thick) as well as Level 0 (thin) and level 2 (mildly thick), which seemed to contradict the result that significant differences of DAS were found between them. If feedforward and feedback learning effects, as well as different measurable characteristics between PI and DAS, were considered, conflict findings between DAS and PI could also be more easily understood.

Our findings contradicted our hypothesis that no significant differences in PI were noticed among bolus swallowing in respect to the different food textures. It might be reasonable that there were no differences in PI that reflected the pharyngeal movement, which did not correlate to DAS representing total swallowing duration or bolus transport speed. Further research is warranted to investigate the association between solid food texture and swallowing durations.

Based on the findings regarding the liquid viscosity and food texture effects on swallowing acoustic signals, we further discussed the influences of NC on the swallowing sounds across different liquids and food in Chapter 3. We noted that influences of NC were more prominent on swallowing acoustic signals for thickened liquids intake. Although fat tissue can attenuate sound intensity, the distribution of sound would have greater speed with increasing fat concentration compared to air.

We hypothesized that the bigger NC was, the lower PI and the shorter DAS of the swallowing sounds would be. However, individuals with larger NC only exhibited shorter DAS in swallowing pudding and applesauce. Larger NC had lower PI while swallowing honey and pudding. Interestingly, swallowing acoustic signals during food intake were not affected by NC. Large NC produced more intense sound signals, which might alter the resonatory characteristics of vocal tracts. We suggested that future investigations of CA should account for NC to further understand effects of neck structures on swallowing acoustic signals.

II. Limitations

In this project, we first recorded the swallowing sounds across 8 levels of liquids and foods, but improvements regarding study design still could be made. The biggest limitation is that we do not have access to the gold standard such as VFSS and FEES, which can enable us to associate the swallowing physiological events to swallowing acoustic signals. In order to reach high intra-reliability of cutting each swallowing sound, only one researcher completed chunking total 720 swallowing sounds. However, without a second person's agreement, single person approach might accidently introduce human errors and personal biases. Moreover, we recruited the convenient samples around the campus area which might not represent the whole population. We utilized self-report of swallowing performance and previously swallowing-related medical history rather than completing a comprehensive swallowing performance assessment for the individuals who participated in the study. Last but not the least, the subjects swallowed the prepared liquid and food boluses in a series of sequences, which might introduce the learning effects of certain level of viscous liquid. All the above limitations including subject recruitment and swallowing analysis could be minimized in the future study.

In addition, we collected swallowing sounds at the anterior neck and at the posterior neck (Figure 4-1) in order to establish a normal swallowing pattern for developing a way to better screen swallowing disorders. We not only assessed the participants' swallowing sounds at the anterior neck by age groups, but also assessed the participants' swallowing sounds at the posterior neck and compared the personal the level difference between them. Healthcare providers commonly differentiate swallowing behavior through volume and consistency of sound using swallowing sounds while people eat or drink different boluses with a stethoscope. Furthermore, researchers have suggested swallowing sounds have the best signal-to-noise ratio (SNR) at the level of the cricoid cartilage among different sites at the anterior neck (Dudik et al., 2015a). Existing studies have focused on determining optimal SNR in the anterior neck. However, placing the swallowing sound collector at the anterior neck cannot enable healthcare workers to directly observe patients' throat movement or manipulate throat movement. This position could lead to a poor clinical practice. In order to remove this barrier, we aimed to design and implement a feasible and efficient method rather than focusing only on anterior neck SNR, as is the current practice. Future research will analyze the swallowing behaviors by using sound wave analysis at the posterior neck and then compared them to signals from the anterior neck. We also predict that there are differences of swallowing sounds collected at the posterior neck regarding the left and right side of the neck among persons with hemiplegia stroke.

Figure 0-1 P (Pleft, Pright) is the intersection of lateral border of trapezius muscle and intermediate line between the third and fourth cervical vertebrae in the posterior neck region. A is at the level of the cricoid cartilage in the anterolateral neck

III. Future Directions

In order to remove potential liquid or food residuals in the throat, we instructed individuals to clear their throat and cough three times respectively (Figure 4-2). Acoustic cough monitoring has been proposed to record cough frequency and strength by use of a microphone. However, research is incomplete regarding the effect of age on voluntary cough sounds after swallowing different viscous liquids and foods. Even though the expiratory flow rate test is normally used to identify cough ability, it cannot directly reflect the physiological process of coughing. Cough and throat clearing sounds provide another pathway for further research monitoring cough ability in the presence of presbyphagia among the elderly and providing biofeedback for decreasing the risk of aspiration. Based on our prior data analysis of cough sounds and throat clearing sounds, we found an effect of age on cough sounds after swallowing different liquids and foods. Cough sounds after swallowing were more associated with changes in liquid viscosity among middle-aged individuals. Cough sounds and throat clearing sounds were illustrated in Figure 4-3. Since coughing after swallowing is one of the clinical identifiers to screen aspiration risk, acoustic cough monitoring as a noninvasive and recordable method can be utilized in pulmonary rehabilitation and screening for dysphagia. However, further studies regarding factors impacting cough sounds are required before clinical applications.

