

A Pilot Study on the Validity and Reliability of Portable Ultrasound Assessment of Swallowing with Dysphagic Patients.

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**Thesis Submission in partial fulfilment of the requirements for
the Degree of Master of Speech Language Therapy**

Department of Communication

The University of Canterbury

2019

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Abstract

Introduction: Ultrasound assessment of swallowing has been documented as reliable in both healthy and dysphagic participants. In addition, there is evidence of good correlation with ‘gold standard’ videofluoroscopic swallowing study (VFSS). Despite this, ultrasound has not translated into clinical practice. This may be due to the cost and accessibility of ultrasound devices as well as the time required to analyse images offline. Recent innovations have produced inexpensive, wireless, portable ultrasound technology, which has the potential for increased access and immediate results. This project explored a number of components of inter- and intra-rater reliability using portable ultrasound. Reliability of measures, from images acquired, selected and measured online in a pressured clinical environment, was compared with reliability of measurement of pre-selected images offline. The project additionally made preliminary assessments of the validity of ultrasound against the gold standard of VFSS.

Methods:

Participants: Eight patients, aged 33-96 with mixed aetiologies were recruited following referral for a clinical VFSS.

Instrumentation: A curvilinear Clarius™ ultrasound device, wirelessly connected to an iPad, was used to acquire images during dynamic swallowing gestures - hyoid excursion and thyrohyoid approximation as well as images for measures of tongue thickness at rest. A linear Clarius™ transducer was used to collect measures of cross-sectional area of submental muscles at rest.

Data acquisition and measurement: Ultrasound data were independently collected by two investigators within the same day. The primary investigator completed ultrasound

concurrently with VFSS for the purposes of validity assessment. Subsequent ultrasound analysis was completed by a co-investigator immediately following. Online measurements of ultrasound images were completed during the exam, using Clarius™ software on an iPad. Offline analyses of ultrasound were completed by two raters with a minimum of eleven days between measures. VFSS measures were completed offline by rater one, using ImageJ software on a large screen.

Reliability assessment: Inter-rater reliability was calculated with intraclass correlation coefficient (ICC) based on linear mixed effects model analyses (in R software). Effect of data acquisition on reliability was explored by calculating online inter-rater ICC and comparing with offline inter-rater ICC. Effect of environmental, equipment and time constraints on online measurement was explored by calculating ICC of online and offline measurement of the same pre-selected acquired images.

Validity assessment: Hyoid excursion and thyrohyoid approximation during liquid and puree swallowing were concurrently assessed using ultrasound and the ‘gold-standard’ instrumentation, VFSS. Pearson correlation coefficients were calculated in order to make a preliminary assessment of correlation between assessment methods.

Results:

Reliability: Inter-rater reliability of online acquisition and measurement ranged from poor (< .50) to moderate (.50 –.75). ICC values for online and offline measurement of the same images were moderate (.50 –.75) for dynamic measures, and excellent (>.90) for static measures. Inter- and intra-rater reliability for offline measures was good (>.75) to excellent (>.90) for hyoid excursion and static morphometry measures and moderate (.50 –.75) for thyrohyoid approximation.

Validity: Pearson coefficient of correlation calculations for hyoid excursion were moderate ($r=0.76$; $p=0.001$) for puree bolus and excellent for liquid bolus ($r=0.92$; $p=0.03$). Thyrohyoid approximation was found to have a moderate but insignificant, relationship between modalities for both puree and liquid bolus ($r=0.61$; $p=0.11$).

Conclusion: The high reliability for offline measurement of ultrasound images is comparable to previous studies using sophisticated instrumentation. Reduction in reliability is noted when measuring the images online within the context of a clinical environment compared with offline measurement. Online data analyses may be affected by the pressure and lighting of a clinical environment paired with lower resolution of the device, size of the screen and use of a touch screen for measurement. Further reduction in reliability of dynamic swallowing measures is noted when data acquisition is added, this may be due to different techniques by examiners as well as variance in patient performance.

The findings suggest that it is important to further explore methods of improving reliability of data acquisition as well as immediate online analysis before clinical translation of ultrasound assessment of swallowing is achieved.

Preliminary data on validity of the portable ultrasound device indicates high correlation between assessment methods (ultrasound and VFSS) for hyoid excursion only. Analysis of a larger cohort is required to provide a robust assessment of the validity of ultrasound images collected with this technology for both hyoid excursion and thyrohyoid approximation.

Acknowledgments

Firstly, I wish to express my gratitude to my supervisor Professor Maggie-Lee Huckabee for her inspiration, knowledge, guidance, teaching, problem solving and belief in my ability to collect the data required for this exciting project. My gratitude extends to my line manager, the local sponsor of this project, Tamzin Brott who immediately said yes when this project was an idea, which felt unlikely to come to fruition. However when it did become a reality, Tamzin supported me throughout to make data collection work while recognising that it did, at times, have an impact on some of the other duties of my role.

I wish to thank all of the participants of my research who each generously gave their time to the data collection process; without their patience there would have been no thesis. To all of my speech-language therapy colleagues at Waitematā District Health Board, I wish to thank each of them for going the extra mile, finding me potential participants for this study and supporting me to carry out data collection. I really enjoyed the extra clinical time I spent with each of them during the year of data collection; I also want to acknowledge their on-going commitment to our patients. Sincere thanks go to the North Shore Hospital radiology department; in particular, Elizabeth McKenzie for supporting the speech-language therapists in conducting clinical research whenever we ask; to Lynne Van Niekerk for finding us the VFSS slots, sometimes with great difficulty; to Candice Alexander and all of the medical radiation technicians who supported the research with interest, diligence, without complaint, all while following our rigid instructions very patiently, I cannot thank them enough.

To my colleague Becca Ross for her initial encouragement, job- sharing with me while pregnant, and for her on-going support throughout this project, despite having had

many more important issues at hand. I thank Becca for her encouragement from the sidelines. Thanks go to Alice Dimmock for stepping in as my co-investigator at the last minute and for being the person I relied upon to ensure that we were following robust processes throughout data collection; not forgetting that she put off her travel plans for a whole year longer than she intended to, in order to get this done.

Thanks to Katharina Winiker who taught me an awful lot about ultrasound, data collection and research in general, for her kindness, support and friendship as well as taking on the journal manuscript write up. It is also critical that I specifically acknowledge Katharina's work in both data analysis and interpretation of data, thank goodness for her knowledge of statistics! I would also like to acknowledge Esther Guiu-Hernandez. Esther is the person we all go to when we are just not sure, and I thank her for her patience.

While I did not spend as much time at the Rose Centre for Stroke Recovery and Research as I would have liked, thanks go to all of the other talented lab members for their friendship and help along the way. I would like to especially mention Phoebe Macrae who is inspiring and incredibly talented. Phoebe has a great way of asking questions that challenge me to think and do better. Special thanks go to Phoebe for taking time out from family life at Christmas to proof read this thesis. Thanks also go to Paige Thomas for agreeing to complete endless hours of VFSS review for the validity study and for her belief in the value of clinical research and the impact it can have on the care we deliver.

Thanks to Jessica Tranter who kept me sane during the write up stage, thanks to Jess for all of the laugh-out-loud moments and for giving up her precious time to proof read my thesis, fixing my paragraph spacing, punctuation (especially those pesky commas), and

keeping me motivated to get it finished. I will endeavour to resend those inspirational quotes to Jess during her final write up. To my friends and extended family, my apologies for my absence in your lives during 2019. Thanks for accepting the apologies and the snatches of time when I have them, and for your understanding and support.

Finally deepest thanks go to my husband Andy. Thank you for taking on the majority role in parenting our girls at a number of intervals during the early stages of the project and much longer intervals during the write up stage. You sacrificed a lot over the past two years because of your belief in me; you are always telling me how amazing it must be to make a difference when I go to work. I hope this is the beginning of more clinical research that really can have an impact. Thanks for your unwavering belief; I cannot wait to have our life back again. To Charlotte and Bella, thanks for understanding that this was just something your Mum had to do, and that it would be over one day. It has not been easy for either of you but I am really looking forward to being your Mum again.

List of Abbreviations

CI	confidence interval
CT	computed tomography
FEES	fibreoptic endoscopic evaluation of swallowing
GH	geniohyoid
ICC	intraclass correlation coefficient
LAB	left anterior belly of the digastric
MRI	magnetic resonance imaging
Q-Q-plot	quantile-quantile plot
RAB	right anterior belly of the digastric
SEM	standard error of measurement
SD	standard deviation
UES	upper oesophageal sphincter
VFSS	videofluoroscopic swallowing study

i1

¹ This thesis was prepared using British spelling conventions. However, direct quotes may contain American Spelling. Additionally the acronym 'UES' (upper esophageal sphincter) is strongly represented in the literature, therefore UES rather than UOS (upper oesophageal sphincter) was used.

Contents

Abstract.....	i
Acknowledgments.....	iv
List of Abbreviations	vii
List of Tables	xi
List of Figures	xii
Introduction.....	1
Literature Review.....	6
Swallowing and Dysphagia.....	6
Stages of Swallowing.....	7
Pre-oral (Anticipatory) Stage	8
Oral Stage.....	8
Pharyngeal Stage.....	10
Oesophageal Stage	16
Instrumental Assessment of Swallowing	17
Reliability of VFSS Measurement of Biomechanical Swallowing Features	21
Ultrasound.....	23
Reliability and Validity of Ultrasound Measures of Swallowing	25
Ultrasound Assessment of Hyoid Excursion	28
Ultrasound Assessment of Thyrohyoid Approximation	31
Ultrasound Assessment of Mid-section of Tongue Thickness.....	33
Ultrasound Assessment of Cross-sectional Area of Submental Muscles.....	35
Study Aims	39
Hypothesis	39
Justification.....	40
Methodology	41
Study Design.....	41
Training.....	41
Participants.....	42
Inclusion Criteria	42
Exclusion Criteria	43
Participant Recruitment.....	43
Procedures.....	44
Safety Assessments and Adverse Events	45
Data Acquisition	46

Ultrasound.....	46
Ultrasound Measurement of Hyoid Excursion.....	46
Ultrasound Measurement of Thyrohyoid Approximation.....	47
Tongue Thickness	48
Submental Muscle Cross-sectional Area	49
VFSS Data Acquisition.....	51
Inter-rater and Intra-rater Reliability Acquisition.....	51
Data Extraction	52
Ultrasound.....	52
Ultrasound Measurement of Hyoid Excursion.....	52
Ultrasound Measurement of Thyrohyoid Approximation.....	53
Tongue Thickness	54
Submental Muscle Cross-sectional Area	54
VFSS Data Extraction.....	55
Post Hoc Analysis of VFSS	55
VFSS Measurement of Hyoid Excursion.....	56
VFSS Measurement of Thyrohyoid Approximation.....	57
Data Analysis.....	59
Descriptive Statistics.....	59
Reliability of Ultrasound.....	59
Inter-rater Reliability.....	59
Intra-rater Reliability.....	60
Effect of Data Acquisition on Ultrasound Reliability.....	60
Effect of Environment on Ultrasound Reliability	61
Validity	63
Results.....	66
Participants.....	66
Data Extraction	68
Reliability.....	68
Descriptive Statistics.....	69
Inter-rater Reliability.....	69
Intra-rater Reliability.....	71
Effect of Data Acquisition and Environment on Ultrasound Reliability	73
Validity	74

Descriptive Statistics.....	74
Correlation	75
Agreement.....	76
Discussion	77
Hyolaryngeal Excursion.....	77
Thyrohyoid Approximation	78
Tongue Thickness	78
Cross Sectional Area of Submental Muscles	79
Online Versus Offline Measurement Reliability.....	79
Effect of Environment on Ultrasound Reliability	80
Effect of Data Acquisition and Frame Selection on Ultrasound Reliability	80
Validity	84
Limitations	87
Future Directions	89
Conclusion	90
References.....	91
Appendix 1: Participant Information Sheet	114
Appendix 2: Consent Form	117
Appendix 3: Data Collection Protocol	118
Appendix 4: Correlation – Assumption Plots:	120
Hyoid, Liquid, VFSS-US Offline	120
Hyoid, Puree, VFSS-Ultrasound Offline.....	121
Thyrohyoid Liquid:	122
Thyrohyoid Puree.....	123
Appendix 5: Bland-Altman Plots for Validity Results	124

List of Tables

Table 1: Summary of Published Reliability Data for Hyoid Displacement as Measured by Ultrasound using Mandible as Anatomic Reference Point	30
Table 2: Summary of Published Reliability Data for Ultrasound Assessment of Thyrohyoid Approximation	32
Table 3	63
Table 4: Guideline for Interpretation of Pearson’s Correlation Coefficients	64
Table 5: Likely Aetiology of Dysphagia for Participants in Validity Study	67
Table 6: Likely Aetiology of Dysphagia for Pre-selected Participants for Reliability Testing	68
Table 7: Descriptive Statistics for Online Ultrasound Measures	69
Table 8: Descriptive Statistics for Inter-rater Reliability of Online Acquisition of Ultrasound Measures (rater 1 and rater 2)	70
Table 9: Descriptive Statistics for Inter-rater Reliability of Offline Measurement	71
Table 10: Descriptive Statistics of Intra-rater Reliability Using Online/Offline Ultrasound Measures	72
Table 11: Descriptive Statistics for Intra-rater Reliability of Rater 2 Offline Measurement of Ultrasound Measures	72
Table 12: Descriptive Statistics of Intra-rater Reliability Using Online/Offline Ultrasound Measures	73
Table 13: Summary of ICC Values as a Relative Measure of Inter- and Intra-rater Reliability	74
Table 14: VFSS and Ultrasound Measures: Mean and Standard Deviation	75
Table 15: Correlation between Ultrasound and VFSS Measurements of Hyoid Excursion and Thyrohyoid Approximation	76

List of Figures

<i>Figure 1: The hyolaryngeal complex.....</i>	13
<i>Figure 2: The Submental Muscles.....</i>	13
<i>Figure 3: Schematic of the components for consideration in reliability of ultrasound assessment of swallowing</i>	26
<i>Figure 4: Submental muscles in coronal plane.....</i>	37
<i>Figure 5: Ultrasound image of hyolaryngeal rest position, depicting anatomical reference points</i>	47
<i>Figure 6: Ultrasound image of thyrohyoid rest position, depicting anatomical reference points.....</i>	48
<i>Figure 7: Ultrasound image of tongue thickness measurement, depicting anatomical and bolus hold reference points for measurement</i>	49
<i>Figure 8: Ultrasound image of cross sectional area of floor of mouth muscles</i>	50
<i>Figure 9: Hyoid displacement, rest</i>	53
<i>Figure 10: Hyoid displacement, maximum displacement.....</i>	53
<i>Figure 11: Ultrasound thyrohyoid approximation, rest</i>	54
<i>Figure 12: Ultrasound thyrohyoid approximation, maximum displacement.....</i>	54
<i>Figure 13: Geniohyoid measured including superior border of mylohyoid</i>	55
<i>Figure 14: Left anterior belly of the digastric</i>	55
<i>Figure 15: Right anterior belly of the digastric</i>	55
<i>Figure 16: VFSS measure of hyoid excursion, rest.....</i>	57
<i>Figure 17: VFSS measure of hyoid maximum excursion</i>	57
<i>Figure 18: VFSS measurement of thyrohyoid approximation, rest.....</i>	58
<i>Figure 19: VFSS measurement of thyrohyoid, maximum approximation.....</i>	58
<i>Figure 20: Online tongue thickness measurement.....</i>	82
<i>Figure 21: Offline tongue thickness measurement.....</i>	82
<i>Figure 22: Online geniohyoid measurement.....</i>	84
<i>Figure 23: Offline geniohyoid measurement.....</i>	84
<i>Figure 24: Online anterior belly of digastric measurement</i>	84
<i>Figure 25: Offline anterior belly of digastric measurement</i>	84
<i>Figure 26: Online anterior belly of digastric measurement.....</i>	84
<i>Figure 27: Offline anterior belly of digastric measurement.....</i>	84

Introduction

The estimated time taken to translate clinically valid research into practice is 17 years (Balas & Boren, 2000). While it is difficult to accurately estimate the true time lags in knowledge translation (Morris, Wooding, & Grant, 2011), it is clear that translating research into day to day clinical practice is challenging (Grimshaw, Eccles, Lavis, Hill, & Squires, 2012; Neta et al., 2015; Riley, Glasgow, Etheredge, & Abernethy, 2013). Barriers to knowledge translation in public healthcare are extensive (Riley et al., 2013) and include engagement of the key stakeholders, resourcing, training, varied methods for knowledge translation, variable review of clinician behaviour and infrequent links and collaboration between research establishments and clinical environments (Jones, Roop, Pohar, Albrecht, & Scott, 2015; O'Connor & Pettigrew, 2009).

Clinical practice should be supported by policies for implementing evidence-informed practice (NHS Executive, 1997; Haynes & Haines, 1998). Knowledge and evidence gathered from peer-reviewed research should be the key driver of service delivery, decision making and strategic direction in clinical environments (Chassin, 1990). This approach provides clinicians with the assurance that they are providing consistent, safe and effective intervention, leading to the best possible outcomes for patients (Haynes & Haines, 1998).

Clinical research and strong relationships between healthcare environments and research establishments, such as universities, have the potential to support the diffusion of research findings and act as a catalyst to knowledge translation in the healthcare environment (Légaré et al., 2011; Sackett, 2000). Clinical research that is generated in the field of

swallowing and swallowing disorders has potential to positively impact clinical practice and patient outcomes.

Dysphagia is defined as “an impediment to the normal passage of swallowed material between the mouth and the stomach” (Spechler, 1999, p. 233). Oropharyngeal dysphagia is restricted to “difficulty in effective passage of solids or liquids from the oropharynx to the upper oesophagus” (Hurwitz, Nelson, & Haddad, 1975, p. 313). Oropharyngeal dysphagia is a common consequence of a wide variety of medical conditions and represents a substantial health issue affecting people across the lifespan (Cook & Kahrilas, 1999). It is prevalent in the elderly population and a feature of many acute and progressive neurological conditions (Groher & Bukatman, 1986; Siebens et al., 1986). Accurate diagnosis of dysphagia is critical to ensure appropriate management and rehabilitation of swallowing, in order to reduce mortality and morbidities associated with the condition such as dehydration (Leibovitz et al., 2007), malnutrition (Foley, Martin, Salter, & Teasell, 2009) and pulmonary compromise (Marik & Kaplan, 2003).

A comprehensive clinical examination of swallowing is critical to provide valuable information on a person’s swallowing ability and in order to make judgement of risk (Carnaby, 2012; Daniels, Huckabee, & Gozdzikowska, 2019; McCullough & Martino, 2013), however some of the findings need to be interpreted with caution (Baylow, Goldfarb, Taveira, & Steinberg, 2009; Brates, Molfenter, & Thibeault, 2019; Horner & Massey, 1988; Leder & Espinosa, 2002; Mann, Hankey, & Cameron, 2000; Martino, Pron, & Diamant, 2000; McCullough, Wertz, & Rosenbek, 2001; Splaingard, Hutchins, Sulton, & Chaudhuri, 1988). Some of the most severely dysphagic patients can be the least obvious on clinical assessment due to the lack of sensory awareness and lack of cough response to food or fluid

entering the airway (McCullough et al., 2001). Splaingard et al. (1988) demonstrated only 42% of patients who were aspirating were identified using clinical observation. Horner and Massey (1988) reported that while the vast majority of dysphagic patients, who did not aspirate, complained of dysphagia; over half of those who were observed to aspirate, did not. More recently, improvements have been made to the clinical swallowing evaluation, especially in identifying high risk patients, by the addition of tools such as the cough challenge (Miles et al., 2013; Perry, Miles, Fink, & Huckabee, 2019) and qualitative measures, with normative data to compare against, such as the Test of Masticating and Swallowing Solids (TOMASS, Huckabee et al., 2018). However diagnosis depends on instrumentation (Huckabee, Macrae, & Lamvik, 2015). There is little dispute in the literature that readily accessible instrumental swallowing assessment methods are required in order to achieve differential diagnosis of dysphagia, to identify the impact of compensatory strategies and to recommend rehabilitation plans (Baylow et al., 2009; Daniels, McAdam, Brailey, & Foundas, 1997; Logemann, 1997; Logemann et al., 2008; Mann et al., 2000; Vose & Humbert, 2018).

Options for instrumental swallowing assessment include videofluoroscopic study of swallowing (VFSS) and fiberoptic endoscopic evaluation of swallowing (FEES). The ‘gold standard’ for accurate diagnosis of oropharyngeal dysphagia is widely considered to be VFSS (Costa, 2010; Logemann, Rademaker, Pauloski, Ohmae, & Kahrilas, 1998) in large part due to its longevity; however, it comes with challenges and limitations. These include exposure to ionising radiation and difficult accessibility for many of the most vulnerable patients, such as those in critical care environments (O’Neil-Pirozzi et al., 2003; Perry & Love, 2001). FEES, while relatively portable, is invasive and though the procedure is often well tolerated (Leder, Sasaki, & Burrell, 1998; Warnecke et al., 2009), it does carry a low risk of

complications such as epistaxis, syncope and laryngospasm. Therefore, it must be completed where access to medical attention can be guaranteed (Nacci et al., 2016; Warnecke et al., 2009).

An alternative option for instrumental assessment of swallowing that may address some of the limitations of VFSS and FEES, is ultrasound (Chi-Fishman, 2005). Ultrasound is a low risk, non-invasive tool that uses high frequency sound waves to acquire real time images of key structures (Venables, 2011). Ultrasound was first used to visualise the tongue, larynx, velum and submental muscles in research in the 1970s for the purpose of assessing speech sound production (Hamlet & Reid, 1972; Shawker, Sonies, & Stone, 1984). This progressed to use in the assessment of swallowing function in the 1980s (Sonies, Parent, Morrish, & Baum, 1988) and, since that time, assessment of swallowing using ultrasound has been investigated by a number of researchers (Ahn et al., 2015; Chi-Fishman, 2005; Huang, Hsieh, Chang, Chen, & Wang, 2009; Kuhl, Eicke, Dieterich, & Urban, 2003; Macrae, Doeltgen, Jones, & Huckabee, 2012; Manabe et al., 2015; Miura et al., 2014). Research using ultrasound assessment of key swallowing features has been conducted on both healthy and dysphagic participants and yet despite reasonable results in both validity and reliability (Hsiao, Chang, Chen, Chang, & Wang, 2012; Kuhl et al., 2003; Macrae et al., 2012), this tool has not yet been translated into clinical environments.

Fundamental to this study is the hypothesis that while there are many possible reasons that ultrasound has not translated into clinical practice for dysphagia assessment; one of these may be due to limited clinical access to the instrumentation that is found in many research labs. However, recent technological advances have resulted in the development of small pocket-sized, portable ultrasound devices that cost much less than standard ultrasound

equipment. The use of these small portable devices could provide a readily accessible, non-invasive tool to screen and identify which patients to refer on for 'gold standard' instrumental swallowing assessment, where VFSS is a limited resource. Portable ultrasound would be especially useful in screening patients who have difficulty accessing VFSS such as those who are severely physically impaired and require ambulance transfers. There is additional potential to compliment VFSS in supporting differential diagnosis of specific impairments of swallowing, such as reduced hyolaryngeal excursion and later it may be useful as a tool to measure change over time, for example, to ascertain the impact of an implemented rehabilitation programme.