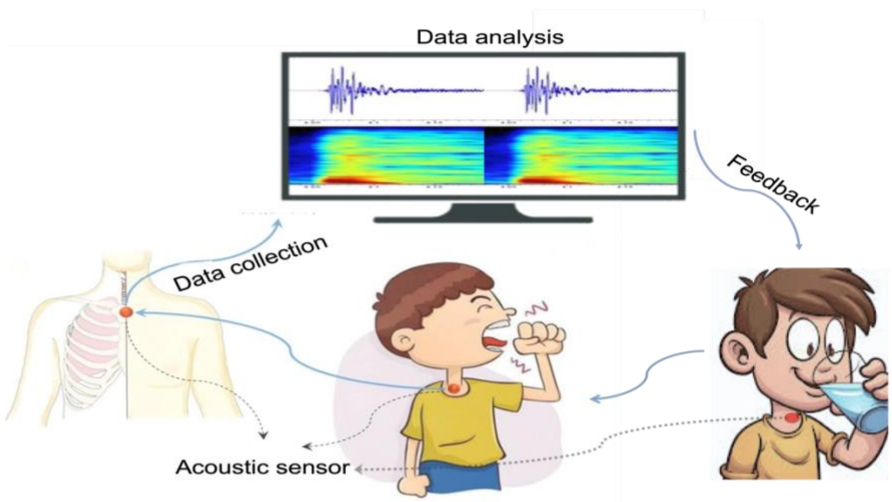

Figure 0-2 Simplified data collection procedure presented above

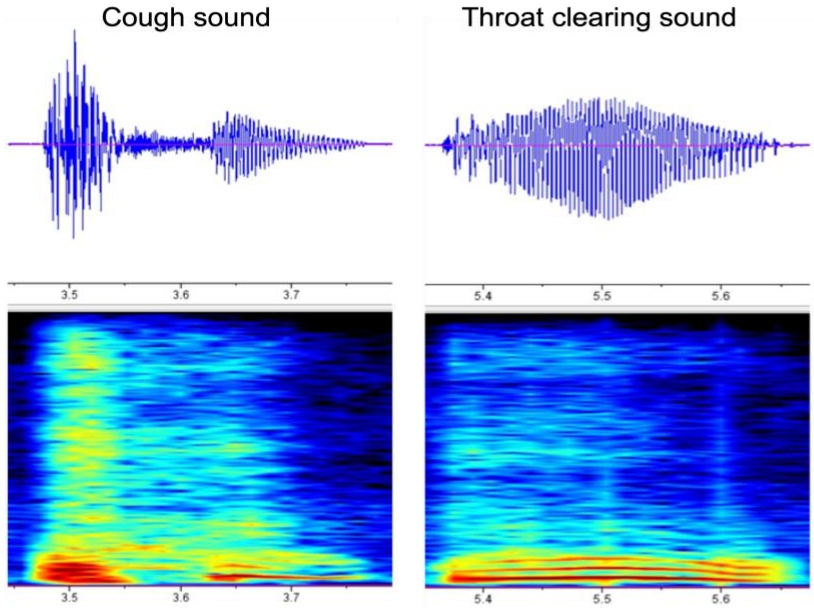

Figure 0-3 Example of acoustic recording regarding cough sounds and throat clearing sounds illustrated in the RavenPro software

Recording acoustics has other applications besides swallowing studies. Auscultation of knee joints was first proposed by Robert Hooke in the 17th century, and Heuter et al. defined the term 'myo-dermato-osteophone' as movement sounds of muscle, skin and bony structure in 1885. Blodgett WE et al. first described a stethoscope as a non-invasive tool for finding the relationship between underlying factors and diminishing or increasing sounds in the 1900s (Blodgett, 1902). Digital joint auscultation has been also emerged for diagnosis of cartilage pathology, early arthritis as well as anticipate the prognosis (Bircher, E., 1913) Acoustic studies are also used in studies on obesity. In order to unveil the etiology of obesity, researchers also investigated the human behavioral pattern of food consumption and energy intake by counting chewing and swallowing events. A microphone or acceleratory device shows potential benefits for long-term MIB, which calculates calorie intake and is important for diet and weight management. (O. Amft et al., 2009; E. Sazonov et al., 2008; E. S. Sazonov et al., 2010; Edward S. Sazonov et al., 2009).