This research focussed on the reliability of portable ultrasound assessment of swallowing in patients with dysphagia. Several components of reliability were explored in order to provide information that would be likely to impact knowledge translation of ultrasound technology into clinical practice. This study was part of a larger project exploring the validity of ultrasound assessment of swallowing using the same hand-held portable instrumentation in both healthy adults and dysphagic patients.

Literature Review

Swallowing and Dysphagia

Swallowing is defined as “an orderly physiological process that transports ingested material from the mouth to the stomach”(Dodds, 1989, p. 171). “The goal of swallowing is to complete this process safely and efficiently in order to maintain adequate nutrition, hydration, and quality of life” (Vose & Humbert, 2018, p. 281). Swallowing is a complex neurophysiological task which involves the bilateral and symmetrical coordination of both contraction and inhibition (Ertekin & Aydogdu, 2003) of thirty-one pairs of striated muscles (Dodds, Stewart, & Logemann, 1990). It is mediated by a complex distributed neural network including multiple cortical centres (Gordon, Hewer, & Wade, 1987; Huckabee, Deecke, Cannito, Gould, & Mayr, 2003; Mihai et al., 2014; Miller, 1982), sub-cortical structures (Daniels et al., 1997; Mihai et al., 2014), the brainstem (Dodds et al., 1990; Kessler & Jean, 1985) and seven peripheral afferent and efferent cranial nerve pathways (Daniels et al., 2019; Dodds et al., 1990; Hamdy et al., 1997). A healthy person will spontaneously swallow their accumulated saliva approximately two to three times per minute while they are awake (Murray, Langmore, Ginsberg, & Dostie, 1996); they increase this frequency when eating or drinking. Many of these swallows, particularly the spontaneous swallows of saliva, occur without significant conscious awareness or input (Dodds, 1989; Ertekin, 2011); however, for some people, swallowing function can be or become impaired and therefore does not function in such an effective and sub-conscious manner.

Dysphagia or disordered swallowing is an interruption to safe and effective swallowing between the mouth and the stomach (Seaman, 1976). Oropharyngeal dysphagia is restricted to difficulty in transferring a bolus between the mouth and oesophagus (Bulat &

Orlando, 2005; Hurwitz et al., 1975). The reported incidence of oropharyngeal dysphagia varies considerably across patient populations. Considering stroke alone, up to 78% will present with dysphagia (Martino et al., 2005). Parkinson's disease has an incidence of up to 90% (Sapir, Ramig, & Fox, 2008). Reports also indicate that dysphagia can occur in up to 50% of elderly people (Clavé & Shaker, 2015) and up to 60% of people living within residential care facilities (Cook & Kahrilas, 1999; Siebens et al., 1986). These statistics indicate a large proportion of the population are affected by dysphagia, highlighting the need for effective identification and management.

The impact of dysphagia can be significant. It is associated with dehydration, nutritional compromise and aspiration, where food or fluid enter the airway, which can lead to respiratory complications including aspiration pneumonia, choking and even death (Berzlanovich, Fazeny-Dörner, Waldhoer, Fasching, & Keil, 2005; Croghan, Burke, Caplan, & Denman, 1994; Martin et al., 1994). Dysphagia and its complications not only present health consequences for the individual but data are beginning to quantify the impact on length of hospital stay and the resultant significant financial implications on stretched public healthcare (Allen, Greene, Sabido, Stretton, & Miles, 2019; Altman, Yu, & Schaefer, 2010; Langmore, Skarupski, Park, & Fries, 2002; Marik & Kaplan, 2003; Niederman, McCombs, Unger, Kumar, & Popovian, 1998), highlighting the need for accessible swallowing assessment and treatment options.

Stages of Swallowing

Swallowing combines both voluntary and involuntary elements and, for ease of conceptualisation, is often separated into phases of swallowing. These classifications vary in

number and description (Dodds, 1989; Dodds et al., 1990; Miller, 1982), however, four stages of swallowing can be considered as pre-oral, oral, pharyngeal and oesophageal (Daniels et al., 2019).

Pre-oral (Anticipatory) Stage

The pre-oral phase involves the anticipatory elements that occur when a person first sees, smells or anticipates food or fluid (Leopold & Kagel, 1997). Depending on the stimulus, anticipatory saliva will be generated and the vocal folds may even begin to close for early airway protection (Ohmae, Logemann, Kaiser, Hanson, & Kahrilas, 1995).

Oral Stage

The oral phase of the swallow begins as the bolus reaches the oral cavity. Complex inhibition and excitation of paired muscle groups is required for the jaw, lips, tongue, cheeks and palate muscles to respond appropriately to the type of bolus and delivery method (Leopold & Kagel, 1997). Fluids delivered via a cup will require different muscle responses to solid foods on a fork. For a solid food bolus, the mouth must first open by contracting the jaw opening muscles, (mylohyoid, geniohyoid, anterior belly of the digastric and lateral pterygoid), while relaxing the jaw closing muscles (masseter, medial pterygoid, and temporalis; Daniels et al., 2019; Fuller, Pimentel, & Peregoy, 2012; Palmer, Rudin, Lara, & Crompton, 1992). Contraction of the accessory facial muscles, (zygomaticus, risorius and quadratus labi superioris) may be required to retract the lips to allow larger boluses to enter the oral cavity (Daniels et al., 2019). As the bolus enters the mouth, the jaw and lips (orbicularis oris) will close to prevent anterior spillage. The posterior tongue elevates to

contact the velum which creates a glossopalatal seal to prevent premature spillage of the bolus into the pharynx (Dodds, 1989). Solid foods require bolus preparation; the tongue manipulates the food within the mouth, mixing food with saliva for lubrication and placing it in a position for the teeth to break down the food into smaller fragments using lateral and rotary jaw movement (Mistry & Hamdy, 2008). The cheek muscles (buccinators), support the tongue to maintain position of the bolus, preventing it from falling into the lateral sulci while preparing it into a manageable state for the pharyngeal swallow (Ertekin & Aydogdu, 2003). Sensory feedback from receptors within the oral cavity monitor the progress of bolus preparation, influencing and modifying the motor sequence accordingly (Ertekin & Aydogdu, 2003; Mistry & Hamdy, 2008).

Preparatory vocal fold adduction (Ohmae et al., 1995; Shaker, Dodds, Dantas, Hogan, & Arndorfer, 1990) and halting of respiration will often occur prior to bolus transfer into the pharynx (Martin-Harris et al., 2005). Once a cohesive bolus is formed, the glossopalatal seal is volitionally released and the tongue propels the bolus into the oropharynx by squeezing against the palate. The base of the tongue drops to allow the onward passage of the bolus and the tongue blade pushes the bolus into the hypopharynx. As the bolus reaches the region of the anterior faucial arches and ramus of the mandible, the oral stage ends (Logemann et al., 1998). Sensory receptors signal the nucleus of the tractus solitarius in the medulla which elicits pharyngeal swallowing (Jean, 2001). Swallowing for ingestion requires cognitive input along with cortically processed sensory information in order to modulate the brainstem motor response for each specific bolus type (Daniels et al., 2019).

Pharyngeal Stage

Variability in the position of bolus at time of onset within the healthy population leads to debate as to the reference point for onset and completion of the pharyngeal phase (Chi-Fishman & Sonies, 2000; Hiimeae & Palmer, 1999; Martin-Harris, Brodsky, Michel, Lee, & Walters, 2007; Perlman, Booth, & Grayhack, 1994; Robbins, Hamilton, Lof, & Kempster, 1992; Shaw et al., 1995). For example, Hiimeae and Palmer (1999) studied a small sample of ten young healthy adults and found on analysis of their VFSS' that with harder foods it was not unusual for the bolus to dwell in the valleculae for 8-10 seconds prior to eliciting the pharyngeal swallow. However for the purposes of classification only, the pharyngeal stage can be considered as beginning once the pharyngeal swallowing response is initiated, as identified by the onset of hyolaryngeal excursion (Young, Macrae, Anderson, Taylor-Kamara, & Humbert, 2015).

During the pharyngeal phase of swallowing a number of biomechanical events occur within approximately one second (Daniels et al., 2019; Kahrilas, Logemann, Lin, & Ergun, 1992). Velopharyngeal closure is achieved by elevating the soft palate (levator palatini, musculus uvulae), closing the nasopharynx and increasing pharyngeal pressure which supports bolus transition (Dodds et al., 1990; Perlman, Schultz, & VanDaele, 1993). As the bolus descends toward the valleculae, the base of tongue retracts to the posterior pharyngeal wall (styloglossus, posterior belly of the digastric, glossopharyngeus and stylohyoid), providing direct pressure on the descending bolus and, along with sequential top to bottom pharyngeal constriction and shortening, supports bolus transition and clearance into the oesophagus (Cerenko, McConnel, & Jackson, 1989; Kahrilas et al., 1992).

In order to protect the airway while swallowing, four levels of laryngeal valving occur, which progress superiorly in a bottom to top sequence (Shaker et al., 1990). The true and false vocal folds adduct, the arytenoid cartilages move medially and tilt anteriorly to approximate the epiglottis, the larynx ascends and the epiglottis inverts. (Ekberg, 1982; Ohmae et al., 1995; Shaker et al., 1990; Van Daele, McCulloch, Palmer, & Langmore, 2005; Vose & Humbert, 2018). In conjunction, supraglottic shortening, achieved in part by contraction of the suprahyoid muscles as well as the thyrohyoid muscle, allows for thyrohyoid approximation and compression of the quadrangular membrane, closing the anterior laryngeal vestibule (Daniels et al., 2019).

Published research on the mechanism for epiglottic inversion typically cites hyolaryngeal excursion as the primary facilitator (Ekberg, 1982; Fink, Martin, & Rohrmann, 1979; Logemann et al., 1992). Hyolaryngeal excursion refers to the synchronistic elevation of the larynx and displacement of the hyoid bone in both an anterior and superior direction (Matsuo & Palmer, 2008). Fink et al. (1979) completed frame by frame analysis of cinefluorograms, finding that epiglottic inversion occurs at the time of maximal elongation of the hyoepiglottic ligament which pulls the base of the epiglottis in an anterior trajectory resulting in deflection of the passive structure. This finding was replicated by Ekberg (1982) and much of the work completed on swallowing physiology and rehabilitation since has followed this understanding (Mepani et al., 2009; Shaker et al., 2002; Watts, 2013; Yoon, Khoo, & Liow, 2014). However, more recently Pearson, Taylor, Blair, and Martin-Harris (2016) used computer software to map anatomical landmarks on VFSS studies completed with dysphagic patients, attempting to evaluate the impact of various muscle groups on epiglottic inversion. Their findings indicate that tongue base retraction and laryngeal elevation alone result in the passive movement of the epiglottic inversion, indicating hyoid

displacement, while correlated, is not the facilitator. While this debate is important when considering which muscles we should consider when providing rehabilitation, assessment of hyolaryngeal excursion remains a critical indication of swallowing safety, as it has previously been consistently correlated with airway closure (Ekberg, 1982; Mepani et al., 2009; Shaker et al., 1990).

The hyolaryngeal complex (see Figure 1) is a group of structures consisting of the laryngeal cartilages (epiglottis, thyroid, cricoid, arytenoids, cuneiforms and corniculates), hyoid bone and the muscles and ligaments connecting them (Fuller et al., 2012; Pearson, Langmore, Louis, & Zumwalt, 2012). Hyolaryngeal excursion is achieved by the contraction of the suprahyoid muscles (posterior belly of the digastric and stylohyoid) and the collective submental muscles which attach to the mental symphysis of the mandible and hyoid bone (mylohyoid, geniohyoid, anterior belly of digastric; see Figure 2). Additionally the larynx is elevated towards the hyoid by contraction of the thyrohyoid muscle (Fuller et al., 2012). This combination displaces the hyolaryngeal complex in a superior and anterior trajectory (Cook et al., 1989; Ertekin & Aydogdu, 2003; Mepani et al., 2009). Recent evidence also indicates the longitudinal pharyngeal muscles (salpingopharyngeus, palatopharyngeus and stylopharyngeus) provide a supporting role in this displacement of the hyolaryngeal complex (Pearson et al., 2012).

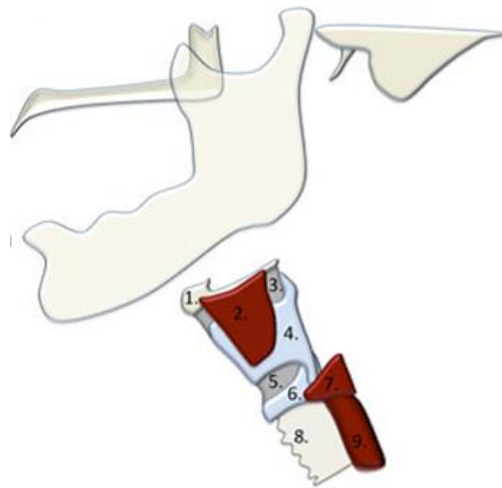


Figure 1: The hyolaryngeal complex: Includes: 1. hyoid, 2. thyrohyoid muscle, 3. thyrohyoid membrane, 4. thyroid cartilage, 5. cricothyroid membrane, 6. cricoid cartilage and 7. cricopharyngeus. 8. Trachea and 9. Oesophagus. Elevation of this complex helps to protect the airway and open a relaxed upper oesophageal sphincter. Reprinted with permission (Pearson Jr & Zumwalt, 2014)

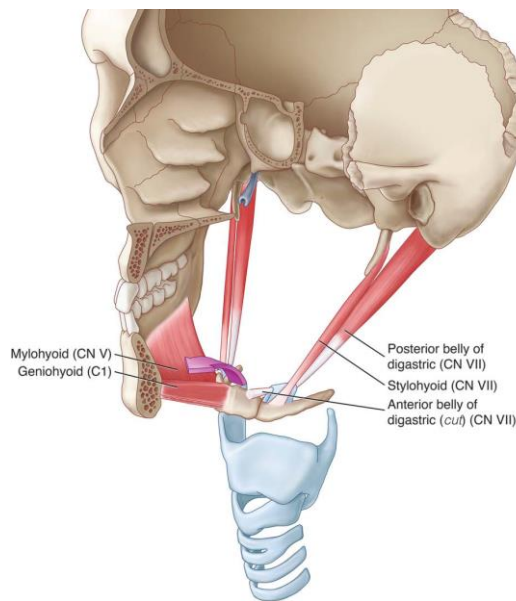


Figure 2: The Submental Muscles. Reprinted with Permission (Pearson Jr, Griffeth, & Ennis, 2019)

The cricopharyngeus muscle attaches to the hyolaryngeal complex, therefore, its anterior and superior displacement along with the relaxation of the cricopharyngeus muscle itself, contributes to the opening of the pharyngoesophageal segment to allow free bolus transit into the oesophagus (Cook et al., 1989; Crary, Carnaby, & Groher, 2006; Ekberg, 1986; Jacob, Kahrilas, Logemann, Shah, & Ha, 1989; Kahrilas, Lin, Rademaker, &

Logemann, 1997; Matsuo & Palmer, 2008; Sivarao & Goyal, 2000; Vandaele, Perlman, & Cassell, 1995).

The literature presents significant variability on the normative data for the degree of superior and anterior movement of the hyoid bone and thyroid cartilage during swallowing (Molfenter & Steele, 2011). This may, in part, be due to variability in the method for quantification. Some researchers used frame by frame analysis of hyoid excursion (Bingjie, Tong, Xinting, Jianmin, & Guijun, 2010; Ishida, Palmer, & Hiimae, 2002; Logemann et al., 2000; Logemann, Pauloski, Rademaker, & Kahrilas, 2002; Paik et al., 2008), while others compare a rest frame with a frame representing maximum displacement position (Dantas et al., 1990; Dodds et al., 1988; Kim & McCullough, 2008; Perlman, VanDaele, & Otterbacher, 1995). Another source of variability may be number and type of boluses presented, some studies presented a single swallow of each bolus texture/size (Ishida et al., 2002; Kang et al., 2010; Kendall & Leonard, 2001; Paik et al., 2008), whereas others used two of each (Dodds et al., 1988; Kim & McCullough, 2008; Logemann et al., 2000; Logemann et al., 2002). Variations may also be found across age range of participants (Kendall & Leonard, 2001; Kim & McCullough, 2008; Logemann et al., 2000). For example Kim and McCullough (2008) found a reduction in anterior displacement of the hyolaryngeal complex in healthy adults over 70 years old compared to those between the ages of 21 and 51. However, no differences were found for superior displacement as a function of age. Logemann et al. (2000) assessed a much older cohort and found men over 80 years old displayed significantly reduced maximum anterior and posterior hyoid displacement compared to men under 30 years, citing reduced muscle reserve as the likely cause. Conversely, Kendall and Leonard (2001) found that with small boluses, adults over 65 years demonstrated increases in hyoid displacement however; this was not replicated with large bolus size. The author hypothesised

that this may be a compensation for a reduction in duration of hyolaryngeal excursion noted as people age; a compensation which cannot be sustained for larger boluses. Ishida et al. (2002) assessed a small sample size of 12 healthy adults and reported that superior hyoid displacement was highly variable particularly with solids compared to liquids, while there was no bolus effect for anterior displacement. This research also identified a discrepancy between the amplitude of upward displacement of the hyoid between the male and female subjects, hypothesising that the significantly lower resting position of the larynx noted in male subjects may explain this.

This variability in normative data for hyoid displacement is important to note when considering what measurement is used to identify normal from abnormal. Some researchers have suggested that calculating percentage change between rest and maximum hyoid excursion may provide superior information to absolute distance travelled (Kuhl et al., 2003; Macrae et al., 2012; Mevani et al., 2009).

Co-ordination of breathing and swallowing is said to be precisely timed to prevent the bolus from being aspirated (Selley, Flack, Ellis, & Brooks, 1989). However in a study exploring breathing and swallowing patterns at various ages, the timing and co-ordination was found to vary amongst healthy adults (Martin-Harris et al., 2005). This discrepancy indicates that while a period of swallow apnoea is essential for airway protection (Jean, 1984; Selley et al., 1989), some variability still allows for swallowing without airway invasion. Martin-Harris et al. (2005) found that apnoea duration varied from 0.5-10 seconds, however, the median period of apnoea was found to be 1 second. Martin-Harris et al. (2005) identified four different respiratory patterns straddled this period of apnoea when swallowing. The dominant respiratory pattern was an expiration/expiration pattern (swallowing mid

expiration) found in approximately 70% of participants, while roughly 20% presented with expiration/inspiration pattern, 4-5% displayed an inspiration/expiration pattern, and inspiration/inspiration was seen in just 2% of participants. Similar findings were discovered in research conducted by Kelly, Huckabee, Jones, and Carroll (2007) with a mid-expiration swallow pattern found in almost 60% of participants, yet the percentage of their participants presenting with an inspiration/expiration pattern (16%) was higher than in the study by Martin-Harris et al. (2005). The dominance of the mid-expiration swallowing pattern is hypothesised to be useful to clear traces of airway penetration using post-swallow expiration (Widdicombe, Addington, Fontana, & Stephens, 2011). The pharyngeal stage of swallowing ends with the cricopharyngus muscle relaxing and the bolus entering the oesophagus (Robbins et al., 1992).

Oesophageal Stage

The oesophageal stage of swallowing begins as the bolus passes through a relaxed and distended cricopharyngeus muscle into the oesophagus (Christrup, 1964). The oesophagus is made up of striated muscle which converts to smooth muscle at roughly the level of the aortic arch (Goyal & Chaudhury, 2008). Sequential top to bottom peristaltic waves propel the bolus through the oesophagus, the lower oesophageal sphincter relaxes and the bolus empties into the stomach (Goyal & Chaudhury, 2008; Miller, 1982).

Oesophageal transit time in healthy adults is said to be approximately 13 seconds (Imam, Shay, Ali, & Baker, 2005; Kahrilas, Dodds, & Hogan, 1988; Torrico, Corazziari, & Habib, 2003) with prolonged oesophageal clearance being identified where bolus remains beyond 20 seconds (Torrico et al., 2003). A recent study by Miles, Clark, Jardine, and Allen

(2016) found that there was overall increased oesophageal transit time and greater variance with 20ml fluid boluses in healthy older adults (60-98 years old). Their research also revealed differences across bolus consistency; they found significant variability in the oesophageal transit time across all ages for both barium pills and dense barium paste, indicating that transit time for solids may be much longer in the healthy population (Miles et al., 2016). The oesophageal phase of swallowing is completed once the bolus tail is cleared from the oesophagus and the lower oesophageal sphincter closes preventing reflux of gastric contents (Palmer et al., 1992).

Instrumental Assessment of Swallowing

Accurate diagnosis of dysphagia is critical to ensure appropriate management and rehabilitation of swallowing. Diagnosis depends on instrumentation (Daniels et al., 1998; Huckabee et al., 2015; Leder & Espinosa, 2002; Leder et al., 1998; Martino et al., 2000; McCullough et al., 2001; Miles, McFarlane, Scott, & Hunting, 2018; Splaingard et al., 1988). Clinical evaluation of swallowing has been compared with instrumental assessment in a number of studies (Daniels et al., 1997; DePippo, Holas, & Reding, 1992; Leder & Espinosa, 2002; Linden, Kuhlemeier, & Patterson, 1993; Mann et al., 2000; McCullough et al., 2001; Splaingard et al., 1988). Many of these studies illustrate the risks of reliance on clinical evaluation alone relative to accurate identification of physiology impairments, pharyngeal residue and airway penetration/aspiration.

Identification of aspiration on clinical evaluation poses significant challenges for clinicians. Some of the most severely dysphagic patients are likely to be the least obvious on clinical evaluation (Horner & Massey, 1988; Splaingard et al., 1988). A study by Leder and

Espinosa (2002), investigated 49 stroke patients with clinical examination of swallowing and then by FEES. They found that clinical evaluation underestimated the risk of aspiration on the most severely dysphagic patients and overestimated it on those patients with low risk. Silent aspiration (aspiration without a cough response), can be impossible to detect on clinical evaluation alone. In a study by Daniels et al. (1998) 67% of consecutively admitted stroke patients ($n=55$) were found to silently aspirate during VFSS. Furthermore, Miles et al. (2018), who assessed 180 mixed aetiology patients referred for FEES, demonstrated that while patients were less likely to aspirate on thickened fluids they were more likely to cough in response to aspiration of a thin fluid and to silently aspirate a thickened fluid. This novel finding indicates that patients with dysphagia do not have the same physiological reaction to aspiration of fluids of different consistencies and highlights the value of instrumental assessment to accurately assess the safety and benefits of diet modification.

Critically, instrumentation supports differential diagnosis in order to guide successful management and rehabilitation of dysphagia. Reliance on clinical evaluation alone has the potential to steer clinicians towards management and compensation for dysphagia rather than diagnosis and remediation, for example the prescription of diet and fluid modifications. Over-prescription of thickened fluids can have negative outcomes, as they are often not well tolerated by patients (Logemann et al., 2008), and as a result can further exacerbate dehydration (Murray, Miller, Doeltgen, & Scholten, 2014). Instrumental assessment of swallowing provides objective data to treat dysphagia and guide rehabilitation with targeted exercises or protocols (Daniels et al., 2019; Elmståhl, Bülow, Ekberg, Petersson, & Tegner, 1999; Linden, 1989). A study completed by Perry et al. (2019) implemented a management protocol in stroke patients with dysphagia, which increased the appropriate onward referral for VFSS prior to initiating oral intake. This resulted in significantly improved outcomes for

patients with dysphagia whereby 81% of patients returned to a standard diet and 67% went home within three months compared to 55% and 55%, respectively, prior to the implementation of the protocol.

Clinically, the most commonly used options for instrumental assessment of swallowing are FEES and VFSS. FEES uses “a flexible laryngoscope to view the pharyngeal and laryngeal structures before during and after deglutition”(Rommel & Hamdy, 2016, p. 54). VFSS is defined as “a dynamic continuous radiological examination of the anatomy and function of the oral cavity, pharynx and UES opening that includes lateral and frontal views while swallowing” (Rommel & Hamdy, 2016). FEES and VFSS both provide a snapshot objective assessment of swallowing function. Endoscopic assessment using FEES provides a reasonably portable, objective assessment of functional swallowing and is useful to identify airway penetration and aspiration over a full meal (Hiss & Postma, 2003; Leder et al., 1998). However, FEES does not allow for visualisation of the oral stage of swallowing, or visualisation or quantification of critical physiological elements of swallowing such as epiglottic deflection, hyolaryngeal excursion or thyrohyoid approximation. This limits the clinical ability to provide targeted rehabilitation. In addition, the procedure requires an invasive endoscopic view of swallowing, which is not always tolerated well by patients (Aviv et al., 2000; Nacci et al., 2008) additionally it must be completed where access to medical attention can be guaranteed given the small risk of complications such as epistaxis, syncope and laryngospasm (Nacci et al., 2016).

The gold standard for validation of emerging tools is considered by many to be VFSS (Costa, 2010; Logemann, 1998). While VFSS and FEES are now both considered highly valuable and complementary (Langmore, 2003), VFSS allows for frame by frame analysis,

providing spatial and temporal information about swallowing biomechanics, thus it remains the most reliable instrumentation to provide accurate differential diagnosis supporting appropriate rehabilitation planning (Daniels et al., 1998; Vose & Humbert, 2018).

Despite its benefits, VFSS has a number of limitations, including challenges with patient access and availability, and exposure to ionizing radiation (Logemann et al., 1998; Perry & Love, 2001). There is an on-going need to balance the duration, frame rate and image resolution required for VFSS with radiation safety issues inherent in prolonged studies or repeated exposure to fluoroscopic imaging (Bonilha et al., 2013). This is particularly limiting when used for assessment of the benefits of rehabilitation, where multiple studies may be indicated to assess change.

In addition to these limitations, clinical interpretation of VFSS is often reliant on a clinician's subjective interpretation and analysis of the study, which have been shown to have poor inter-rater reliability (Sia, Carvajal, Carnaby-Mann, & Crary, 2012; Wilcox, Liss, & Siegel, 1996). It is possible to complete specific biomechanical measurements from VFSS imaging (Kim & McCullough, 2008; Leonard, Kendall, McKenzie, Gonçalves, & Walker, 2000; Leonard & McKenzie, 2006; Logemann et al., 2000) but these have not translated well into standard clinical practice, possibly due to the time required for analysis and requirements for specialist training and software (Baijens, Barikroo, & Pilz, 2013). Access to radiographic imaging is also an issue in many speech-language therapy departments due to competing demands for imaging and physical constraints on the most vulnerable of patients, such as those with severe mobility issues, significant fatigue or those in intensive care units (O'Neil-Pirozzi et al., 2003). Identification and development of alternative or complementary

methods of instrumental swallowing assessment, such as ultrasound, that address some of these limitations would be of significant clinical value.

Reliability of VFSS Measurement of Biomechanical Swallowing Features

VFSS has been used by multiple researchers to produce quantitative objective measurements of key biomechanical swallowing features such as hyolaryngeal excursion and thyrohyoid approximation (Ekberg, 1986; Kim & McCullough, 2008; Leonard et al., 2000; Leonard & McKenzie, 2006; Logemann et al., 2000; Sia et al., 2012; Thompson et al., 2014; Wang, Chang, Chen, Lin, & Hsiao, 2010). Good inter-rater reliability for these displacement measures has been consistently reported. Leonard et al. (2000) reported excellent inter-rater reliability amongst four raters for hyolaryngeal displacement ($r > 0.90$) and high reliability for hyoid to larynx approximation ($r = 0.75$) in 15 healthy participants. Similar high inter-rater reliability ($r = 0.83$, $p < 0.01$) and intra-rater ($r = 0.88$, $p < 0.01$) was reported by Kim and McCullough (2008) for hyoid excursion in eight healthy participants, inter-rater ($r = 0.83$, $p < 0.01$) and intra-rater ($r = 0.88$, $p < 0.01$). Sia et al. (2012) analysed VFSS studies of 10 patients with dysphagia and reported good reliability of both hyoid excursion and laryngeal displacement (intra-rater ICC > 0.92 , inter-rater ICC = 0.77), however, this was only based on two videos as a 10% sample of the twenty videos analysed. Thompson et al. (2014) used the co-ordinates of anatomical landmarks on 80 VFSSs to assess key kinematic measures and found excellent inter-rater reliability amongst six raters (ICC = 0.90 - 0.97).

While good reliability has been well reported, various methods for measurement have been used across studies. For measurement of hyoid excursion several studies have used cervical vertebra as a reference point to account for postural changes by participants during

the study (Kendall & Leonard, 2001; Kim & McCullough, 2008; Leonard et al., 2000; Logemann et al., 2000; Paik et al., 2008), while others have not accounted for postural changes in the same way (Ekberg, 1986; Wang et al., 2010). Thompson et al. (2014) indicated that measuring hyoid excursion in reference to the stable reference point of the mandible was the superior choice, as it most accurately represents underlying functional anatomy.

Much of the research uses a marker of known diameter which allows for image calibration to be completed post-hoc, accounting for image distortion, participant movement and magnification (Leonard et al., 2000; Logemann et al., 2000; Paik et al., 2008). Other researchers have used the average length of cervical vertebra (15mm) as a calibration tool based on estimates made from skeletons (Kim & McCullough, 2008). Sia et al. (2012) explored the impact of image rotation and location of calibration marker and found that location of calibration marker did not have an impact on measurement reliability but that image rotation affected horizontal displacement measures, thus indicating that methodological differences must be considered when comparing across studies. Finally a study by Nordin, Miles, and Allen (2017) found that experience using objective VFSS measures dramatically increased the reliability over a short eight week period, (ICC = .31-.60 in week one, ICC = .71 to .98 in week eight) regardless of years of experience. These findings indicate the importance of training packages and practice to achieve reliable measures.

Ultrasound

Ultrasound or ultrasonography is a method of imaging tissues using the reflected energy from high frequency sound waves inaudible to human hearing (Venables, 2011). Ultrasound transducers generate ultrasonic pulses to create sound waves, the frequency of the sound wave depends on the frequency of the ultrasonic pulses (Thorsen & Lakin, 2010). Medical devices typically use frequencies ranging between 2 -10 MHz (Aldrich, 2007; Kundra, Mishra, & Ramesh, 2011). As an ultrasound beam travels through tissues, reflection of the sound waves occurs at interfaces between tissues which have different acoustic impedance, producing an echo; this echo is received by the transducer and an ultrasound image is generated (Kundra et al., 2011; Venables, 2011). Distinct two dimensional boundaries are able to be visualised as a result of the acoustic shadow cast by these boundary changes in tissue surfaces (Watkin, 1999). Weak echos, which show up as grey, occur where tissues have similar acoustic impedance such as the difference between soft tissue and water (Aldrich, 2007). Distinct boundaries are more obvious where tissue boundaries have different acoustic impedance such as soft tissue and bone (Kossoff, 2000).

Ultrasound brightness-mode (B-mode), also known as grey scale imaging, produces a rapid sequence of two dimensional images that allow motion to be viewed in real time, and as such, is a useful modality to visualise dynamic body movements, such as swallowing (Aldrich, 2007; Ardakani, 2006; Kossoff, 2000). Transducer type impacts the field of view produced on ultrasound; linear transducers produce a rectangular image and are typically used for imaging of superficial structures, curvilinear transducers produce a wedge shaped view and are typically used for visualising deeper structures (Kundra et al., 2011). Electronic callipers within most ultrasound systems can be used to measure the distance between key

structures as well as make two-dimensional and three-dimensional estimate measures of muscles (Arts, Pillen, Schelhaas, Overeem, & Zwarts, 2010).

Ultrasound has the potential to offer quantifiable instrumental assessment of key elements of swallowing biomechanics (Chi-Fishman, 2005). Recent technology has developed highly portable devices, increasing accessibility to some of the highest risk and most vulnerable patients who are unable to access outpatient clinics. Ultrasound has the potential to augment diagnostic information, while eliminating some of the challenges faced by FEES and VFSS, as it is non-invasive and does not use ionising radiation (Barnett et al., 2000; Jain, 2008; D. L. Miller, 1991). Diagnostic ultrasound has been used since the 1970s in phonetic research to examine the tongue shape used in different speech sounds (Keller & Ostry, 1983; Minifie, Kelsey, Zagzebski, & King, 1971; Morrish, Stone, Sonies, Kurtz, & Shawker, 1984; Sonies, Shawker, Hall, Gerber, & Leighton, 1981; Stone, Morrish, Sonies, & Shawker, 1987; Watkin & Zagzebski, 1973). Ultrasound assessment of swallowing has progressed over a similar timeframe (Shawker et al., 1984; Skolnick, Zagzebski, & Watkin, 1975; Sonies et al., 1988). In the 1980s, Sonies et al. (1988) first examined timing of normal oropharyngeal swallowing with frame by frame analysis of the motion of the tongue, as well as hyoid bone movement from initial rest to final rest position during swallowing.

Research using b-mode ultrasound imaging creating 'real-time' video suggested that ultrasound may provide an accurate measurement of quantifiable temporal and spatial measures such as hyolaryngeal excursion and thyrohyoid approximation, offering insights into these swallowing biomechanics (Chi-Fishman, 2005). In addition to measurement of the kinematic, biomechanical swallowing events, research comparing ultrasound measurement of muscle morphometry with both magnetic resonance imaging (MRI) and computed

tomography (CT) has shown good agreement. This suggests that ultrasound is a valid and reliable method to measure the cross-sectional area of muscles (Alanen, Falck, Kalimo, Komu, & Sonninen, 1994; Macrae, Jones, Myall, Melzer, & Huckabee, 2013). Ultrasound may therefore allow for differentiation between healthy and myopathic muscles (Chi-Fishman, Hicks, Cintas, Sonies, & Gerber, 2004). Other studies have used ultrasound assessment of overall tongue thickness as an indicator of deterioration in muscle mass associated with progressive neurological or neuromuscular diseases, such as amyotrophic lateral sclerosis (Nakamori et al., 2016; Tamburrini et al., 2010) and Duchenne muscular dystrophy (Van den Engel-Hoek et al., 2013).

Reliability and Validity of Ultrasound Measures of Swallowing

When reviewing the published reliability data for ultrasound assessment of swallowing, it is important to consider which components impact measurement of reliability. Clinical translation of a tool into standard clinical practice requires a clear understanding of each of these components. Reliability of ultrasound has several variables that should be considered, including: image acquisition by the clinician, image selection (from the acquired images) for analysis, measurement of the selected image, and the impact of measurement environment (online immediately within the clinical environment using the internal calibration of the system, or offline from stored images using specific technology for measurement). Where analysis is completed offline it is also important to know if this is from video, where image selection is required, or from stored pre-chosen still images, (see Figure 3 for summary). This is particularly important for the purposes of knowledge translation, as ultrasound may be completed by a number of different clinicians and the impact of image acquisition on reliability is, therefore, an important consideration.

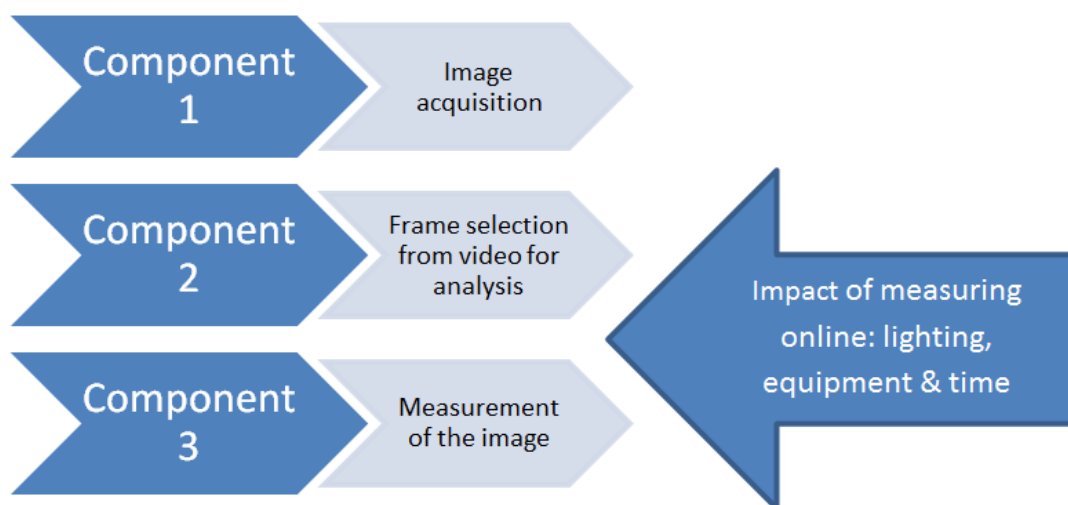


Figure 3: Schematic of the components for consideration in reliability of ultrasound assessment of swallowing

Some studies describe all components when assessing reliability. For example, Huang et al. (2009) reported on reliability of acquisition by different technicians, and indicated that the dynamic images were stored, implying that image selection and measurement by the two raters were completed offline. While Hsiao et al. (2012) also reported on acquisition by different technicians, they did not make it clear whether each examiner was expected to select the image for analysis or whether images were measured from pre-selected still frames. It is therefore difficult to compare reliability of ultrasound across existing studies, given the variance in reported methodology.

One of the key benefits of ultrasound instrumentation is the opportunity for immediate online measurement and calculation using the internal calibration, which is intrinsically relative to the settings of the image acquisition. Review of the published research using ultrasound for swallowing assessment has demonstrated that most completed ultrasound calculations offline from stored images (Ardakani, 2006; Chi-Fishman & Sonies, 2002; Feng et al., 2015; Kuhl et al., 2003; Lee, Lee, Kang, Im Yi, & Kim, 2016; Macrae et al., 2012;

Macrae et al., 2013; Yabunaka et al., 2012; Yabunaka et al., 2011). One study that performed VFSS, FEES and ultrasound simultaneously on a small sample (n=8) of healthy subjects, indicated that their ultrasound measures were completed on the ultrasound monitor using internal calibration, however, they were not explicit about whether the measures were made live/online or offline (Komori, Hyodo, & Gyo, 2008). A number of the studies using ultrasound for assessment of swallowing do not explicitly outline whether their calculations were completed online using the internal calibration system or whether the data captured were in fact measured offline from stored images (Ahn et al., 2015; Chen, Hsiao, Wang, Fu, & Wang, 2017; Hsiao et al., 2012; Huang et al., 2009; Tamburrini et al., 2010). Analysis of the reliability of online assessment using ultrasound would be of great value when considering the translation of this tool into standard clinical practice, as one potential barrier to the clinical translation of dynamic swallowing measures may be the time required to complete these measures offline.

In addition to the reliability of ultrasound, it is also important to consider validity. Information on validity is necessary to identify whether the instrumentation provides you with the information that is required from it (Portney & Watkins, 2000). The validity of ultrasound assessment of kinematic swallowing measures can be measured by exploring the association between measures made on a validated tool, such as VFSS, against ultrasound measures (Chen et al., 2017; Hsiao et al., 2012). For measures of muscle morphometry, the association between ultrasound and imaging techniques such as MRI is completed. When considering validity of ultrasound measures as compared with VFSS, only correlation should be considered, as the exact measure of the same biomechanical feature may differ, due to the nature of the images acquired.

Ultrasound Assessment of Hyoid Excursion

Measurement of both lingual imaging and swallowing using ultrasound was initially fraught with concerns over errors as a result of transducer-imposed restriction on jaw mobility, and measurement errors resulting from technician movement during data collection (Sonies et al., 1988). Ultrasound transducer position must be maintained relative to the head, in order to ensure accurate measures of swallowing kinematics are obtained and to control for movement artefact (Chi-Fishman, 2005). A number of researchers developed various head/transducer stabilisation systems to ensure a participant's head remained stable in order to achieve good reliability (Peng, Jost-Brinkmann, & Miethke, 1996; Stone & Davis, 1995). However the need for head support systems does pose challenges in terms of translation of this assessment method into standard clinical practice. Further research exploring other methods to minimise measurement errors resulting from transducer or head movement during data collection have been employed; however, these still required careful design and head positioning (Gick, Bird, & Wilson, 2005; Scarborough, Waizenhofer, Siekemeyer, & Hughes, 2010).

More recent use of an anatomic reference point has been found to eliminate the need for head stabilisation while maintaining good reliability (Chen et al., 2017; Hsiao et al., 2012; Lee et al., 2016; Macrae et al., 2012; Perry, Winkelman, & Huckabee, 2016). In each of these studies electronic callipers were used to measure the distance between the mandible, as a reference point that remains relatively stable to the hyoid, first at rest, prior to the initiation of swallowing, and again when the hyoid bone is at maximal anterior displacement. Calculations from rest to maximal excursion represent hyolaryngeal displacement. Research conducted by Perry et al. (2016) specifically compared ultrasound measures of hyolaryngeal excursion using a head stabilisation system with the hand-held method. In both conditions,

the mandible was used as a stable reference point. The researchers repeatedly assessed 24 healthy adults over 51 years old, within and across sessions, using both methods, resulting in a total of 720 measures. Overall they found no significant difference in mean measurement of hyolaryngeal displacement across methods. Additionally they found that use of the fixed transducer reduced the movement flexibility required for clear echoic reflection off tissues when swallowing. This inflexibility resulted in almost 6% of the images being of poor quality and unable to be analysed, compared with less than 1% of the hand held images (Perry et al., 2016).

Reliability data for measurement of hyolaryngeal displacement using ultrasound are encouraging, (published data is summarised in Table 1). Macrae et al. (2012) collected data on five healthy participants and measured inter-rater reliability using ICC. The authors calculated ICC values of 0.86 for both rest and maximal displacement; intra-rater reliability was found to be higher with an ICC value of 0.95 for rest and 0.98 for maximal displacement. As part of a larger study, Hsiao et al. (2012) analysed reliability data from assessment of ten of 40 healthy participants and reported high intra-rater ICC values for hyoid excursion at 0.92 and 0.84 for the two examiners and inter-rater reliability ICC values between raters at 0.80. Hsiao et al. (2012) calculated the absolute distance travelled across subjects, whereas Macrae et al. (2012) and Lee et al. (2016) calculated percentage change in addition to absolute change. Macrae et al. (2012) found that a reduction in the variance of measurement was found when calculating percentage change compared to absolute change. These reliability statistics are encouraging and indicate that further assessment of hyolaryngeal excursion using ultrasound in a clinical environment would be of value.

Table 1: Summary of Published Reliability Data for Hyoid Displacement as Measured by Ultrasound using Mandible as Anatomic Reference Point

Authors & year	Measure	Participants	Reliability components ²	No of raters	Intra-rater ICC	Inter-rater ICC
Macrae et al. (2012)	Absolute and percentage displacement	5 healthy subjects	Image selection and offline measurement from stored images	3	0.90	0.64
					0.93	0.70
Hsiao et al. (2012)	Absolute displacement	10 healthy subjects	Data acquisition and measurement (not specified if online/offline)	2	0.927 0.842	0.806
Chen et al. (2017)	Absolute displacement	10 dysphagic patients	Image measurement (not specified if online/offline)	2	0.996	0.892
					0.959	

Validation of ultrasound assessment of hyolaryngeal excursion has been explored in a variety of ways in the literature. Hsiao et al. (2012) completed ultrasound evaluation of 40 healthy participants, 30 stroke patients with dysphagia, and 30 stroke patients without dysphagia. Ultrasound measures of hyoid excursion in dysphagic patients (mean 1.3 cm) were significantly less than both healthy controls (mean 1.7 cm) and stroke patients without dysphagia (mean 1.6 cm). Hyolaryngeal movement below 1.5 cm was determined to be the cut-off point for tube-feeding-dependent dysphagia, with a calculated sensitivity and specificity of 73.3% and 66.7%, respectively. Lee et al. (2016) explored validation of hyolaryngeal displacement using ultrasound by comparing it against key indicators of dysphagia. They assessed fifty-two patients identified as having dysphagia on VFSS and rated their penetration-aspiration scale (PAS) with thin fluids and later measured their hyoid excursion on ultrasound and analysed the images offline. This study found that a reduction in hyoid excursion, as assessed by ultrasound, correlated with an increased PAS rating. Hyoid excursion in the group who did not aspirate (n=21, 15.9±2.7 mm) was significantly greater

² Reliability components include: acquisition, image selection, measurement online/offline

than those who demonstrated airway penetration ($n=20$, 11.5 ± 2.8 mm) or aspiration ($n=11$, 8.0 ± 1.0 mm) however, reliability was not explored.

These data suggest that under research conditions ultrasound analysis of hyolaryngeal displacement, using an anatomic reference point, can result in high reliability and validity against VFSS. Reliability data in both healthy and dysphagic participants is promising and therefore has the potential to provide useful information on the degree of dysphagia.

Ultrasound Assessment of Thyrohyoid Approximation

Measurement of this biomechanical feature of swallowing has been evaluated using ultrasound in both healthy and dysphagic individuals. Kuhl et al. (2003) measured thyrohyoid approximation using ultrasound on 42 healthy and 18 dysphagic participants; analysis was completed offline from stored images. These researchers reported significantly reduced thyrohyoid approximation in the dysphagic patients, with a mean relative laryngeal reduction of 42% (± 10), compared with healthy volunteers who had a mean relative laryngeal reduction of 61% (± 3). However, neither validity against VFSS nor reliability of these measures was investigated.

Huang et al. (2009) collected data on 15 healthy participants and 40 patients following stroke, 20 of whom were dysphagic and 20 who presented with normal swallowing. A proportion of the dysphagic participants also underwent VFSS for validation purposes. Percentage change measures of thyrohyoid approximation in stroke patients were similar between ultrasound ($40.4 \pm 7.1\%$) and VFSS ($42 \pm 16.1\%$). Construct validity was provided by documenting greater thyrohyoid approximation in healthy individuals ($47.2 \pm$

4.9%) than in stroke patients with normal swallowing (42.6 +/- 8.3%, $p = .02$) and stroke patients with dysphagia (34.0 +/-10.9%, $p = .02$). These measures produced a sensitivity of 0.75 and specificity of 0.77 for detection of dysphagia, yet did not define specific functional, physiologic outcomes. Finally, assessment of inter-rater reliability (summarised in Table 2) produced an ICC > 0.97 for measures in each of the groups, however, it was unclear whether the reliability was based on immediate online measurement or measurement of stored images offline.