The research of swallowing acoustic signals is not fully accomplished. More opportunities still remain for further exploration. Our study potentially indicates that acoustic swallowing monitoring can be used for swallowing behavior detection when intaking different viscous liquids in order to achieve clinical feeding management.

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Chapter 5 APPENDICES

I. APPENDIX A: Basic Information Sheet

Basic Information Sheet

Num.__________

Gender	**Male □ Female □**
Birthday (mm/dd/yy)	
Weight (kg)	
Height (cm)	
Neck Circumference (cm)	
Mastoid Process Spacing	
Swallowing difficulty	**Yes □ No □**
Remark	

II. APPENDIX B: Healthy Volunteer Data Sheet

Device Check □

Spoon: 1.25ml□ 2.5ml□ 5ml□ 10ml□

Position: Pleft □, Pright □, A □

Num.___

Trial Num.	Sensor Position (Pleft, Pright, A)	Food or drink level	Cough(1) or Clear throat(2)	Remarks

Data Collector_____________

Date___

III. APPENDIX B: ADULT CONSENT - CLINICAL BIOMEDICAL

ADULT CONSENT - CLINICAL BIOMEDICAL

Title of this Research Study

Invitation

You are invited to take part in this research study. You have a copy of the following, which is meant to help you decide whether or not to take part:

Informed consent form

"What Do I need to Know Before Being in a Research Study?"

The Rights of Research Subjects

Why are you being asked to be in this research study?

You are being asked to be in this study because you: 1) are 19-80 years old; 2) self-report no history of swallowing disorders, no previous history of neurological diseases or cancer of the mouth, neck and brain, or head or neck surgery; 3) currently have no other diseases that will affect swallowing function; 4) are able to sign the consent form after the whole study is explained to you; and 5) able to sit upright with or without the back support of a chair.

If you are pregnant or plan to become pregnant during this study, you may not be in this study.

What is the reason for doing this research study?

The goal of this study is to develop and implement a non-invasive swallowing acoustic detecting method among dysphagia patients to examine their swallowing sounds. The device to detect swallowing sounds is not FDA approved.

What will be done during this research study?

After determining your eligibility to participate, and completing the process of consent, your height, weight and neck circumference will be measured. Then a sound detection device will be placed on your neck. The device is light and non-invasive. Your swallowing sounds will be recorded a total of nine times at three different locations (at the front of your neck, at the left side and right side of the back of your neck) with your head-trunk in a neutral position. You will use a 5mL spoon to intake 7 levels of different consistency foods or liquids at room temperature.

You will also be instructed to do one of the following: clear your throat after a cough or cough after clearing your throat. You can try to do it several times if you want. You will complete two study visits, and each visit will take two hours. Your swallowing sounds will be recorded at UNMC when you swallow different foods and liquids. The instruction words and your conversations during data collection will also be recorded to remind investigators the sequence of the study when they analyze the data. The recordings will be stored on a computer server until completion of data analysis, at which time the recordings will be removed from the server.

What are the possible risks of being in this research study?
There is a possible risk of a loss of confidentiality. Additional possible risks also associated with the study procedures include aspiration and difficulty swallowing. You may feel uncomfortable when you first wear the sound detection device when you eat food. We will wear it first to demonstrate for you.

What are the possible benefits to you?
You may not receive any direct benefit by participating in this study. However, you might benefit from being in this study because you can understand the current status of your swallowing function and which level of food and drink is safe for you. You may also improve your swallowing function and reduce the chances of aspiration while monitoring your swallowing behavior by swallowing sounds.

What are the possible benefits to other people?
This study will collect objective data of swallowing sound accordance to different food textures and viscous liquids. The information we learn may be useful because it may provide a method to screen aspiration/penetration among dysphagia patients without the direct aid of videofluoroscopy. This study may provide information that may help dysphagia patients in the future.

What are the alternatives to being in this research study?
Instead of being in this research study, you can choose not to participate.

What will being in this research study cost you?
There is no cost to you to be in this research study.

Will you be paid for being in this research study?
You will be given a five dollar Walmart gift card after completing the research.

Who is paying for this research?
This research is being paid for by the Department of Physical Therapy Education, College of Allied Health Professions at the University of Nebraska Medical Center.