Table 2: Summary of Published Reliability Data for Ultrasound Assessment of Thyrohyoid Approximation

Authors & year	Measure	Participants	Reliability components	No of raters	Intra-rater ICC	Inter-rater ICC
Huang et al. (2009)	Percentage displacement	5 healthy subjects	Data acquisition, image selection and measurement (not specified if online /offline)	2	0.974 0.989	0.983

More recently Ahn et al. (2015) explored impact of positional change on measures of thyrohyoid approximation when assessed with ultrasound. Twenty healthy participants were assessed in supine and sitting positions; each set of measures was taken three times by the same examiner and averaged. They reported no significant difference in the percentage change between rest and maximum thyrohyoid approximation in supine (38.30 ± 4.52) or sitting position (38.44 ± 7.04). This study did not explore reliability using standard inter-rater reliability calculations, or specify whether measures were completed immediately online or offline from stored images. However this research provides some assurance that the use of anatomical landmarks for thyrohyoid approximation measures may eliminate the need to

control for positioning, which is likely to improve the translation of this assessment tool into clinical practice.

These data indicate some promising findings about reliability and validity of measures of thyrohyoid approximation using ultrasound, however, the research is limited and, therefore these measures require further investigation.

Ultrasound Assessment of Mid-section of Tongue Thickness

In addition to assessment of swallowing kinematics, ultrasound has been used for a number of measures of muscle morphometry. The association between tongue thickness and dysphagia is gaining evidence (Hsiao et al., 2012; Nakamori et al., 2016; Tamburrini et al., 2010; Tamura, Kikutani, Tohara, Yoshida, & Yaegaki, 2012). Ultrasound offers a simple method to provide immediate quantifiable data in assessment of tongue thickness.

Several studies have explored assessment of tongue thickness as a predictor of dysphagia. Tamburrini et al. (2010) used ultrasound to assess nine patients with amyotrophic lateral sclerosis (ALS) for both tongue morphometry and functional tongue evaluation. The participants additionally underwent VFSS for correlation measures. The static evaluation of tongue thickness provided subjective evaluation of the presence or absence of tongue atrophy, and the researchers found that, the presence of tongue atrophy was associated with at least one dynamic swallowing abnormality on VFSS. This assessment of tongue atrophy, made without quantifiable measures of tongue thickness or reliability analysis, demonstrated a preliminary indication that there may be a link between tongue morphometry and dynamic swallowing. Nakamori et al. (2016) expanded on this research using ultrasound to

quantitatively assess tongue thickness in 18 patients with ALS compared with age matched healthy controls. They found that tongue thickness was significantly lower in the ALS group (40.9 ± 1.0 mm, $p = 0.016$) compared with healthy participants (44.6 ± 0.7 mm, $p = 0.004$). Additionally they noted that tongue thickness progressively reduced with progression of the disease ($p = 0.002$). A reduction in tongue thickness was found to be a predictor of dysfunction in the oral preparatory and oral transit elements of swallowing as assessed by VFSS, though reliability was not explored.

The use of ultrasound for assessment of tongue thickness in an elderly population was explored by Tamura et al. (2012) who assessed 104 healthy elderly individuals between 70 and 90 years old using ultrasound in the coronal plane. This study explored tongue thickness correlated with measures of malnutrition, and reported a significant relationship between tongue thickness and nutritional status. Their study used several measures to evaluate nutritional status including: skinfold thickness of the triceps, arm muscle area, body weight and height. Their findings showed some correlation between tongue thickness and measures of nutrition, for example, arm muscle area ($r = 0.424$; $p = 0$), however, this finding was similar for body weight ($r = 0.434$; $p = 0$). It is therefore unclear whether these findings indicated that malnutrition may induce sarcopenia in the tongue or if tongue thickness is associated with the person's overall size. Their study did however report good intra-rater reliability of the tongue thickness measurement (ICC = 0.856, 95% CI: 0.741-0.924), it is unclear from the manuscript which reliability components were considered.

Hsiao et al. (2012) combined two ultrasound measures in an attempt to predict the degree of dysphagia in patients following stroke. Their study included the difference between maximum tongue thickness and minimum tongue thickness during swallowing to determine maximum change in tongue thickness. They used the ultrasound transducer in the sagittal

plane. The authors claim that these measures, in conjunction with hyoid excursion estimates, can predict the need for tube-feeding in dysphagic patients. Those with a tongue thickness change of less than 1.0 cm and hyoid bone displacement of less than 1.5 cm were likely to require tube-feeding. Reliability of the tongue thickness change measures were calculated using ICC. Intra-rater values were 0.758 and 0.661 and the inter-rater value was 0.685. These data indicate that there is potential for ultrasound measures of tongue thickness to predict the degree of dysphagia in a clinical setting. However, the pathophysiologic link between tongue thickness and functional swallowing measures still needs to be elucidated; given the methodological variation across studies, further research is required in order to understand the meaning of these apparent correlations.

Ultrasound Assessment of Cross-sectional Area of Submental Muscles

It has been reported that the size of submental muscles can be increased by swallowing exercises in healthy subjects (Pearson, Hindson, Langmore, & Zumwalt, 2013; Watts, 2013). The findings of a clinical case study reported by Huckabee et al. (2015) indicate that there is potential for ultrasound measurement of the submental muscles as an indicator of potential gains gathered from targeted submental rehabilitation exercises. In addition to the potential benefits of quantifying increases in cross-sectional area of submental muscles as a result of targeted exercise, there is also potential for quantifying decreases in cross-sectional area caused by sarcopenia or muscle weakness. Reduced cross-sectional area of the submental muscles has been proposed to be an accurate predictor of swallowing difficulties in older adults (Feng et al., 2012).

Measurement of the cross-sectional area of submental muscles with ultrasound (see Figure 5), has been shown to correlate highly with the gold standard of measurement using magnetic resonance imaging (MRI; Macrae et al., 2013). Macrae et al. (2013) compared the measurement of bilateral anterior belly of the digastric on both ultrasound and MRI on 11 healthy participants and found that while MRI measures were slightly larger than those made on ultrasound, there was high correlation between the methods (left: $r = 0.909$, $p = 0.001$; right: $r = 0.776$, $p = 0.005$). Reliability was not investigated. An additional finding from this study was that ultrasound was the superior tool of the two when used to measure the geniohyoid, as MRI was unable to allow for sufficient differentiation of the borders of the muscle.

In order to maintain consistency of measures, the methods described in the literature for assessing cross-sectional area of submental muscles were reviewed. Initially, Watkin et al. (2001) used a technique where a sweep of the submental muscles was completed from mandible to hyoid, the mid-point of the muscle was then calculated as the half-way point in the total number of still frames. Both Macrae et al. (2013) and Perry et al. (2016) reported placing the transducer approximately mid-way between the mandible and the thyroid cartilage. Perry et al. (2016) compared use of a fixed transducer to a hand held method and found very little difference between techniques; however, the authors indicated concerns regarding the degree of variability in measures, regardless of the method used.

A study by Feng et al. (2012) explored the relationship between dysphagia and geniohyoid cross-sectional area. They investigated the size of the geniohyoid, using CT scanning, in 40 young adults and 40 older adults, 20 of the 40 older adults were known to aspirate and 20 did not. They found geniohyoid atrophy was associated with both ageing ($p=$

<0.05) and aspiration but only in the older male subjects ($p = < 0.01$), however they did not explore reliability. Feng et al. (2015) later explored the relationship between geniohyoid measurement and hyoid excursion. They reported that in a supine position maximal hyolaryngeal displacement, as measured with ultrasound, correlated with the size of the geniohyoid muscles. However they were unable to replicate this finding in a seated position or when side lying; additionally reliability was not explored. The use of ultrasound to measure the cross-sectional area of submental muscles, as with measures of tongue thickness, may have implications for both the identification of swallowing disorders and outcome measures in dysphagia rehabilitation.

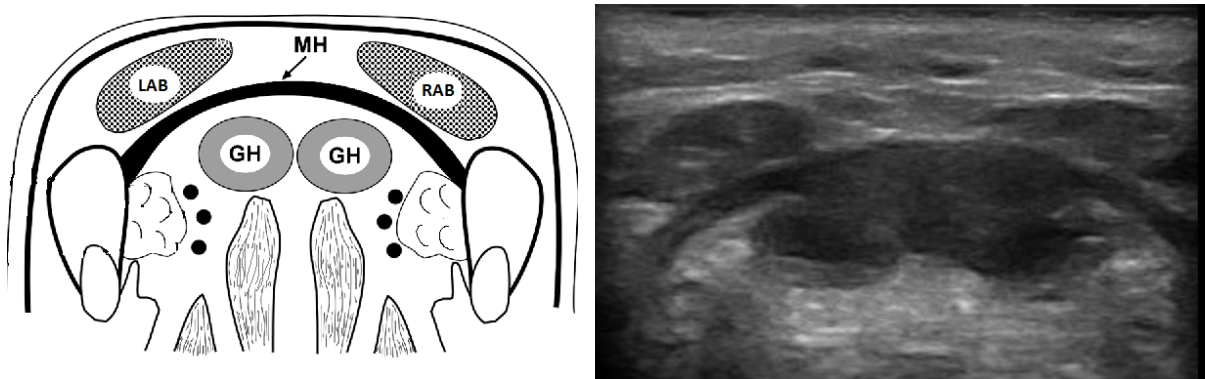


Figure 4: Submental muscles in coronal plane.

Left Image: line drawing, (adapted from Yasumoto, Nakagawa, Shibuya, Suzuki, & Satoh, 1993).

Right image: ultrasound view captured with Clarius™ L7 Transducer.

LAB: left anterior belly of the digastric; RAB: right anterior belly of the digastric; GH: geniohyoid; MH: mylohyoid

To date, research using ultrasound assessment of swallowing kinematics has focussed on hyolaryngeal excursion and thyrohyoid approximation. These measures have been chosen due to their significant role in the safety and effectiveness of swallowing. Hyolaryngeal excursion allows for epiglottic deflection to assist airway protection whilst pulling open the upper oesophageal sphincter (UES) to allow bolus transfer through the pharynx into the oesophagus (Ekberg, 1982; Fink et al., 1979; Logemann et al., 1992). Reduced hyolaryngeal excursion has been associated with aspiration risk and pharyngeal residue in both dysphagia and aging (Paik et al., 2008; Steele et al., 2011). Therefore, accurate assessment of distance

travelled has significant clinical applicability. Thyrohyoid approximation plays a critical role in supraglottic airway compression and thus, airway protection when swallowing (Dodds et al., 1990; Jacob et al., 1989). Reduced thyrohyoid approximation has been associated with aspiration risk (Shaker et al., 2002). Accurate measurement of thyrohyoid approximation provides additional, clinically valid data to support assessment and treatment of pharyngeal dysphagia.

Submental muscles including geniohyoid, mylohyoid and anterior belly of digastric attach to the mental symphysis and the hyoid bone (Miller, 1986); their function is critical to both hyolaryngeal excursion and thyrohyoid approximation (Dodds, 1989). Early data is beginning to demonstrate a link between size of these muscles and swallowing function (Feng et al., 2015; Feng et al., 2012; Hsiao et al., 2012; Nakamori et al., 2016). Therefore, further exploration of reliability of ultrasound measures of submental muscle morphometry including both tongue thickness and cross-sectional area of submental muscles is of value. At present, there are encouraging data on the reliability of sophisticated ultrasound technology in the assessment of swallowing (Chen et al., 2017; Hsiao et al., 2012; Huang et al., 2009; Lee et al., 2016; Macrae et al., 2012). However, no research has yet been published on the reliability or validity of portable ultrasound technology, which offers increased access for patients most at risk and also supports clinical translation.

Study Aims

This study examined the intra- and inter-rater reliability of portable ultrasound measures in the assessment of swallowing. In the assessment of reliability, the impact of data acquisition, image selection and environmental factors on accuracy of online ultrasound measures was explored in comparison to the reliability of offline measurement. Two kinematic swallowing measures were evaluated: hyoid excursion and thyrohyoid approximation during swallowing. In addition, two measures of tongue morphometry were evaluated: tongue thickness and the cross-sectional area of submental muscles. Validity of portable ultrasound measurement against the ‘gold standard’ of VFSS was also explored in a small preliminary sample. This study was one of the first to compare portable ultrasound measurements with kinematic measurements made from images captured concurrently on VFSS.

Hypothesis

It was hypothesised that:

- Portable ultrasound measures of hyoid excursion, thyrohyoid approximation, cross-sectional area of submental muscles and tongue thickness would demonstrate at least moderate inter- and intra-rater ICC reliability values.
- Kinematic swallowing measures of hyoid excursion and thyrohyoid approximation derived from VFSS would correlate with those derived from ultrasound imaging.

Justification

The 'gold standard' in swallowing assessment, VFSS, has limitations primarily in ease of quantifiable measurement, and clinical availability and accessibility for a number of populations. Ultrasound imaging offers a non-invasive, easily accessible and more affordable method of assessment and reassessment, allowing direct quantification of swallowing kinematics and morphometry with no inherent risk. Emerging research on this technique suggests quite reasonable reliability of measurement and validity against VFSS. However these data have been derived using sophisticated instrumentation that is likely well outside the financial feasibility of most allied health services. Perhaps, in part because of this, clinicians have resisted the implementation of ultrasound in clinical practice. Recent technological advances have produced ultrasound instrumentation that is small, portable and is more affordable, within the reach of allied health resourcing, offering the opportunity for online measurements to be made in real time. Thus translation into standard clinical practice may be feasible. It is unknown if clinical use with this technology can match the reliability and validity of more sophisticated instrumentation used in prior experimental research and, thus, is a current obstacle to clinical translation.

Methodology

Study Design

This research was conducted as part of a larger health research council funded project exploring the translation of ultrasound imaging of swallowing to clinical dysphagia assessment and diagnosis. Funding for the project was granted under the Research Partnerships for New Zealand Health Delivery Initiative. Ethical approval was sought from the New Zealand Health and Disability Ethics Committee along with Waitematā District Health Board Maori and locality approval.

The research consisted of three components:

1. First, a prospective validation study of portable ultrasound assessment of swallowing against the 'gold standard' VFSS for measuring both hyolaryngeal displacement and thyrohyoid approximation during swallowing in dysphagic patients.
2. Second, a prospective reliability study of the online portable ultrasound assessment of swallowing data on dysphagic patients between two independent speech-language therapists trained in the use of ultrasound.
3. Finally, a prospective reliability study of the offline measurement of ultrasound data gathered in these dysphagic patients.

Training

The primary investigator underwent training in the use of ultrasound for assessment of swallowing at the Rose Centre for Stroke Recovery and Research in Christchurch on two

separate occasions. Rose Centre staff and students have a proven competency in the use of ultrasound for assessment of swallowing (Huckabee et al., 2015; Macrae et al., 2012; Macrae et al., 2013; Perry et al., 2016). Training included clinical practice using ultrasound and observation of data collection in the laboratory. A consensus guideline was developed amongst the researchers who would be collecting data using the hand-held ultrasound equipment. The co-investigator was initially trained by the primary investigator, using the guideline developed at the Rose Centre to support the training. A second training session for both the primary and co-investigators was conducted by the principal supervisor at the hospital site where data collection would occur. This allowed problem solving around the logistics of data collection in a clinical environment within an allocated time slot. This training closely replicates the typical training provided for the acquisition of new clinical skills within a standard workplace and was therefore felt to be appropriate in order to accurately comment upon clinical translation.

Participants

Inclusion Criteria

All participants were required to be over 18 years old and able to give informed consent, although, for patients with aphasia, this could be done using supported conversation where the treating speech-language therapist indicated it was appropriate. Participants were appropriate for inclusion if they demonstrated either reduced hyolaryngeal excursion or reduced thyrohyoid approximation, identified perceptually by the primary investigator, during their standard care VFSS.

Exclusion Criteria

Individuals who had undergone head or neck surgery or reported relevant allergies, such as allergy to barium, were excluded. Men with large beards who were unwilling to shave were also excluded, as the ultrasound transducer was unable to make adequate contact with the skin surface for ultrasound data collection.

Participant Recruitment

Study participants were recruited from patients, identified as having dysphagia, who were referred for VFSS by a speech-language therapist as part of their usual care. These were both in-patients and out-patients at Waitematā District Health Board. All patients referred for VFSS were invited to participate in the study providing they met inclusion criteria.

Prior to their standard care VFSS, the primary investigator advised potential participants of what participation in the research project would involve. All potential participants received a Participant Information Sheet (see Appendix 1) and were offered an opportunity to consult with family/whānau and/or Māori cultural support prior to recruitment. Potential participants were advised that their decision to participate in the research would not affect their standard care and were given the opportunity to ask the primary investigator questions prior to giving their written consent using the study consent form (see Appendix 2). In circumstances where participants were unable to physically sign the consent form, for example due to a significant limb weakness, the participant provided verbal consent and written consent was gained via proxy.

Participants who did not demonstrate reduced hyolaryngeal excursion or reduced thyrohyoid approximation during their standard care VFSS, were then withdrawn from the study. The primary investigator identified these features perceptually. Where the movement of the hyolaryngeal complex appeared to be only mildly impaired or unclear, the co-investigator was consulted for a second opinion, in order to reduce inclusion bias.

Participant information gathered for the purposes of description included: likely aetiology for dysphagia, date of birth, age, ethnicity and handedness (see Data Collection Protocol, Appendix 3). Based on prior published data, a sample size of 20 was selected for the concurrent study on healthy participants; sample size for this study of patients with dysphagia was increased to 40 to allow for adequate statistical power in the presence of presumed greater variability in task performance. Inter- and intra-rater reliability data were collected on 20% (n=8) of participants. For the purposes of this Master's thesis only data collected on those eight participants will be reported.

Procedures

Liquid barium contrast was prepared in a blender following a recipe of 100grams of X-Opaque–HD barium sulphate suspension formulation powder to 150ml water. The pureed food bolus was prepared following a recipe of 100grams of Watties™ apple puree to 20 grams of X-Opaque–HD barium sulphate suspension formulation powder, stirred until thoroughly dispersed.

A standardised bolus presentation protocol was used. Participants were required to swallow a liquid barium bolus (5ml) and a pureed apple bolus mixed with barium (5ml) under VFSS, while the primary investigator concurrently assessed particular swallowing gestures using the Clarius™ handheld ultrasound in two different ultrasound recording positions (four swallows in total). The examiner was positioned directly in line with the participant and presented the metered bolus using a syringe to minimise body or head movements. Verbal cues were provided to the participant to maintain their head in a neutral position. Where the participant moved during the assessment and/or image quality was low or partially obscured, the bolus was repeated. Participants were never subjected to longer than an additional 120 seconds of radiation screening time as per the protocol approved by the New Zealand and Disability Ethics Committee. All ultrasound measures, completed concurrently with VFSS, were captured by the primary investigator. The primary investigator wore a full lead apron and sleeve, eyewear and glove. Radiation monitoring was carried out using two radiation dosimeters, one worn under the lead apron and one worn outside. These levels were monitored by a district health board senior medical radiography technician.

Safety Assessments and Adverse Events

The increased radiation dosage required by participants was considered to be minimal. Assessment by radiation physicists at the Rose Centre for Stroke Research and Rehabilitation did not highlight any safety concerns for data collection on healthy participants, patients or researchers, providing appropriate lead protection was worn. No adverse events were experienced by participants in the study; however, two participants withdrew due to fatigue following their standard care VFSS.

Data Acquisition

Ultrasound

The ultrasound images were captured using curvilinear (C3: frequency range: 2-6 MHz, depth: 3-30 cm) and linear (L7: frequency range: 2-6 MHz, depth: 3-30 cm) Clarius™ transducers, which connected wirelessly to an iPad for visualisation of images on the Clarius™ ultrasound application. Agreed pre-settings available on the Clarius™, which were found to be most suitable for accurate imaging of each measure, were selected. Depth and gain settings were adjusted with each individual, when required, to improve image clarity according to their specific anatomy. This provided optimal visualisation of the acoustic shadows cast by key anatomical landmarks. Participants were advised to maintain neutral head position and to avoid flexing their neck to accommodate the transducer. Transducer position was maintained by the primary investigator throughout sonogram acquisition, with visual monitoring assuring consistent image quality. Greyscale sonograms were obtained as individual video segments of 20 seconds to record each swallowing event or cross-sectional assessment of the submental muscles. Video segments were reviewed online and frame selection for measurement was completed manually by the ultrasound operator on the iPad. Each still frame, both measured and un-measured, along with video segments were uploaded and saved in the Clarius™ cloud, a password protected website.

Ultrasound Measurement of Hyoid Excursion

A curvilinear (C3) Clarius™ transducer was pre-set to the ‘Abdomen’ examination type. The transducer was generously coated with Aquagel™ for acoustic coupling and manually placed in the sagittal plane on the skin surface submentally; it was held

perpendicular to the floor of mouth with minimal pressure against the skin surface, thus providing a view of anatomical reference points, the mandible and hyoid, for hyoid excursion (see Figure 5). Hyoid rest position was identified while the participant was holding the bolus in their mouth pre-swallow. Participants', who aspirated, coughed or those who required several swallows to clear a single bolus were found to have a great deal of difficulty returning to rest position and therefore a bolus hold position was considered most consistent.

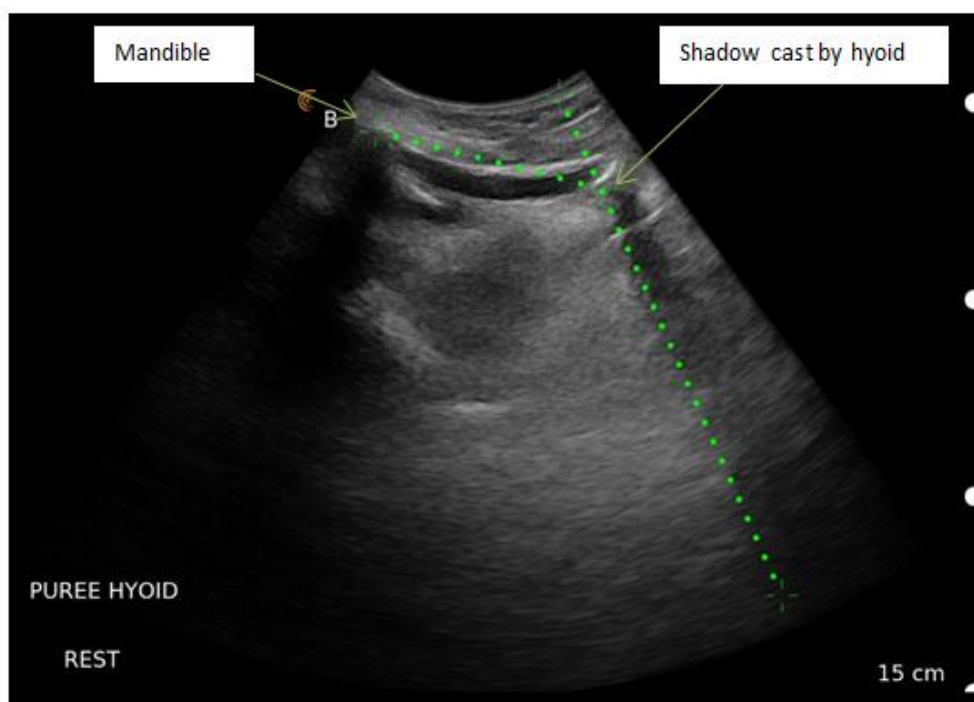


Figure 5: Ultrasound image of hyolaryngeal rest position, depicting anatomical reference points

Ultrasound Measurement of Thyrohyoid Approximation

A curvilinear C3 Clarius™ transducer was pre-set to the 'superficial' examination type, generously coated with AquageI™ for acoustic coupling and manually placed in a longitudinal position over the thyroid which allowed visualisation of the hyoid bone and thyroid cartilage. Thyrohyoid approximation was recorded with the transducer held at the mid-sagittal plane overlying the thyrohyoid muscle with the image encasing the superior

aspect of the hyoid and the inferior aspect of the thyroid cartilage laterally. In participants with a prominent thyroid cartilage, transducer position was moved slightly to one side to prevent the transducer from slipping during laryngeal excursion and to maintain visualisation of the acoustic shadow of the hyoid bone and the thyroid cartilage as anatomical reference points (see Figure 6).



Figure 6: Ultrasound image of thyrohyoid rest position, depicting anatomical reference points

Tongue Thickness

Tongue thickness was measured using sagittal imaging with a bolus hold in order to achieve a consistent measurement point, as coronal imaging has no clear method to manage accurate anterior-posterior positioning (Nakamori et al., 2016; Tamura et al., 2012). The tongue thickness measure used a curvilinear (C3) Clarius™ transducer, pre-set to the ‘Abdomen’ examination type, generously coated with Aquagel™ for acoustic coupling. The transducer was manually placed under the chin and held perpendicular to the floor of mouth

with minimal pressure against the skin surface, thus providing a view of anatomical reference points, the mandible and hyoid and tongue surface. Tongue thickness was measured using a 5ml puree bolus held anteriorly in the mouth, to support identification of the tongue surface as differentiated from the inferior surface of the palate. Puree was chosen as this was most likely texture to be successfully held as a cohesive bolus anteriorly in the oral cavity by patients with oro-pharyngeal dysphagia, (see Figure 7). The 5ml bolus of pureed apple was measured using a syringe and given to the participant who was instructed to hold the bolus on their tongue to allow for measurement prior to swallowing.

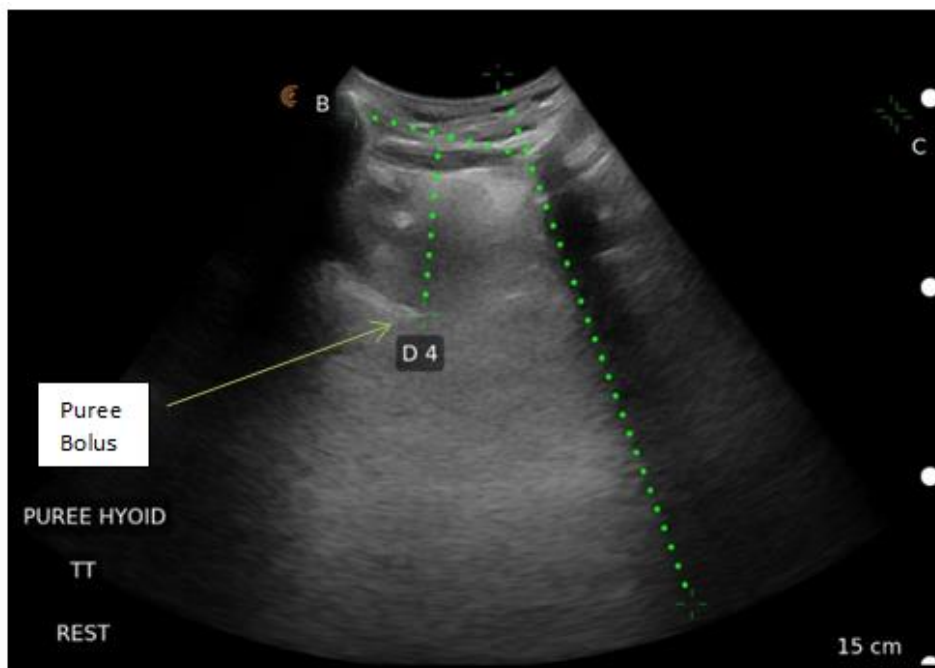


Figure 7: Ultrasound image of tongue thickness measurement, depicting anatomical and bolus hold reference points for measurement

Submental Muscle Cross-sectional Area

A linear (L7) Clarius™ transducer was pre-set to the ‘small parts’ examination type, generously coated with Aquagel™ for acoustic coupling and manually placed under the chin, with minimal pressure against the skin surface. For the measure of submental muscle cross-

sectional area, the transducer was held in in a transverse position, overlying the bilateral anterior belly of digastric, mylohyoid and geniohyoid muscles. In attempt to obtain images of the middle of the muscle, the transducer was moved anterior to posterior to find the largest and clearest boundaries of the floor of mouth muscles (see Figure 8). It is acknowledged that the submental muscles are unlikely to be uniform in size along the anterior-posterior plane. However, choice of measured mid-point between mandible and hyoid did not always provide clear images so this method was chosen to provide most consistency, despite possible subjectivity in image selection. In circumstances where not all of the submental muscles were visible within frame, the transducer was moved laterally to allow full view of the bilateral anterior belly of digastric muscles, taking care to maintain even lateral pressure and consistent anterior-posterior plane to minimise examiner error. The participants were instructed to relax, keep their mouth closed and sit with their chin in a neutral position, without trying to accommodate the transducer by tilting their chin. Once imaging was achieved the operator scrolled through the sonogram to identify an image where the borders of the muscles were clearest and the most consistent in size.

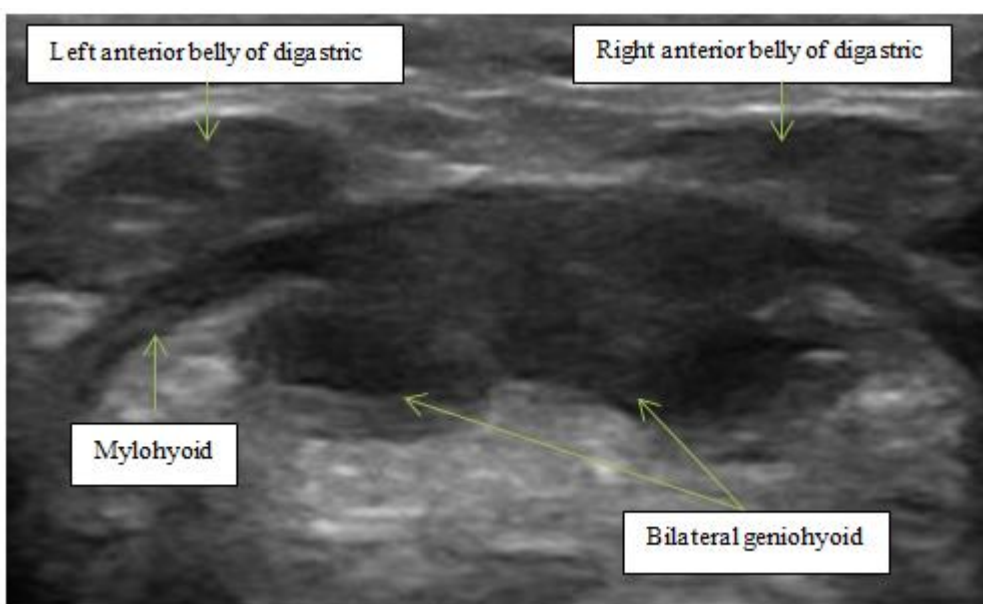


Figure 8: Ultrasound image of cross sectional area of floor of mouth muscles

VFSS Data Acquisition

VFSS images were captured using a Toshiba Ultimix Fluoroscopy unit, using low dose continuous screening mode, which was digitally recorded at 30 frames per second using a Medi-capture USB 170 recorder (USB 170 Medicap). A small metal disc of known diameter (18mm) was taped to the participants' lateral face or spine to calibrate measurement for post-hoc analysis. Each participant was required to sit upright in a chair throughout their assessment. As VFSS was conducted concurrently with ultrasound; the primary investigator was required to sit on a small mobile stool, in order to successfully hold the transducer in position during the procedure. For all simultaneous VFSS and ultrasound measurements the co-investigator monitored the VFSS images captured to ensure visibility of key anatomical markers and calibration disc were maintained, while the primary investigator captured ultrasound data. The primary investigator gave the verbal command to start screening and stop screening to the medical radiography technician, based upon the acquisition of the ultrasound data.

Inter-rater and Intra-rater Reliability Acquisition

For the purpose of analysing inter-rater reliability of ultrasound acquisition and online image selection and measurement the co-investigator completed additional ultrasound evaluations on 20% of the 40 participants in the larger concurrent validation study (n=8), immediately after the primary investigator had completed their ultrasound data collection (concurrently with VFSS). This was usually completed in an adjoining clinic room but on occasion the VFSS suite was used. Every fifth patient was pre-selected in order to prevent selection bias.

Inter-and intra-rater reliability of offline measurement was completed using pre-selected still images acquired by the primary researcher of the same eight patients used in inter-reliability of online acquisition and measurement. Each investigator was blinded to the measurements made by the other investigator and their own measurements.

The shortest gap between online data acquisition and measurement and offline measurement was 27 days. Each rater measured all images offline twice with at least 11 days between offline measures. This time period was a replication of the time used for data collection on healthy individuals in a second concurrent project, allowing for comparison, and is considered long enough to ensure that recall of the previous measurement is highly improbable (Vaz, Falkmer, Passmore, Parsons, & Andreou, 2013).

Data Extraction

Ultrasound

Ultrasound Measurement of Hyoid Excursion

The reference point for the mandible was defined as the “point at which the shadow cast by the spine of the mandible intersected with the brightly echogenic cortical surface of the mandibular bone” (Macrae et al., 2012, p. 76). A best fit line was drawn along the anterior border of the shadow of the hyoid bone in order to improve consistency of this reference point (see Figure 9). The distance between the acoustic shadows cast by the mental spine of the mandible and that of the hyoid bone were calculated at both rest position and at maximum displacement of the hyoid. Maximum hyoid excursion (see Figure 10) was measured where the hyoid bone reached maximal anterior displacement during each swallow.

The ultrasound operator selected these frames from the 20 second sonogram recording for online measurement purposes, with the ability to manually scroll backwards and forwards for accurate frame selection. Maximum excursion of the hyoid bone was calculated as a percentage change between the rest frame and maximum distance frame, ($\text{max distance} - \text{rest distance} / \text{rest distance} \times 100$).

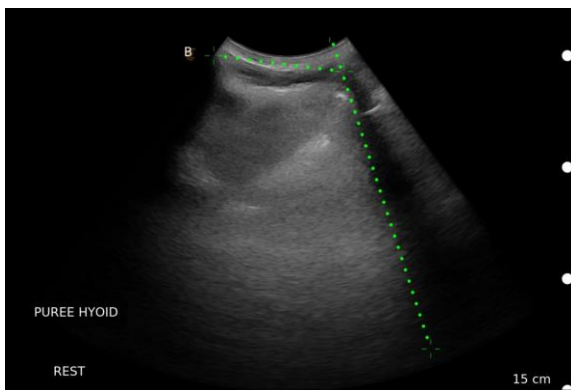


Figure 9: Hyoid displacement, rest

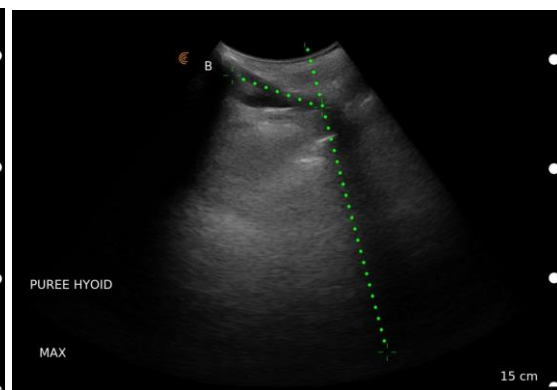


Figure 10: Hyoid displacement, maximum displacement

Ultrasound Measurement of Thyrohyoid Approximation

The visibility of the acoustic shadows cast by the hyoid and thyroid cartilage for thyrohyoid approximation was much more variable across patients than for hyoid excursion. Therefore, the reference point did need to vary across subjects, requiring the use of either the inferior shadow or superior shadow of the hyoid or thyroid cartilage at different times. However for each participant, the same visible reference point was used for both rest (see Figure 11) and maximum approximation (see Figure 12). Measurement between the acoustic shadows cast by the hyoid and thyroid cartilage was made using the straight line measurement tool in both rest position and maximum approximation. Maximum thyrohyoid approximation was calculated as a percentage change between the rest frame and maximum distance frame, ($\text{max distance} - \text{rest distance} / \text{rest distance} \times 100$).

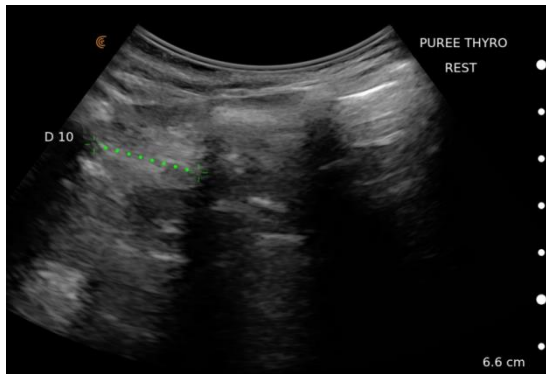


Figure 11: Ultrasound thyrohyoid approximation, rest

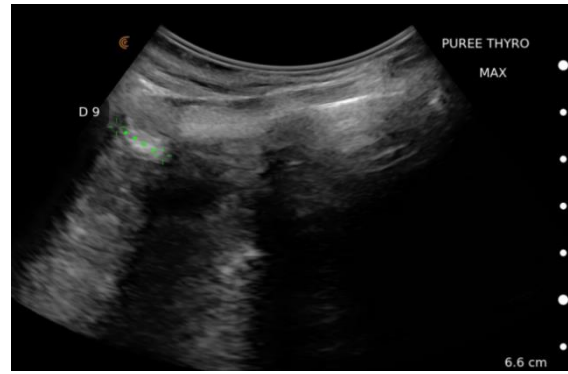


Figure 12: Ultrasound thyrohyoid approximation, maximum displacement

Tongue Thickness

Measurement of tongue thickness was made by bisecting the distance between shadows cast by the mandible and the hyoid (see Figure 7). One calliper was placed at the calculated mid-point of the line between the mandible and hyoid shadows to provide a consistent reference point. The other calliper was placed at the posterior edge of the held bolus, which appeared as a triangle shape in the majority of cases. The video segment was reviewed where context was required as viewing the bolus in transit allowed accurate placement of the callipers at rest.

Submental Muscle Cross-sectional Area

Using the freehand measurement tool on the Clarius™ application, the muscles of interest were traced to calculate the area (see Figures 13-15). For the bilateral geniohyoid muscles they were calculated as a single unit. However, as differentiation between the mylohyoid and geniohyoid at the superior surface (see Figure 13) was frequently indistinct,

the mylohyoid at the superior border was always included in the measure while, left and right borders were excluded.

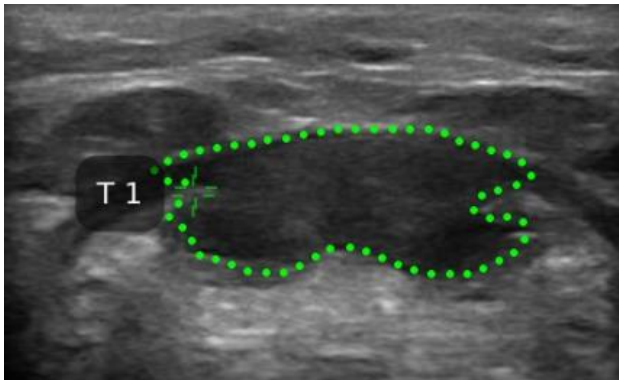


Figure 13: Geniohyoid measured including superior border of mylohyoid

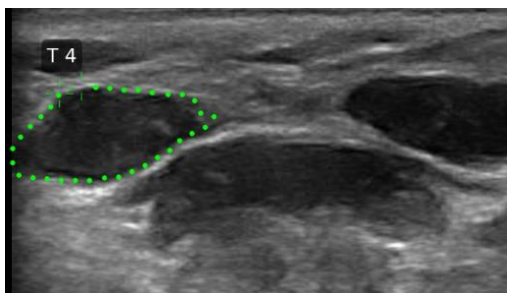


Figure 14: Left anterior belly of the digastric

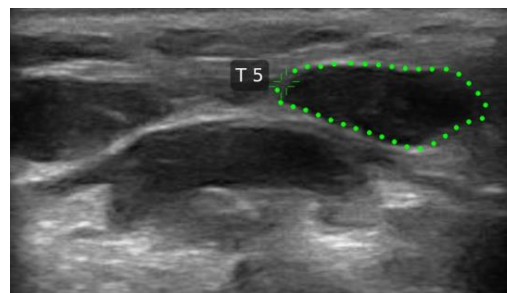


Figure 15: Right anterior belly of the digastric

VFSS Data Extraction

Post Hoc Analysis of VFSS

The VFSS video segments for each participant were reviewed in real time and then frame by frame using GOM media player (GOMLab). This software was chosen as the only frame by frame video analysis tool available which was compatible with the size and format of the VFSS video files captured using the Medi-capture USB 170 recorder.

For each swallowing gesture, two still images were identified. To measure hyoid excursion, one image represented rest position and the other represented the peak of hyolaryngeal excursion. To measure thyrohyoid approximation, one image represented rest

position and the other represented maximal displacement of the thyroid relative to hyoid position. Once the frame was selected, the still image was copied and saved as a Jpeg file in ImageJ, public domain software developed by the National Institute of Health to allow for measurement analysis (Schneider, Rasband, & Eliceiri, 2012).

Using ImageJ analysis software, all still images were calibrated for measurement using the calibration disc which was taped to the participant's lateral face or neck. Given the positioning of the disc, calibration was undertaken using a circle measurement tool. Natural tilting of the disc meant that measurement was made where the circle edges covered the largest diameter across, thus ensuring consistency. Each frame measured was calibrated first to account for any potential participant movement that may have been made between rest position and maximum position. Some images were adjusted in brightness or contrast using ImageJ, to improve identification and differentiation of either anatomical landmarks or the calibration disc.

VFSS Measurement of Hyoid Excursion

Hyoid excursion was measured using the same stable anatomical reference points as ultrasound to allow for correlation assessment to be made and to allow for small movements made by the participant during VFSS. Rest position was identified as the first frame when the hyoid was at its lowest point in the bolus hold position, (see Figure 16). Maximum hyoid excursion was identified as the point of maximal anterior superior displacement of the hyoid (see Figure 17). The mandible landmark was mapped using the ImageJ freehand drawing tool as per the method described by Thompson et al. (2014). The mandible was identified as the point "where the inferior line of the body of the mandible meets the symphyseal outline of

the mandible” (Thompson et al., 2014, p. 6). The anterior inferior edge was used as the consistent point of the hyoid (Thompson et al., 2014).

The straight line tool was used to draw and measure a line between these two anatomical reference points for both rest position (Figure 16) and maximum displacement (Figure 17). Maximum hyoid excursion was calculated as a percentage change between the distance calculated on the rest frame and the distance calculated on the maximum distance frame ($\text{max distance} - \text{rest distance} / \text{rest distance} \times 100$).



Figure 16: VFSS measure of hyoid excursion, rest



Figure 17: VFSS measure of hyoid maximum excursion

VFSS Measurement of Thyrohyoid Approximation

Thyrohyoid approximation was measured using the same anatomical reference points as ultrasound. The anatomical reference point used for the hyoid was the anterior inferior edge (Thompson et al., 2014). The thyroid landmark visibility was more variable across participants than the hyoid. Where visible, the anterior inferior edge of the thyroid cartilage was used, otherwise the anterior aspect of the vocal folds was used (Leonard et al., 2000).

The video was used to provide context for the consistent identification of the vocal fold landmarks, as they were not always visible on the still shots.

The rest frame for thyrohyoid approximation was identified as the point where the thyroid and hyoid were at their lowest with the bolus in the hold position. Maximum approximation was identified at the point where the thyroid cartilage and hyoid were most approximated. If several frames showed the same distance between the two structures, the first frame of maximum approximation was used. A straight line tool was used to draw and measure a line between these two anatomical landmarks at rest (Figure 18) and at maximum approximation (Figure 19). Maximum thyrohyoid approximation was calculated as a percentage change between the rest frame and maximum distance frame ($\text{max distance} - \text{rest distance} / \text{rest distance} \times 100$).



Figure 18: VFSS measurement of thyrohyoid approximation, rest Figure 19: VFSS measurement of thyrohyoid, maximum approximation

Data Analysis

Descriptive Statistics

Descriptive statistics included mean and standard deviation of each ultrasound and kinematic swallowing measure. Measures were separated by bolus type.

Reliability of Ultrasound

This research considered two different levels of reliability (refer to Figure 3).

1. Complete process required: Image acquisition, frame selection and measurement.
2. Measurement alone.

In addition, the impact of environmental factors, equipment and time constraints on reliability of immediate online measurement was explored.

Inter-rater Reliability

ICC values were calculated from online ultrasound data collected by the primary investigator and the co-investigator for each measure: hyolaryngeal displacement, thyrohyoid approximation, tongue thickness and cross-sectional area of submental muscles. Inter-rater reliability therefore included the reliability components: image acquisition, frame selection and measurement on a portable device in a clinical environment.

Intra-rater Reliability

ICC values were calculated from offline measurements of pre-selected ultrasound images, collected by the primary investigator for each measure: hyolaryngeal displacement, thyrohyoid approximation, tongue thickness and cross-sectional area of submental muscles. Therefore intra-rater reliability only included the measurement reliability component. Still ultrasound images, without measurement detail, were saved into a folder with only the participant number and measurement label available to the reviewer. The 20 second video segments of each image were also available where the reviewer required context of the swallowing event. This allowed identification of specific landmarks required for measurement, such as bolus position for tongue thickness and which echoic shadow to use for thyrohyoid approximation. Each still image was saved as a Jpeg file in ImageJ then measured by each rater, using ImageJ analysis software. For measurement purposes, each still image was manually calibrated.

The method of measurement for each image was identical to online ultrasound measures except a mouse was used for freehand and straight line drawing and measurement on a 23 inch screen whereas, a 9.7 inch iPad was used for online measures.. Intra rater reliability was calculated using each rater's first measurement.