What should you do if you are injured or have a medical problem during this research study?

Your welfare is the main concern of every member of the research team. If you are injured or have a medical problem or some other kind of problem as a direct result of being in this study, you should immediately contact one of the people listed at the end of this consent form.

How will information about you be protected?

You have rights regarding the protection and privacy of your medical information collected before and during this research. This medical information is called "protected health information" (PHI). PHI used in this study may include your medical record number, address, birth date, medical history, the results of physical exams, blood tests, x-rays as well as the results of other diagnostic medical or research procedures. Only the minimum amount of PHI will be collected for this research. Your research and medical records will be maintained in a secure manner.

Who will have access to information about you?

By signing this consent form, you are allowing the research team to have access to your PHI. The research team includes the investigators listed on this consent form and other personnel involved in this specific study at UNMC.

Your PHI will be used only for the purpose(s) described in the section "What is the reason for doing this research study?"

You are also allowing the research team to share your PHI, as necessary, with other people or groups listed below:

- The UNMC Institutional Review Board (IRB)
- Institutional officials designated by the UNMC IRB
- Federal law requires that your information may be shared with these groups:
  - The HHS Office for Human Research Protections (OHRP)
  - The Food and Drug Administration (FDA)
- The HIPAA Privacy Rule requires the following groups to protect your PHI:
  - Your health insurance company

You are authorizing us to use and disclose your PHI for as long as the research study is being conducted. You may cancel your authorization for further collection of PHI for use in this research at any time by contacting the principal investigator in writing. However, the PHI which is included in the research data obtained to date may still be used. If you cancel this authorization, you will no longer be able to participate in this research.

How will results of the research be made available to you during and after the study is finished?
In most cases, the results of the research can be made available to you when the study is completed, and all the results are analyzed by the investigator or the sponsor of the research. The information from this study may be published in scientific journals or presented at scientific meetings, but your identity will be kept strictly confidential.

What will happen if you decide not to be in this research study?
You can decide not to be in this research study. Deciding not to be in this research will not affect your medical care or your relationship with the investigator or UNMC. Your doctor will still take care of you and you will not lose any benefits to which you are entitled.

What will happen if you decide to stop participating once you start?
You can stop participating in this research (withdraw) at any time by contacting the Principal Investigator or any of the research staff. Deciding to withdraw will not affect your care or your relationship with the investigator or UNMC. You will not lose any benefits to which you are entitled. Any research data obtained to date may still be used in the research.

Will you be given any important information during the study?
You will be informed promptly if the research team gets any new information during this research study that may affect whether you would want to continue being in the study.

What should you do if you have any questions about the study?
You have been given a copy of "*What Do I Need to Know Before Being in a Research Study?*" If you have any questions at any time about this study, you should contact the Principal Investigator or any of the study personnel listed on this consent form or any other documents that you have been given.

What are your rights as a research participant?
You have rights as a research subject. These rights have been explained in this consent form and in The Rights of Research Subjects that you have been given. If you have any questions concerning your rights, or want to discuss problems, concerns, obtain information or offer input, or make a complaint about the research, you can contact any of the following:

The investigator or other study personnel
Institutional Review Board (IRB)

Telephone: (402) 559-6463
Email: IRBORA@unmc.edu
Mail: UNMC Institutional Review Board, 987830 Nebraska Medical Center, Omaha, NE 68198-7830

Research Subject Advocate
Telephone: (402) 559-6941
Email: unmcrsa@unmc.edu

Documentation of informed consent

You are freely making a decision whether to be in this research study. Signing this form means that:

You have read and understood this consent form.
You have had the consent form explained to you.
You have been given a copy of The Rights of Research Subjects
You have had your questions answered.
You have decided to be in the research study.
If you have any questions during the study, you have been directed to talk to one of the investigators listed below on this consent form.
You will be given a signed and dated copy of this consent form to keep.

Signature of Subject ____________________________
Date ____________

My signature certifies that all the elements of informed consent described on this consent form have been explained fully to the subject. In my judgment, the subject possesses the legal capacity to give informed consent to participate in this research and is voluntarily and knowingly giving informed consent to participate.

Signature of Person obtaining consent ____________________________
Date ____________

Authorized Study Personnel

Principal

* Feng, Chun (Emily)
alt #: 402-591-9746
degree: BS

Secondary

* Volkman, Kathleen

phone: 402-559-5014
alt #: 402-559-6415
degree: PT, MS

Faculty Advisor
Siu, Ka-Chun (Joseph)
phone: 402-559-8464
alt #: 402-559-8464
degree: PhD