Effect of Data Acquisition on Ultrasound Reliability

Comparison of online inter-rater ICC with offline inter-rater ICC was used to explore the effect of ultrasound data acquisition on reliability. Offline inter –rater ICC was calculated

using the data from the first of two offline measurements by both the primary investigator and the co-investigator.

Effect of Environment on Ultrasound Reliability

Effect of environmental factors, equipment and time constraints on reliability of immediate online measurement was explored by calculating ICC for rater one's online and offline ultrasound measurements of the same pre-selected still frames. This eliminates the variables of acquisition and frame selection. The variables that are considered in the interpretation of this data are the difference between the measurement tools: Clarius™ measurement application on a 9.7 inch ipad versus imageJ software used on a computer with a large 23 inch screen as well as the considerations of working in a clinical environment with time constraints and variable lighting. The ICC measures for intra-rater reliability between online and offline measurement of ultrasound data calculation was based on the first of the two offline measurement occasions.

Inter- and intra-rater reliability is analysed using the ICC as a relative measure of reliability. This allows for comparisons to be made with results of other studies. In order to quantify measurement errors in the units they are measured in, standard error of measurement (SEM) was reported as an absolute measure of reliability. ICC measures were reported with confidence intervals to indicate the uncertainty with which they were estimated. The between-subject variance was reported, as the ICC depends on the homogeneity of the sample (Bartlett & Frost, 2008). R software (R Core Team, 2017) and lme4 (Bates, Maechler, Bolker, & Walker, 2014) were used to perform linear mixed effect analyses of intra- and inter-rater reliability. A two-way mixed effects model based on single measures was used to

analyse intra-rater reliability, while a two-way random effects model based on single measures was used for inter-rater reliability. For intra-rater reliability, participant was entered as a random effect and measurement trial entered as a fixed effect. For inter-rater reliability, rater and subject were entered as a random effect.

The effect of bolus type on intra- and inter-rater reliability was tested for hyoid excursion and thyrohyoid approximation. A likelihood ratio test allowed comparison of a full model, using bolus as a fixed effect, to a reduced model, in which bolus was not a fixed effect. Analysis was continued using the full model if a significant bolus effect was present, whereas the reduced model was continued where no bolus effect was identified. As bolus visibility was required for measurement of tongue thickness, a separate ICC was calculated for each bolus type. Ultrasound measurement error was estimated using the width of the 95% confidence interval for mean values. Confidence intervals for each ICC were calculated using a bootstrap distribution to indicate the uncertainty with which they have been estimated. Homoscedasticity patterns were ensured using residual versus fitted plots. Visual inspection of residual quantile-quantile (Q-Q) plots allowed detection of possible deviation from normality. For interpretation, criteria published by Koo and Li (2016) were used and are summarised in Table 3. The between-subject variance was calculated, as the ICC depends on the homogeneity of the sample (Bartlett & Frost, 2008). SEM is reported as an absolute measure of reliability.

Table 3**Guideline for Interpretation of ICC Values**

ICC value	Interpretation
< 0.5	Poor reliability
0.50 - 0.75	Moderate reliability
0.75 - 0.9	High reliability
> 0.9	Excellent reliability

Validity

For assessment of validity of measurement of swallowing kinematics using portable ultrasound against the ‘gold standard’ of VFSS, the first of two offline ultrasound measures completed by rater one were correlated against the measures made from VFSS.

Using offline ultrasound measures allowed for a fair comparison of portable ultrasound images against measures made from VFSS, which were completed offline. Both measures were thus completed using the same size screen, identical measurement techniques on ImageJ software and a mouse rather than a stylus. In addition, using offline ultrasound measures allowed better comparisons with data from other studies, which have been largely obtained from offline measurement.

The association between measurement of swallowing kinematics derived from ultrasound and VFSS was calculated using a Pearson’s correlation coefficient (r ; Udovičić, Baždarić, Bilić-Zulle, & Petrovečki, 2007). A p -value was calculated to determine the strength of the evidence for an association. If the coefficient of correlation was significant ($p < .05$) the correlation co-efficient value was interpreted as strong evidence, however if it was not significant ($p > .05$) the correlation coefficient was considered as weak evidence (Bartlett & Frost, 2008).

Analyses were performed using R software (R Core Team, 2017). The assumptions of a Pearson’s correlation analysis were checked. Scatter plots were generated using sample ultrasound and VFSS measurement data, to assess whether there was a linear relationship between the two variables. In addition, residual versus fitted plots were used to assess linearity and to identify any variance patterns of the residuals. Visual inspection of Q-Q plots was performed to assess normality of the data and a Shapiro-Wilk’s test was conducted. If the assumptions were not met, a non-parametric Kendall’s correlation coefficient (tau) was calculated. For interpretation, criteria published by Dawson and Trapp (2004) were used (as depicted in Table 4).

Table 4: Guideline for Interpretation of Pearson’s Correlation Coefficients

Positive <i>r</i>-value	Negative <i>r</i>-value	Interpretation
0 to 0.25 or	0 to -0.25	Absence of correlation
0.25 to 0.50	-0.25 to -0.50	Poor correlation
0.50 to 0.75	-0.50 to -0.75	Moderate to good correlation
0.75 to 1	-0.75 to -1	Very good to excellent correlation

Agreement analyses were completed in order to quantify differences in measurements across methods, recognising that the methods used to measure ultrasound and VFSS are not identical (Giavarina, 2015). If the assumption was met, the ‘95% limits of agreement approach’ was used (Bland & Altman, 1995). This approach involved calculating the mean of the two values ± 1.96 times the standard deviations to provide a value range in which the two methods were estimated to lie within for the majority of participants. Thus creating 95% confidence intervals which express the uncertainty of these estimates (Giavarina, 2015). Bias between ultrasound and VFSS was defined by assessment of the line of equality, (zero on the

Y-axis), noted if it did not lie within the 95% confidence interval of the mean difference (Bartlett & Frost, 2008; Giavarina, 2015). If the assumption was violated, analysis was not further continued. To visualise agreement between measures derived from ultrasound and VFSS, a Bland-Altman plot was generated. Here, differences between paired measurements derived from the two methods were plotted against the mean of these measurements (Altman & Bland, 1983).

Results³

Participants

For the validation study, 92 individuals agreed to participate in the research study. Fifty of these met the inclusion criteria for data collection, demonstrating either clinically impaired hyolaryngeal displacement or pharyngeal shortening, during their standard care VFSS. Data collection was intended for 40 participants, however was completed with 43 of the 50 eligible participants. This larger cohort of participants allowed compensation for potential errors in data capture, given the pressure of working within a time-constrained clinical environment and secondary to equipment error which plagued initial data collection (For example, incomplete visibility of the calibration disc and ultrasound cloud-based data capture errors).

Of the 50 eligible participants, three participants became fatigued and the study was abandoned prior to completion of data collection. One participant was excluded as his mild movement disorder was exacerbated by his attempts to remain still for ultrasound data collection. One participant had a recessed chin and the ultrasound transducer did not make adequate contact for data collection. One participant was unable to complete data analysis due to limited time availability in the VFSS suite and one participant was excluded due to a failure to record the VFSS to enable data analysis. Of the 43 participants included in the study, 36 were male and seven were female. These participants had a variety of underlying diagnoses. Table 5 illustrates the likely aetiologies of dysphagia for all participants.

³ The author would like to acknowledge the assistance of Dr. Katharina Winiker in both data analysis and interpretation of data.

Of the 43 participants, every fifth patient completed reliability testing. On one occasion, the participant that was due to have secondary reliability measures became too fatigued to endure same day evaluation, therefore the following participant completed reliability testing in their place. Table 6 displays the likely aetiology of dysphagia for the participants who underwent reliability testing. Of these eight participants, seven were male and all eight participants were right handed. For the purpose of this Master’s study, only the data collected on these eight participants was analysed, thus providing assessment of inter- and Intra-rater reliability and preliminary indications of validity of pocket sized ultrasound against VFSS.

Table 5: Likely Aetiology of Dysphagia for Participants in Validity Study

Aetiology	No of Participants	Ages
Stroke	13	85,74,71,76,84,77,84,87,76,77,76,81,89
Parkinson’s Disease	6	89,70,82,66,62,83
Current / recurrent lower respiratory tract infection	6	79,86,88,74,92,81
Inclusion body myositis	3	70,69,78
Deconditioned/otherwise unwell	3	82,74,88
Post abdominal surgery	2	91,88
Myotonic dystrophy	1	62
Motor neurone disease	1	53
Traumatic brain injury	1	88
Post spinal surgery	1	77
Oesophageal cancer and vocal fold palsy	1	96
Dysphagia of unknown cause	6	89,69,93,66,33,84

Table 6: Likely Aetiology of Dysphagia for Pre-selected Participants for Reliability Testing

Participant	Aetiology	Age
1	Myotonic dystrophy	62
2	Stroke	89
3	Inclusion body myositis	78
4	Oesophageal cancer and vocal fold palsy	96
5	Chronic cough, dysphagia of unknown cause	81
6	Solid food dysphagia of unknown cause	33
7	Parkinson's Disease	83
8	Deconditioned: Rectal cancer new onset dysphagia of unknown aetiology	84

Data Extraction

Three video segments were unsuccessfully captured to the Clarius™cloud for offline data extraction purposes, due either to user error or equipment failure. In these cases, the reviewer was not able to review swallowing context, e.g., visualisation of the movement of a shadow to identify a consistent reference point, where the still frame was unclear. Of those missing, one was of hyoid excursion and two were of thyrohyoid approximation. Thirty-seven of a possible 40 videos were available for review.

Reliability

The sample size of eight limited assumption checking; where assumptions did not appear to be completely satisfied, the ICC was noted within square brackets []. ICC data were reported for all measures. Appendix 4 provides assumptions plots for review.

Descriptive Statistics

Table 7 depicts descriptive statistics for rater one's ultrasound data acquisition, frame selection and measurement online.

Table 7: Descriptive Statistics for Online Ultrasound Measures

Measure	Bolus	Mean (Standard Deviation)
Hyoid excursion	Liquid	26.70% ⁴ (9.41)
	Puree	26.82% (11.31)
	Liquid, puree	26.76% (10.05)
Thyrohyoid approximation	Liquid	54.27% (22.97)
	Puree	63.02% (12.56)
	Liquid, puree	58.64% (18.45)
Tongue thickness	Apple sauce	53.54 mm (6.46)
	GH	-
FOM ⁵	LAB	159.22 mm ² (46.00)
	RAB	-
	-	61.82 mm ² (18.32)
		61.51 mm ² (18.20)

Inter-rater Reliability

Table 8 depicts descriptive statistics for inter-rater reliability of online acquisition. This measure of reliability includes: ultrasound data acquisition, frame selection and immediate measurement (online). Table 9 depicts descriptive statistics for inter-rater reliability of offline measurement only, using pre-selected still images. There was no bolus effect for inter-rater reliability for hyoid excursion or thyrohyoid approximation. ICC values for inter-rater reliability of online data acquisition and measurement were found to range from poor to moderate with only one static measure, the left anterior belly of the digastric

⁴ % refers to percentage change from rest to maximum displacement for all values

⁵ FOM: floor of mouth, GH: geniohyoid, LAB: left anterior belly of digastric, RAB: right anterior belly of digastric

(ICC of .78), demonstrating good reliability. ICC values for inter-rater reliability of offline measurement of pre-selected images were all found to have good to excellent reliability (ICC range from .78 to .99). All reliability ICC values are depicted in Table 13 to enable visual comparison across conditions, reflecting different components of reliability.

Table 8: Descriptive Statistics for Inter-rater Reliability of Online Acquisition of Ultrasound Measures (rater 1 and rater 2)

Measure	Bolus	SEM (95% CI)	Between-subject Standard Deviation
Hyoid excursion	Liquid, puree	10.23 % (7.90, 13.98)	7.15 % change
Thyrohyoid approximation	Liquid, puree	14.55 % (11.19, 20.12)	19.02 % change
Tongue thickness	Apple sauce	[5.72 mm] (3.86, 8.19)	0.00 mm
	GH	-	[43.92 mm ²] (28.30, 82.30)
FOM	LAB	-	10.63 mm ² (6.98, 19.09)
	RAB	-	14.17 mm ² (9.19, 24.54)

Table 9: Descriptive Statistics for Inter-rater Reliability of Offline Measurement⁶

Measure	Bolus	SEM (95% CI)	Between-subject SD
Hyoid excursion	Liquid, puree	3.75 % change (2.90, 5.13)	8.28 % change
Thyrohyoid approximation	Liquid, puree	8.23 % change (6.33, 11.36)	16.41 % change
Tongue thickness	Apple sauce	1.70 mm (1.10, 3.06)	4.01 mm
	GH	-	[4.96 mm ² (3.26, 8.91)
FOM	LAB	-	[8.23 mm ² (5.39, 14.77)
	RAB	-	[3.75 mm ² (2.44, 6.73)

Intra-rater Reliability

Tables 10 and 11 depict descriptive statistics for intra-rater reliability for rater 1 and rater 2, respectively. This measure of reliability includes the measurement component only, completed offline from stored pre-selected still images. There was no bolus effect for intra-rater reliability of hyoid excursion and thyrohyoid approximation. ICC values for intra-rater reliability of measurement of pre-selected images were found to be similar across both raters, all measures were within the good to excellent range, and these values are depicted in Table 13.

⁶ Based on first measurement occasion of rater 1 and 2

Table 10: Descriptive Statistics of Intra-rater Reliability Using Online/Offline Ultrasound Measures

Measure	Bolus	SEM (95% CI)	Between-subject SD
Hyoid excursion	Liquid, puree	3.82 % change (2.89, 5.11)	8.51 % change
Thyrohyoid approximation	Liquid, puree	[9.01 % change (6.81, 12.06)]	15.76 % change]
Tongue thickness	Apple sauce	0.66 mm (0.41, 1.11)	4.34 mm
	GH	-	5.35 mm ² (3.28, 8.98)
FOM	LAB	-	[1.84 mm ² (1.13, 3.08)]
	RAB	-	[6.24 mm ² (3.83, 10.47)]

Table 11: Descriptive Statistics for Intra-rater Reliability of Rater 2 Offline Measurement of Ultrasound Measures

Measure	Bolus	SEM (95% CI)	Between-subject SD
Hyoid excursion	Liquid, puree	3.68 % change (2.78, 4.92)	8.40 % change
Thyrohyoid approximation	Liquid, puree	9.55 % change (7.22, 12.77)	17.77 % change
Tongue thickness	Apple sauce	0.30 mm (0.19, 0.51)	4.52 mm
	GH	-	4.18 mm ² (2.56, 7.01)
FOM	LAB	-	2.85 mm ² (1.75, 4.79)
	RAB	-	1.59 mm ² (0.98, 2.67)

Effect of Data Acquisition and Environment on Ultrasound Reliability

Table 12 depicts the descriptive statistics of intra-rater reliability using online data, which includes data acquisition, frame selection and immediate measurement and the first offline measurement occasion of two completed. The ICC measures for intra-rater reliability of online and offline measurement of ultrasound data when compared against the online data acquisition inter-rater ICC values demonstrates the impact of both acquisition and environment on reliability, both data sets are depicted in Table 13 to enable visual comparison.

Table 12: Descriptive Statistics of Intra-rater Reliability Using Online/Offline Ultrasound Measures⁷

Measure	Bolus	SEM (95% CI)	Between-subject SD
Hyoid excursion	Liquid, puree	5.65 percentage change (4.27, 7.56)	8.06 percentage change
Thyrohyoid approximation	Liquid, puree	11.85 percentage change (9.15, 16.19)	15.43 percentage change
Tongue thickness	Apple sauce	3.29 mm (2.02, 5.53)	4.37 mm
	GH	-	6.86 mm ² (4.21, 11.52)
FOM	LAB	-	4.53 mm ² (2.78, 7.60)
	RAB	-	1.86 mm ² (1.14, 3.13)

⁷ based on rater 1's first offline measurement occasion

Table 13: Summary of ICC Values as a Relative Measure of Inter- and Intra-rater Reliability

Measure	Bolus	Online Data Acquisition Inter-rater ICC (95% CI)	Online/offline Intra-rater ICC (95% CI)	Offline (R1) Intra-rater ICC (95% CI)	Offline (R2) Intra-rater ICC (95% CI)	Offline Inter-rater ICC (95% CI)
Hyoid excursion	Liquid, puree	.33 (.00, .66)	.67 (.27, .87)	.83 (.52, .94)	.84 (.51, .94)	.83 (.49, .94)
Thyrohyoid approximation	Liquid, puree	.56 (.12, .82)	[.63] (.19, .83)	[.75] (.30, .91)	.78 (.40, .92)	.78 (.35, .91)
Tongue thickness	Apple sauce	* ⁸ (.00, .65)	.64 (.00, .93)	.98 (.90, 1.00)	.99 (.98, 1.00)	.85 (.44, .97)
	GH	[.60] (.00, .90)	.98 (.93, 1.00)	.98 (.93, 1.00)	.99 (.96, 1.00)	[.99] (.94, 1.00)
FOM	LAB	.78 (.25, .94)	[.99] (.97, 1.00)	[.99] (.97, 1.00)	.97 (.89, .99)	[.84] (.44, .96)
	RAB	[.42] (.00, .85)	[.91] (.93, 1.00)	[.91] (.93, 1.00)	.99 (.96, 1.00)	[.95] (.77, .99)

Validity

Descriptive Statistics

Descriptive measures of mean and standard deviation of both ultrasound and VFSS measures of swallowing kinematics can be seen in Table 14.

⁸ for this measure, data is based on estimates of variance only as the model is over fitted

Table 14: VFSS and Ultrasound Measures: Mean and Standard Deviation

Measure	Bolus	Mean (SD) for VFSS	Mean (SD) for Ultrasound
Hyoid excursion	Liquid	22.65% (9.03)	24.17 % (9.61)
	Puree	24.57 % (8.83)	25.67 % (9.31)
Thyrohyoid approximation	Liquid	32.54 % (12.94)	49.87 % (21.70)
	Puree	30.29 % (12.50)	52.69 % (17.52)

Correlation

It was initially intended that online ultrasound data be used for assessment of validity of measurement of swallowing kinematics using portable ultrasound against the ‘gold standard’ of VFSS as it was hypothesised that that the success of online ultrasound measurement method would improve translation into clinical practice. However, following reliability calculations, which demonstrated poor reliability of the online ultrasound measures; the first of two offline ultrasound measures were used instead

The assumptions for Pearson’s correlation analysis were met for hyoid excursion and thyrohyoid approximation during liquid and puree swallowing. The association between measurement using ultrasound and measurement using VFSS can be seen in Table 15. There was evidence of an association between VFSS and ultrasound for hyoid excursion, the positive correlation was moderate for puree bolus and excellent for liquid bolus. The p -values at 0.001 and 0.03 for hyoid excursion of liquid and puree boluses respectively indicate the coefficient is significant ($p<0.05$). Thyrohyoid approximation was also found to have a

moderate relationship between modalities for both puree and liquid bolus ($r=0.61$) but significance wasn't reached ($p=0.11$).

Table 15: Correlation between Ultrasound and VFSS Measurements of Hyoid Excursion and Thyrohyoid Approximation

Measure	Bolus	Correlation Coefficient, <i>p</i> -value
Hyoid excursion	Liquid	$r = 0.92, p \leq .001$
	Puree	$r = 0.76, p = 0.03$
Thyrohyoid approximation	Liquid	$r = 0.61, p = 0.11$
	Puree	$r = 0.61, p = 0.11$

Agreement

Assumptions for agreement analyses were met for hyoid excursion (liquid: $p = .41$, puree: $p = .0518$) and thyrohyoid approximation during puree swallowing ($p = .10$). For thyrohyoid approximation, the assumptions were violated for liquid swallowing ($p = .02$).

For hyoid excursion during liquid and puree swallowing, the upper limits of agreement for ultrasound measurements were calculated at 8.90 percentage change for liquid swallows and 13.54 percentage change for puree swallows. The lower limits were calculated at -5.87 percentage change for liquid swallows and -11.33 percentage change for puree swallows. Upper limits of agreement for ultrasound measurements of thyrohyoid approximation were calculated at 51.17 percentage change for liquid swallows and 49.92 percentage change for puree swallows. The lower limits were calculated at -16.49 percentage change for liquid swallows, and -5.13 percentage change for puree swallows. See Appendix 5 for Bland Altman plots.

Discussion

This study investigated the reliability and validity of handheld portable ultrasound to quantify a number of measures of swallowing. A mixed-aetiology cohort of individuals with dysphagia was assessed, which is representative of a typical speech-language therapy caseload. Measures included biomechanical kinematic measures of hyoid excursion and thyrohyoid approximation and muscle morphometry measures of tongue thickness and cross-sectional area of submental muscles. This research provides important data on the various components that impact reliability, to ultimately support knowledge translation of a tool that has showed significant promise in research laboratories.

Reliability data generated from this research indicates that raters can achieve high levels of agreement when measurement of portable ultrasound images is completed offline from pre-selected images with some of these data comparing favourably with published research to date.

Hyolaryngeal Excursion

This study demonstrated high inter- and intra-rater reliability of offline measurement, using pre-selected images, for hyolaryngeal displacement using portable ultrasound (ICC .83-.84; CI: .49 - .94). These data are comparable to previous published research, conducted using sophisticated technology (Chen et al., 2017; Hsiao et al., 2012; Macrae et al., 2012). Whereas this study demonstrated low inter-rater reliability of online acquisition and measurement of the same biomechanical feature of swallowing, (ICC of .33; CI: .0 - .66),

thus indicating a significant reduction associated with the acquisition and image selection of the data measured for this dynamic swallowing feature when using the portable technology.

Thyrohyoid Approximation

Inter- and intra-rater reliability of offline measurement, using pre-selected images, for thyrohyoid approximation was, although overall slightly lower than those for hyoid displacement, also found to have relatively high levels of agreement (ICC of $>.75$), however confidence intervals were larger (CI: $.30 - .91$). Online inter-rater reliability, which included acquisition, image selection and measurement, was moderate (ICC of $.56$). These data do not compare favourably to published research; Huang et al. (2009) demonstrated excellent inter-rater reliability (ICC of >0.97) for the same measure; their reliability data included the acquisition, image selection and measurement components and as such demonstrated superior outcomes with sophisticated instrumentation.

Tongue Thickness

Offline measures of tongue thickness produced high to excellent ICC values in this research. Intra-rater ICC values for measuring tongue thickness were excellent for the two raters (ICC $>.98$; CI: $.90 - 1.0$), the inter-rater ICC value was also high (ICC of $.85$) although had larger confidence intervals ($.44 - .97$). Online measures of tongue thickness could only be measured based on estimates of variance as the model was over fitted, confidence intervals were calculated at between 0 and $.65$, indicating a high degree of variability associated with data acquisition and online image selection and measurement.

Cross Sectional Area of Submental Muscles

Intra-rater ICC values for measuring cross-sectional area of submental muscles, offline, also fell within the excellent range, across all measures (ICC: .91 - .99; CI: .89 – 1.0). Additionally Inter-rater ICC values for these measures ranged from high to excellent (ICC of > .84). These values compare favourably with published research (Hsiao et al., 2012; Macrae et al., 2013). Online inter-rater reliability ICC values for these measures (ICC: .42 - .78), were significantly higher than those for the dynamic biomechanical swallowing measures. However the confidence intervals remained large ranging from .0 to .94, thus high degrees of variability were evident.

Online Versus Offline Measurement Reliability

While offline inter- and intra-rater reliability of swallowing kinematic and static measures, using Clarius™ portable ultrasound, was consistently high in this research, it is clear from the data collected that data acquisition and frame selection of the ultrasound images as well as the factors associated with online live measurement in pressured clinical environment had a big impact on reliability. This study showed a significant reduction in ICC values, with larger confidence intervals, for all measures when acquiring and measuring the images online compared to offline measurement alone. Reductions in online reliability measures were most significant for the biomechanical, kinematic, measures of swallowing. It is hypothesised that this is due to the dynamic nature of these measures, requiring careful image selection, of rest and maximum displacement, prior to measurement being completed. Additionally use of a scroll function on an iPad screen compared with frame by frame analysis on a computer, lighting, and time constraints associated with immediate online

measurement are likely to have further contributed to reduce reliability for these measures. In order to attempt to identify the impact of the environmental factors alone further exploration of the data was undertaken.

Effect of Environment on Ultrasound Reliability

The effect that environmental factors had on reliability was analysed by calculating intra-rater ICC values for rater one's online and offline ultrasound measurements of the same pre-selected still images, thus eliminating the impact of data acquisition. These ICC values can be seen in Table 13, (column labelled online/offline intra-rater ICC). These calculations, when compared with offline intra-rater ICC demonstrate that ICC values increased significantly when environmental factors associated with lighting, time pressure of a live VFSS clinic, and image resolution on a small screen were eliminated. ICC values for hyoid excursion increased from .67 to .83; thyrohyoid approximation ICC values increased from .63 to .75. Tongue thickness inter-rater ICC increased from .64-.98. However static measures of cross-sectional area of each of the submental measures did not show any increase in ICC. This finding indicates that ultrasound analysis of kinematic swallowing measures of the tongue, using a ClariusTM portable device, are unlikely to be reliable under these conditions and that the resolution of the device to view and measure images live may not be adequate. These factors will need to be further explored prior to knowledge translation into the clinical environment.

Effect of Data Acquisition and Frame Selection on Ultrasound Reliability

Further reduction of reliability was noted where the acquisition and frame selection components as well as environment factors were included, this is evidenced by comparing

Offline inter-rater ICC with online data acquisition inter-rater ICC (refer to Table 13). ICC values for hyoid excursion decreased from .83 to .33; and thyrohyoid approximation ICC values decreased from .78 to .56. Additionally static measures of cross-sectional area of each of the submental measures decreased significantly (.99 to .60, .84 to .78 and .95 to .42) with the inclusion of acquisition and frame selection and environmental components. However, there were larger differences with kinematic swallowing measures compared to static measures. It is hypothesised that a number of factors contributed to the differences in data acquisition between raters. Firstly, rater one acquired the sonogram for kinematic swallowing measures concurrently with VFSS, while the second rater acquired the sonogram without VFSS. In addition, the second rater completed data collection after the participant had already undergone a standard VFSS procedure and research data collection by the first rater. It is therefore possible that there may have been greater than usual variance in the dynamic swallowing gestures of hyoid excursion and thyrohyoid approximation, as a result of fatigue or patient performance across assessment periods. It is also possible that sonogram acquisition differences between raters may relate to different technique as well as variance as a result of slightly different conditions for data collection. Inter-rater reliability data from online data acquisition in this study was poor in comparison to the reliability data collected by Hsiao et al. (2012), for hyoid excursion, who included data acquisition and still achieved high inter- and intra-rater reliability (intra-rater ICC: .92 and .84, inter-rater ICC: .80.). It is possible that this discrepancy may be as a result of research methodology or potentially as a result of the impact of the associated with portable ultrasound equipment, (small screen, crude measurement calipers and touch-screen scroll function for frame selection).

Further research on inter-rater reliability using the portable device for online data acquisition under identical conditions is required. Further assessment on sonogram

acquisition reliability across raters, and test–retest reliability across sessions, using healthy subjects, was completed concurrently with this project and those data may help in the establishment of training protocols for clinical translation.

The data generated in this study indicates that reliability decreases as a result of both the pressure of a clinical environment and variation in sonogram acquisition, the images acquired and measured online were therefore reviewed to further qualify these findings. Review of the ultrasound images revealed a number of environmental factors that appeared to influence measurement reliability. An example of a tongue thickness measure made online in the pressure of a clinical environment can be seen in Figure 20. In this example the examiner incorrectly identified the bolus, instead of choosing the intersecting point between the bolus and the surface of the tongue; the palate was identified in error as the tongue surface. The same image measured offline can be seen in Figure 21 for comparison. It is hypothesised that time pressure prevented full review of the cine loop which would have allowed the examiner see where the bolus was situated at rest thus providing context when swallowed.

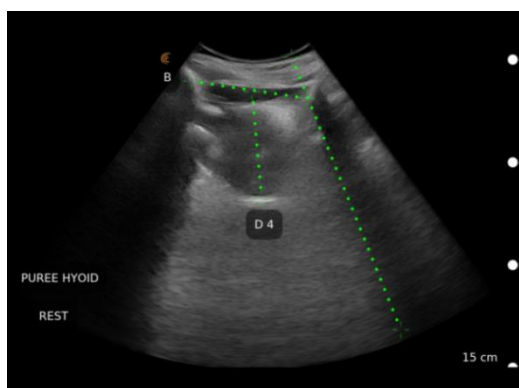


Figure 20: Online tongue thickness measurement



Figure 21: Offline tongue thickness measurement

Similarly, the impact of the software used to measure the images was reviewed. The portable ultrasound connected wirelessly to a 9.7 inch iPad screen and a standard stylus was used to draw either freehand or straight lines for measurement purposes. The software's spatial resolution and accuracy was poorer than that of ImageJ, and thus did not allow for finer details to be measured. This was particularly evident when measuring cross-sectional area of submental muscles (see Figures 22 to 25 for examples). In addition when measuring freehand, the software did not allow the measurement callipers to meet when measuring area, as it would refresh when they connected (See Figure 26). Instead the software accounted for the distance between the two ends of the freehand line, which for certain measures had more impact than others (see Figures 26 and 27 for examples). Offline measurement was completed using ImageJ software on a 23 inch screen where brightness and contrast were able to be adjusted to improve image quality as needed and accuracy of calliper placement was superior.

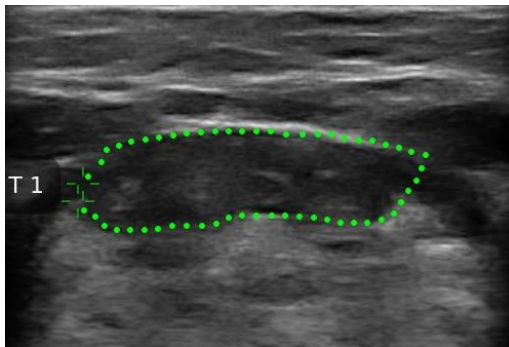


Figure 22: Online geniohyoid measurement

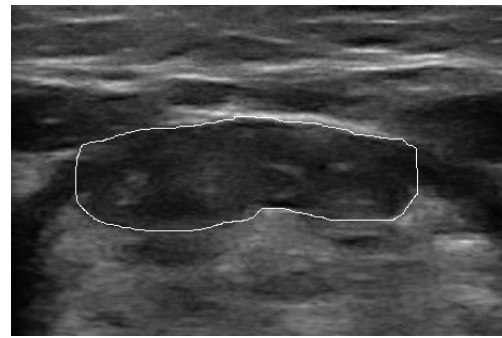


Figure 23: Offline geniohyoid measurement

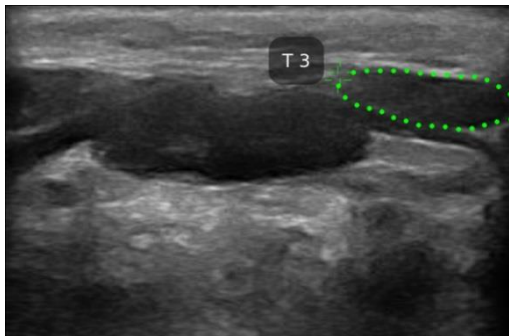


Figure 24: Online anterior belly of digastric measurement

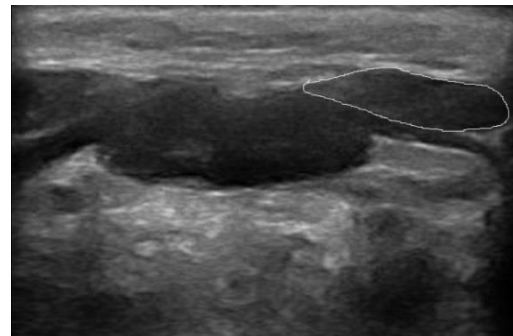


Figure 25: Offline anterior belly of digastric measurement

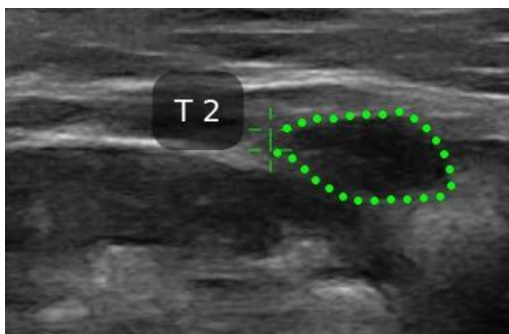


Figure 26: Online anterior belly of digastric measurement

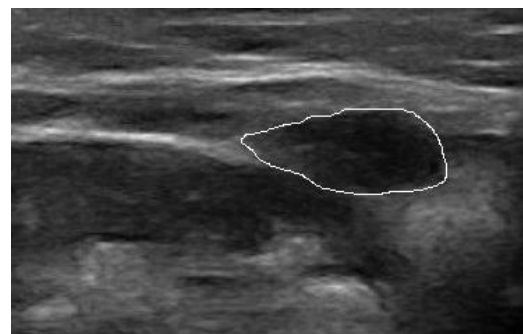


Figure 27: Offline anterior belly of digastric measurement

Validity

Preliminary assessment of validity of the portable ultrasound measures against the gold standard of VFSS, for the measurement of hyoid excursion, was encouraging during liquid boluses ($r = 0.92$, $p \leq .001$) and puree boluses ($r = 0.76$, $p = .003$) demonstrating good to excellent correlation with VFSS. Further, the range of percentage change from rest to maximum hyoid displacement was reasonably consistent across VFSS and ultrasound. These data suggest that the quality of hyolaryngeal displacement images gathered by portable

ultrasound technology are adequate, as they correlate strongly with VFSS when measured offline. These data are similar to the findings of other studies using more sophisticated ultrasound technology (Hsiao et al., 2012; Lee et al., 2016).

Measures of thyrohyoid approximation were found to be more variable on ultrasound than on VFSS. The mean percentage change was much higher on ultrasound than on VFSS. Thyrohyoid approximation measures were not shown to correlate significantly with VFSS, ($r = 0.61$, $p = 0.11$). The lack of significant correlation for this measure may be influenced by several factors. Firstly, the resolution of the portable device and secondly, the thyroid cartilage having multiple acoustic shadows on ultrasound, some of which were inconsistently visible as thyrohyoid approximation was achieved. Therefore, it was not possible on ultrasound to use a consistent landmark across participants, as was used for hyolaryngeal displacement. Given the multiple acoustic shadows cast by the thyroid cartilage on ultrasound, it is also unclear whether the measures on VFSS are anatomically identical to those on ultrasound. Further analysis of the 43 participants with dysphagia on whom data were collected is required, in order to improve statistical power and draw stronger conclusions of the validity of portable ultrasound against VFSS.

The validity and reliability data from this study provides important information to support knowledge translation from research laboratories into the clinical environment. For example, the data indicates the need for future research to ensure that protocols for data acquisition are robust and allow consistent repeatability. It is anticipated that increased availability and accessibility of objective assessments of swallowing will result in improved patient diagnostics, targeted treatments and outcomes, reduced incidence of aspiration pneumonia and an increase in nutrition and hydration in a highly vulnerable population.

The data presented in this study are preliminary, but encouraging, suggesting that portable ultrasound has potential for use in clinical care with further refinements. Portable ultrasound instrumentation has the potential to increase the availability of objective assessment to the most dependant patients, by providing assessment in their home environment and, subsequently, decreasing dependence on hospital-based diagnostic services and reducing the associated costs. However, in order to achieve clinical translation, further research is required to assess the impact of the variance in patient performance across assessment periods accounting for fatigue or variability across swallows, as well as exploring methods to improve reliability of online analysis.

Limitations

The portion of the concurrent larger study that was covered by this Master's research had a small sample size of eight. When conducting a reliability study, a sample size of 30 heterogeneous samples involving at least three raters is optimal (Koo & Li, 2016). The findings on validity cannot be generalised based on this study alone and should be considered in conjunction with the validity assessment of the larger cohort once analysed. Reliability should be considered alongside concurrent data collected on healthy participants (pending publication), which explored multiple levels of reliability using the same equipment and three raters.

Participants in this study of dysphagic individuals displayed a wide range of severity, from a mild to profound reduction in either hyoid excursion, or thyrohyoid approximation. The primary investigator identified these participants through perceptual assessment of reduced hyolaryngeal excursion or thyrohyoid approximation, posing a risk of inclusion bias. In an attempt to mitigate this limitation, the co-investigator was consulted for a second opinion where the movement of the hyolaryngeal complex appeared to be only mildly impaired or unclear, however, inclusion bias cannot be discounted as a possibility.

There were some data capture errors as a result of initial equipment failure. Of the eight participants, one participant's still images failed to store on the built-in software. In this case, screen shots of thyrohyoid approximation were taken for measurement purposes. It could not be guaranteed that these images were identical to those stored on the Clarius™ cloud software, however, calibration on these screen shot images should have accounted for minor image differences. As video capture was unable to be completed for this participant, context of the still image was not able to be obtained by review of the cine loop, limiting ability

to make accurate judgements of the still images during offline measurement. All other participants had video segments available for improved analysis of still image measures. This may have resulted in potential errors in inter- and intra-rater reliability for those data.

This study made use of only two raters for assessment of inter-rater reliability. Other studies of inter-rater reliability have used more than two raters to provide superior information on variance. (Kuhlemeier, Yates, & Palmer, 1998; Macrae et al., 2012; Miles & Huckabee, 2013; Scott, Perry, & Bench, 1998)

Inter- and intra-rater reliability of VFSS measures were not completed in this study. Given research evidence questions reliability of some methods of obtaining VFSS objective measures (Sia et al., 2012), further exploration of this would be useful when assessing validity of ultrasound measures against ‘gold standard’ VFSS.

Future Directions

Researchers have indicated that the likelihood of having aspiration is 3.7 times greater for individuals who demonstrate reduced hyoid excursion than it is for individuals who have adequate hyoid excursion during swallowing (Perlman, Booth, & Grayhack, 1994). Similarly, reduced thyrohyoid approximation has been shown to be associated with aspiration risk (Shaker et al., 2002). In line with research by Hsiao et al. (2012) and Lee et al. (2016), the ability to develop a quantifiable percentage change range or cut-off point for these kinematic biomechanical measures using portable ultrasound as an indicator of dysphagia severity may be of enormous clinical value.

This study limited the VFSS imaging completed concurrently with ultrasound to a single swallow with a 5ml bolus and did not continue screening beyond this to ascertain post-swallow aspiration risk. The single bolus trial would also not allow for known physiological variability (Molfenter & Steele, 2011). Future research using ultrasound to assess swallowing could focus on identifying a percentage range that may indicate higher risk of aspiration and pharyngeal residue associated with the degree of hyoid excursion and or thyrohyoid approximation. However the potential for differences across gender (Feng et al., 2015; Ishida et al., 2002) and age (Kendall & Leonard, 2001; Kim & McCullough, 2008; Logemann et al., 2000) would also need to be considered within the data analyses.

Conclusion

The data in this study indicate that the image quality gathered using portable ultrasound is adequate for some, but not all, swallowing measures when made offline. Use of free open access software (ImageJ) allows for discrete measures to be made on a large screen with appropriate lighting and the ability to adjust images to improve contrast or brightness as required. However, clinical translation of ultrasound measurement offline is hypothesised to face similar challenges as those faced by objective measures of VFSS (Baijens et al., 2013), as the time required completing these measures does pose significant challenges in a busy, clinical environment. Therefore, it is hypothesised that in order to achieve clinical translation, exploring methods to improve reliability of online analysis is important.

References

- Ahn, Cho, Beom, Park, Jee, & Nam. (2015). Reliability of Ultrasound Evaluation of Hyoid–Larynx Approximation with Positional Change. *Ultrasound in medicine & biology*, 41(5), 1221-1225.
- Alanen, Falck, Kalimo, Komu, & Sonninen. (1994). Ultrasound, computed tomography and magnetic resonance imaging in myopathies: correlations with electromyography and histopathology. *Acta neurologica scandinavica*, 89(5), 336-346.
- Aldrich. (2007). Basic physics of ultrasound imaging. *Critical care medicine*, 35(5), S131-S137.
- Allen, Greene, Sabido, Stretton, & Miles. (2019). Economic costs of dysphagia among hospitalized patients. *The Laryngoscope*.
- Altman, & Bland. (1983). Measurement in medicine: the analysis of method comparison studies. *Journal of the Royal Statistical Society: Series D (The Statistician)*, 32(3), 307-317.
- Altman, Yu, & Schaefer. (2010). Consequence of dysphagia in the hospitalized patient: impact on prognosis and hospital resources. *Archives of Otolaryngology–Head & Neck Surgery*, 136(8), 784-789.
- Ardakani. (2006). Evaluation of swallowing patterns of the tongue using real-time B-mode sonography. *J Contemp Dent Pract*, 7(3), 67-74.
- Arts, Pillen, Schelhaas, Overeem, & Zwarts. (2010). Normal values for quantitative muscle ultrasonography in adults. *Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine*, 41(1), 32-41.

- Aviv, Kaplan, Thomson, Spitzer, Diamond, & Close. (2000). The safety of flexible endoscopic evaluation of swallowing with sensory testing (FEESST): an analysis of 500 consecutive evaluations. *Dysphagia*, *15*(1), 39-44.
- Baijens, Barikroo, & Pilz. (2013). Intrarater and interrater reliability for measurements in videofluoroscopy of swallowing. *European journal of radiology*, *82*(10), 1683-1695.
- Balas, & Boren. (2000). Managing clinical knowledge for health care improvement. *Yearbook of medical informatics*, *9*(01), 65-70.
- Barnett, Ter Haar, Ziskin, Rott, Duck, & Maeda. (2000). International recommendations and guidelines for the safe use of diagnostic ultrasound in medicine. *Ultrasound in medicine & biology*, *26*(3), 355-366.
- Bartlett, & Frost. (2008). Reliability, repeatability and reproducibility: analysis of measurement errors in continuous variables. *Ultrasound in Obstetrics and Gynecology: The Official Journal of the International Society of Ultrasound in Obstetrics and Gynecology*, *31*(4), 466-475.
- Bates, Maechler, Bolker, & Walker. (2014). lme4: Linear mixed-effects models using Eigen and S4. *R package version*, *1*(7), 1-23.
- Baylow, Goldfarb, Taveira, & Steinberg. (2009). Accuracy of clinical judgment of the chin-down posture for dysphagia during the clinical/bedside assessment as corroborated by videofluoroscopy in adults with acute stroke. *Dysphagia*, *24*(4), 423.
- Berzlanovich, Fazeney-Dörner, Waldhoer, Fasching, & Keil. (2005). Foreign body asphyxia: a preventable cause of death in the elderly. *American journal of preventive medicine*, *28*(1), 65-69.
- Bingjie, Tong, Xinting, Jianmin, & Guijun. (2010). Quantitative videofluoroscopic analysis of penetration-aspiration in post-stroke patients. *Neurology India*, *58*(1), 42.

- Bland, & Altman. (1995). Comparing methods of measurement: why plotting difference against standard method is misleading. *The lancet*, 346(8982), 1085-1087.
- Bonilha, Blair, Carnes, Huda, Humphries, McGrattan, . . . Martin-Harris. (2013). Preliminary investigation of the effect of pulse rate on judgments of swallowing impairment and treatment recommendations. *Dysphagia*, 28(4), 528-538.
- Brates, Molfenter, & Thibeault. (2019). Assessing hyolaryngeal excursion: comparing quantitative methods to palpation at the bedside and visualization during videofluoroscopy. *Dysphagia*, 34(3), 298-307.
- Bulat, & Orlando. (2005). Oropharyngeal dysphagia. *Current treatment options in Gastroenterology*, 8(4), 269-274.
- Carnaby. (2012). Food for thought: importance of a clinical exam/cranial nerve assessment. *Perspectives on Swallowing and Swallowing Disorders (Dysphagia)*, 21(4), 143-149.
- Cerenko, McConnel, & Jackson. (1989). Quantitative assessment of pharyngeal bolus driving forces. *Otolaryngology—Head and Neck Surgery*, 100(1), 57-63.
- Chassin. (1990). Practice guidelines: best hope for quality improvement in the 1990s. *Journal of occupational medicine.: official publication of the Industrial Medical Association*, 32(12), 1199-1206.
- Chen, Hsiao, Wang, Fu, & Wang. (2017). Reliability of ultrasonography in evaluating hyoid bone movement. *Journal of medical ultrasound*, 25(2), 90-95.
- Chi-Fishman, Hicks, Cintas, Sonies, & Gerber. (2004). Ultrasound imaging distinguishes between normal and weak muscle. *Archives of physical medicine and rehabilitation*, 85(6), 980-986.
- Chi-Fishman, & Sonies. (2000). Motor strategy in rapid sequential swallowing: new insights. *Journal of Speech, Language, and Hearing Research*, 43(6), 1481-1492.

- Chi-Fishman, & Sonies. (2002). Effects of systematic bolus viscosity and volume changes on hyoid movement kinematics. *Dysphagia*, 17(4), 278-287.
- Chi-Fishman. (2005). Quantitative lingual, pharyngeal and laryngeal ultrasonography in swallowing research: a technical review. *Clinical linguistics & phonetics*, 19(6-7), 589-604.
- Christrup. (1964). Normal swallowing of foodstuffs of pasty consistence. A cinefluorographic investigation of a normal material. *Danish Med Bull*, 11, 79-91.
- Clavé, & Shaker. (2015). Dysphagia: current reality and scope of the problem. *Nature Reviews Gastroenterology & Hepatology*, 12(5), 259.
- Cook, Dodds, Dantas, Massey, Kern, Lang, . . . Hogan. (1989). Opening mechanisms of the human upper esophageal sphincter. *American Journal of Physiology-Gastrointestinal and Liver Physiology*, 257(5), G748-G759.
- Cook, & Kahrilas. (1999). AGA technical review on management of oropharyngeal dysphagia. *Gastroenterology*, 116(2), 455-478.
- Costa. (2010). Videofluoroscopy: the gold standard exam for studying swallowing and its dysfunction. *Arquivos de gastroenterologia*, 47(4), 327-328.
- Crary, Carnaby, & Groher. (2006). Biomechanical correlates of surface electromyography signals obtained during swallowing by healthy adults. *Journal of Speech, Language, and Hearing Research*.
- Croghan, Burke, Caplan, & Denman. (1994). Pilot study of 12-month outcomes of nursing home patients with aspiration on videofluoroscopy. *Dysphagia*, 9(3), 141-146.
- Daniels, Brailey, Priestly, Herrington, Weisberg, & Foundas. (1998). Aspiration in patients with acute stroke. *Archives of physical medicine and rehabilitation*, 79(1), 14-19.
- Daniels, Huckabee, & Gozdzikowska. (2019). *Dysphagia following stroke*: Plural Publishing.

- Daniels, McAdam, Brailey, & Foundas. (1997). Clinical assessment of swallowing and prediction of dysphagia severity. *American Journal of Speech-Language Pathology*, 6(4), 17-24.
- Dantas, Kern, Massey, Dodds, Kahrilas, Brasseur, . . . Lang. (1990). Effect of swallowed bolus variables on oral and pharyngeal phases of swallowing. *American Journal of Physiology-Gastrointestinal and Liver Physiology*, 258(5), G675-G681.
- Dawson, & Trapp. (2004). Chapter 3. Summarizing Data & Presenting Data in Tables & Graphs *Basic & Clinical Biostatistics, 4e*. New York, NY: The McGraw-Hill Companies.
- DePippo, Holas, & Reding. (1992). Validation of the 3-oz water swallow test for aspiration following stroke. *Archives of neurology*, 49(12), 1259-1261.
- Dodds. (1989). The physiology of swallowing. *Dysphagia*, 3(4), 171-178.
- Dodds, Man, Cook, Kahrilas, Stewart, & Kern. (1988). Influence of bolus volume on swallow-induced hyoid movement in normal subjects. *American Journal of Roentgenology*, 150(6), 1307-1309.
- Dodds, Stewart, & Logemann. (1990). Physiology and radiology of the normal oral and pharyngeal phases of swallowing. *AJR. American journal of roentgenology*, 154(5), 953-963.
- Ekberg. (1982). Closure of the laryngeal vestibule during deglutition. *Acta oto-laryngologica*, 93(1-6), 123-129.
- Ekberg. (1986). The normal movements of the hyoid bone during swallow. *Investigative radiology*, 21(5), 408-410.
- Elmståhl, Bülow, Ekberg, Petersson, & Tegner. (1999). Treatment of dysphagia improves nutritional conditions in stroke patients. *Dysphagia*, 14(2), 61-66.

- Ertekin. (2011). Voluntary versus spontaneous swallowing in man. *Dysphagia*, 26(2), 183-192.
- Ertekin, & Aydogdu. (2003). Neurophysiology of swallowing. *Clinical Neurophysiology*, 114(12), 2226-2244.
- Executive. (1997). *Promoting Clinical Effectiveness-a Framework for Action in and Through the NHS*: Department health.
- Feng, Cartwright, Walker, Bargoil, Hu, & Butler. (2015). Ultrasonographic evaluation of geniohyoid muscle and hyoid bone during swallowing in young adults. *The Laryngoscope*, 125(8), 1886-1891.
- Feng, Todd, Lintzenich, Ding, Carr, Ge, . . . Butler. (2012). Aging-related geniohyoid muscle atrophy is related to aspiration status in healthy older adults. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences*, 68(7), 853-860.
- Fink, Martin, & Rohrmann. (1979). Biomechanics of the human epiglottis. *Acta otolaryngologica*, 87(3-6), 554-559.
- Foley, Martin, Salter, & Teasell. (2009). A review of the relationship between dysphagia and malnutrition following stroke. *Journal of rehabilitation medicine*, 41(9), 707-713.
- Fuller, Pimentel, & Peregoy. (2012). *Applied Anatomy & Physiology for Speech-language Pathology and Audiology*: Wolters Kluwer/Lippincott Williams & Wilkins Health.
- Giavarina. (2015). Understanding bland altman analysis. *Biochemia medica: Biochemia medica*, 25(2), 141-151.
- Gick, Bird, & Wilson. (2005). Techniques for field application of lingual ultrasound imaging. *Clinical linguistics & phonetics*, 19(6-7), 503-514.
- Gordon, Hewer, & Wade. (1987). Dysphagia in acute stroke. *Br Med J (Clin Res Ed)*, 295(6595), 411-414.

- Goyal, & Chaudhury. (2008). Physiology of normal esophageal motility. *Journal of clinical gastroenterology*, 42(5), 610.
- Grimshaw, Eccles, Lavis, Hill, & Squires. (2012). Knowledge translation of research findings. *Implementation science*, 7(1), 50.
- Groher, & Bukatman. (1986). The prevalence of swallowing disorders in two teaching hospitals. *Dysphagia*, 1(1), 3-6.
- Hamdy, Aziz, Rothwell, Hobson, Barlow, & Thompson. (1997). Cranial nerve modulation of human cortical swallowing motor pathways. *American Journal of Physiology-Gastrointestinal and Liver Physiology*, 272(4), G802-G808.
- Hamlet, & Reid. (1972). Transmission of ultrasound through the larynx as a means of determining vocal-fold activity. *IEEE transactions on biomedical engineering*(1), 34-37.
- Haynes, & Haines. (1998). Barriers and bridges to evidence based clinical practice. *BmJ*, 317(7153), 273-276.
- Hiiemae, & Palmer. (1999). Food transport and bolus formation during complete feeding sequences on foods of different initial consistency. *Dysphagia*, 14(1), 31-42.
- Hiss, & Postma. (2003). Fiberoptic endoscopic evaluation of swallowing. *The Laryngoscope*, 113(8), 1386-1393.
- Horner, & Massey. (1988). Silent aspiration following stroke. *Neurology*, 38(2), 317-317.
- Hsiao, Chang, Chen, Chang, & Wang. (2012). Application of ultrasonography in assessing oropharyngeal dysphagia in stroke patients. *Ultrasound Med Biol*, 38(9), 1522-1528. doi:10.1016/j.ultrasmedbio.2012.04.017
- Huang, Hsieh, Chang, Chen, & Wang. (2009). Ultrasonographic evaluation of hyoid-larynx approximation in dysphagic stroke patients. *Ultrasound in medicine & biology*, 35(7), 1103-1108.

- Huckabee, Deecke, Cannito, Gould, & Mayr. (2003). Cortical control mechanisms in volitional swallowing: the Bereitschaftspotential. *Brain topography*, 16(1), 3-17.
- Huckabee, Macrae, & Lamvik. (2015). Expanding instrumental options for dysphagia diagnosis and research: ultrasound and manometry. *Folia Phoniatrica et Logopaedica*, 67(6), 269-284.
- Huckabee, McIntosh, Fuller, Curry, Thomas, Walshe, . . . Frank. (2018). The Test of Masticating and Swallowing Solids (TOMASS): Reliability, validity and international normative data. *International journal of language & communication disorders*, 53(1), 144-156.
- Hurwitz, Nelson, & Haddad. (1975). Oropharyngeal dysphagia. *The American journal of digestive diseases*, 20(4), 313-324.
- Imam, Shay, Ali, & Baker. (2005). Bolus transit patterns in healthy subjects: a study using simultaneous impedance monitoring, videoesophagram, and esophageal manometry. *American Journal of Physiology-Gastrointestinal and Liver Physiology*, 288(5), G1000-G1006.
- Ishida, Palmer, & Hiimeae. (2002). Hyoid motion during swallowing: factors affecting forward and upward displacement. *Dysphagia*, 17(4), 262-272.
- Jacob, Kahrilas, Logemann, Shah, & Ha. (1989). Upper esophageal sphincter opening and modulation during swallowing. *Gastroenterology*, 97(6), 1469-1478.
- Jain. (2008). High-resolution sonography of sublingual space. *Journal of medical imaging and radiation oncology*, 52(2), 101-108.
- Jean. (1984). Brainstem organization of the swallowing network. *Brain, behavior and evolution*, 25(2-3), 109-116.
- Jean. (2001). Brain stem control of swallowing: neuronal network and cellular mechanisms. *Physiological reviews*, 81(2), 929-969.

- Jones, Roop, Pohar, Albrecht, & Scott. (2015). Translating knowledge in rehabilitation: systematic review. *Physical therapy, 95*(4), 663-677.
- Kahrilas, Dodds, & Hogan. (1988). Effect of peristaltic dysfunction on esophageal volume clearance. *Gastroenterology, 94*(1), 73-80.
- Kahrilas, Lin, Rademaker, & Logemann. (1997). Impaired deglutitive airway protection: a videofluoroscopic analysis of severity and mechanism. *Gastroenterology, 113*(5), 1457-1464.
- Kahrilas, Logemann, Lin, & Ergun. (1992). Pharyngeal clearance during swallowing: a combined manometric and videofluoroscopic study. *Gastroenterology, 103*(1), 128-136.
- Kang, Oh, Kim, Chung, Kim, & Han. (2010). Influence of aging on movement of the hyoid bone and epiglottis during normal swallowing: a motion analysis. *Gerontology, 56*(5), 474-482.
- Keller, & Ostry. (1983). Computerized measurement of tongue dorsum movements with pulsed-echo ultrasound. *The Journal of The Acoustical Society of America, 73*(4), 1309-1315.
- Kelly, Huckabee, Jones, & Carroll. (2007). The influence of volition on breathing-swallowing coordination in healthy adults. *Behavioral neuroscience, 121*(6), 1174.
- Kendall, & Leonard. (2001). Hyoid movement during swallowing in older patients with dysphagia. *Archives of Otolaryngology–Head & Neck Surgery, 127*(10), 1224-1229.
- Kessler, & Jean. (1985). Identification of the medullary swallowing regions in the rat. *Experimental brain research, 57*(2), 256-263.
- Kim, & McCullough. (2008). Maximum hyoid displacement in normal swallowing. *Dysphagia, 23*(3), 274-279.

- Komori, Hyodo, & Gyo. (2008). A swallowing evaluation with simultaneous videoendoscopy, ultrasonography and videofluorography in healthy controls. *ORL*, 70(6), 393-398.
- Koo, & Li. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of chiropractic medicine*, 15(2), 155-163.
- Kossoff. (2000). Basic physics and imaging characteristics of ultrasound. *World journal of surgery*, 24(2), 134-142.
- Kuhl, Eicke, Dieterich, & Urban. (2003). Sonographic analysis of laryngeal elevation during swallowing. *Journal of neurology*, 250(3), 333-337.
- Kuhlemeier, Yates, & Palmer. (1998). Intra-and interrater variation in the evaluation of videofluorographic swallowing studies. *Dysphagia*, 13(3), 142-147.
- Kundra, Mishra, & Ramesh. (2011). Ultrasound of the airway. *Indian journal of anaesthesia*, 55(5), 456.
- Langmore. (2003). Evaluation of oropharyngeal dysphagia: which diagnostic tool is superior? *Current opinion in otolaryngology & head and neck surgery*, 11(6), 485-489.
- Langmore, Skarupski, Park, & Fries. (2002). Predictors of aspiration pneumonia in nursing home residents. *Dysphagia*, 17(4), 298-307.
- Leder, & Espinosa. (2002). Aspiration risk after acute stroke: comparison of clinical examination and fiberoptic endoscopic evaluation of swallowing. *Dysphagia*, 17(3), 214-218.
- Leder, Sasaki, & Burrell. (1998). Fiberoptic endoscopic evaluation of dysphagia to identify silent aspiration. *Dysphagia*, 13(1), 19-21.
- Lee, Lee, Kang, Im Yi, & Kim. (2016). Usefulness of submental ultrasonographic evaluation for dysphagia patients. *Annals of rehabilitation medicine*, 40(2), 197.

- Légaré, Borduas, MacLeod, Sketris, Campbell, & Jacques. (2011). Partnerships for knowledge translation and exchange in the context of continuing professional development. *Journal of Continuing Education in the Health Professions*, 31(3), 181-187.
- Leibovitz, Baumoehl, Lubart, Yaina, Platinovitz, & Segal. (2007). Dehydration among long-term care elderly patients with oropharyngeal dysphagia. *Gerontology*, 53(4), 179-183.
- Leonard, Kendall, McKenzie, Gonçalves, & Walker. (2000). Structural displacements in normal swallowing: a videofluoroscopic study. *Dysphagia*, 15(3), 146-152.
- Leonard, & McKenzie. (2006). Hyoid-bolus transit latencies in normal swallow. *Dysphagia*, 21(3), 183-190.
- Leopold, & Kagel. (1997). Dysphagia—ingestion or deglutition?: A proposed paradigm. *Dysphagia*, 12(4), 202-206.
- Linden. (1989). Videofluoroscopy in the rehabilitation of swallowing dysfunction. *Dysphagia*, 3(4), 189-191.
- Linden, Kuhlemeier, & Patterson. (1993). The probability of correctly predicting subglottic penetration from clinical observations. *Dysphagia*, 8(3), 170-179.
- Logemann. (1997). Role of the modified barium swallow in management of patients with dysphagia. *Otolaryngology--Head and Neck Surgery*, 116(3), 335-338.
- Logemann. (1998). The evaluation and treatment of swallowing disorders. *Current opinion in otolaryngology & head and neck surgery*, 6(6), 395-400.
- Logemann, Gensler, Robbins, Lindblad, Brandt, Hind, . . . Gramigna. (2008). A randomized study of three interventions for aspiration of thin liquids in patients with dementia or Parkinson's disease. *Journal of Speech, Language, and Hearing Research*.

- Logemann, Kahrilas, Cheng, Pauloski, Gibbons, Rademaker, & Lin. (1992). Closure mechanisms of laryngeal vestibule during swallow. *American Journal of Physiology-Gastrointestinal and Liver Physiology*, 262(2), G338-G344.
- Logemann, Pauloski, Rademaker, Colangelo, Kahrilas, & Smith. (2000). Temporal and biomechanical characteristics of oropharyngeal swallow in younger and older men. *Journal of Speech, Language, and Hearing Research*, 43(5), 1264-1274.
- Logemann, Pauloski, Rademaker, & Kahrilas. (2002). Oropharyngeal swallow in younger and older women. *Journal of Speech, Language, and Hearing Research*.
- Logemann, Rademaker, Pauloski, Ohmae, & Kahrilas. (1998). Normal swallowing physiology as viewed by videofluoroscopy and videoendoscopy. *Folia Phoniatica et Logopaedica*, 50(6), 311.
- Macrae, Doeltgen, Jones, & Huckabee. (2012). Intra-and inter-rater reliability for analysis of hyoid displacement measured with sonography. *Journal of clinical ultrasound*, 40(2), 74-78.
- Macrae, Jones, Myall, Melzer, & Huckabee. (2013). Cross-sectional area of the anterior belly of the digastric muscle: comparison of MRI and ultrasound measures. *Dysphagia*, 28(3), 375-380.
- Manabe, Kusunoki, Kamada, Inoue, Hata, & Haruma. (2015). 844 Newly Developed Ultrasonographic Screening Method for Oropharyngeal Dysphagia: Tissue Doppler Imaging. *Gastroenterology*, 148(4), S-168.
- Mann, Hankey, & Cameron. (2000). Swallowing disorders following acute stroke: prevalence and diagnostic accuracy. *Cerebrovascular diseases*, 10(5), 380-386.
- Marik, & Kaplan. (2003). Aspiration pneumonia and dysphagia in the elderly. *Chest*, 124(1), 328-336.

- Martin-Harris, Brodsky, Michel, Ford, Walters, & Heffner. (2005). Breathing and swallowing dynamics across the adult lifespan. *Archives of Otolaryngology–Head & Neck Surgery*, *131*(9), 762-770.
- Martin-Harris, Brodsky, Michel, Lee, & Walters. (2007). Delayed initiation of the pharyngeal swallow: normal variability in adult swallows. *Journal of Speech, Language, and Hearing Research*.
- Martin, Corlew, Wood, Olson, Golopol, Wingo, & Kirmani. (1994). The association of swallowing dysfunction and aspiration pneumonia. *Dysphagia*, *9*(1), 1-6.
- Martino, Foley, Bhogal, Diamant, Speechley, & Teasell. (2005). Dysphagia after stroke: incidence, diagnosis, and pulmonary complications. *stroke*, *36*(12), 2756-2763.
- Martino, Pron, & Diamant. (2000). Screening for oropharyngeal dysphagia in stroke: insufficient evidence for guidelines. *Dysphagia*, *15*(1), 19-30.
- Matsuo, & Palmer. (2008). Anatomy and physiology of feeding and swallowing: normal and abnormal. *Physical Medicine and Rehabilitation Clinics of North America*, *19*(4), 691-707.
- McCullough, & Martino. (2013). Clinical evaluation of patients with dysphagia: Importance of history taking and physical exam *Manual of diagnostic and therapeutic techniques for disorders of deglutition* (pp. 11-30): Springer.
- McCullough, Wertz, & Rosenbek. (2001). Sensitivity and specificity of clinical/bedside examination signs for detecting aspiration in adults subsequent to stroke. *Journal of communication disorders*, *34*(1-2), 55-72.
- Mepani, Antonik, Massey, Kern, Logemann, Pauloski, . . . Shaker. (2009). Augmentation of deglutitive thyrohyoid muscle shortening by the Shaker Exercise. *Dysphagia*, *24*(1), 26-31.

- Mihai, Otto, Platz, Eickhoff, Lotze, & Martin. (2014). Sequential evolution of cortical activity and effective connectivity of swallowing using fMRI. *Human brain mapping*, 35(12), 5962-5973.
- Miles, Clark, Jardine, & Allen. (2016). Esophageal swallowing timing measures in healthy adults during videofluoroscopy. *Annals of Otolaryngology, Rhinology & Laryngology*, 125(9), 764-769.
- Miles, & Huckabee. (2013). Intra-and inter-rater reliability for judgement of cough following citric acid inhalation. *International journal of speech-language pathology*, 15(2), 209-215.
- Miles, McFarlane, Scott, & Hunting. (2018). Cough response to aspiration in thin and thick fluids during FEES in hospitalized inpatients. *International journal of language & communication disorders*, 53(5), 909-918.
- Miles, Moore, McFarlane, Lee, Allen, & Huckabee. (2013). Comparison of cough reflex test against instrumental assessment of aspiration. *Physiology & behavior*, 118, 25-31.
- Miller. (1982). Deglutition. *Physiological reviews*, 62(1), 129-184.
- Miller. (1986). Neurophysiological basis of swallowing. *Dysphagia*, 1(2), 91.
- Miller. (1991). Update on safety of diagnostic ultrasonography. *Journal of clinical ultrasound*, 19(9), 531-540.
- Minifie, Kelsey, Zagzebski, & King. (1971). Ultrasonic scans of the dorsal surface of the tongue. *The Journal of The Acoustical Society of America*, 49(6B), 1857-1860.
- Mistry, & Hamdy. (2008). Neural control of feeding and swallowing. *Physical Medicine and Rehabilitation Clinics of North America*, 19(4), 709-728.
- Miura, Nakagami, Yabunaka, Tohara, Murayama, Noguchi, . . . Sanada. (2014). Method for detection of aspiration based on B-mode video ultrasonography. *Radiological physics and technology*, 7(2), 290-295.

- Molfenter, & Steele. (2011). Physiological variability in the deglutition literature: hyoid and laryngeal kinematics. *Dysphagia*, 26(1), 67-74.
- Morris, Wooding, & Grant. (2011). The answer is 17 years, what is the question: understanding time lags in translational research. *Journal of the Royal Society of Medicine*, 104(12), 510-520.
- Morrish, Stone, Sonies, Kurtz, & Shawker. (1984). Characterization of tongue shape. *Ultrasonic Imaging*, 6(1), 37-47.
- Murray, Langmore, Ginsberg, & Dostie. (1996). The significance of accumulated oropharyngeal secretions and swallowing frequency in predicting aspiration. *Dysphagia*, 11(2), 99-103.
- Murray, Miller, Doeltgen, & Scholten. (2014). Intake of thickened liquids by hospitalized adults with dysphagia after stroke. *International journal of speech-language pathology*, 16(5), 486-494.
- Nacci, Matteucci, Romeo, Santopadre, Cavaliere, Barillari, . . . Fattori. (2016). Complications with fiberoptic endoscopic evaluation of swallowing in 2,820 examinations. *Folia Phoniatria et Logopaedica*, 68(1), 37-45.
- Nacci, Ursino, La Vela, Matteucci, Mallardi, & Fattori. (2008). Fiberoptic endoscopic evaluation of swallowing (FEES): proposal for informed consent. *Acta Otorhinolaryngologica Italica*, 28(4), 206.
- Nakamori, Hosomi, Takaki, Oda, Hiraoka, Yoshikawa, . . . Maruyama. (2016). Tongue thickness evaluation using ultrasonography can predict swallowing function in amyotrophic lateral sclerosis patients. *Clinical Neurophysiology*, 127(2), 1669-1674.
- Neta, Glasgow, Carpenter, Grimshaw, Rabin, Fernandez, & Brownson. (2015). A framework for enhancing the value of research for dissemination and implementation. *American Journal of Public Health*, 105(1), 49-57.

- Niederman, McCombs, Unger, Kumar, & Popovian. (1998). The cost of treating community-acquired pneumonia. *Clinical therapeutics*, 20(4), 820-837.
- Nordin, Miles, & Allen. (2017). Measuring competency development in objective evaluation of videofluoroscopic swallowing studies. *Dysphagia*, 32(3), 427-436.
- O'Connor, & Pettigrew. (2009). The barriers perceived to prevent the successful implementation of evidence-based practice by speech and language therapists. *International journal of language & communication disorders*, 44(6), 1018-1035.
- O'Neil-Pirozzi, Momose, Mello, Lepak, McCabe, Connors, & Lisiecki. (2003). Feasibility of swallowing interventions for tracheostomized individuals with severely disordered consciousness following traumatic brain injury. *Brain injury*, 17(5), 389-399.
- Ohmae, Logemann, Kaiser, Hanson, & Kahrilas. (1995). Timing of glottic closure during normal swallow. *Head & Neck*, 17(5), 394-402.
- Paik, Kim, Lee, Jeon, Lim, & Han. (2008). Movement of the hyoid bone and the epiglottis during swallowing in patients with dysphagia from different etiologies. *Journal of Electromyography and Kinesiology*, 18(2), 329-335.
- Palmer, Rudin, Lara, & Crompton. (1992). Coordination of mastication and swallowing. *Dysphagia*, 7(4), 187-200.
- Pearson, Hindson, Langmore, & Zumwalt. (2013). Evaluating swallowing muscles essential for hyolaryngeal elevation by using muscle functional magnetic resonance imaging. *International Journal of Radiation Oncology* Biology* Physics*, 85(3), 735-740.
- Pearson Jr, Griffeth, & Ennis. (2019). Functional Anatomy Underlying Pharyngeal Swallowing Mechanics and Swallowing Performance Goals. *Perspectives of the ASHA Special Interest Groups*, 4(4), 648-655.

- Pearson Jr, & Zumwalt. (2014). Visualising hyolaryngeal mechanics in swallowing using dynamic MRI. *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization*, 2(4), 208-216.
- Pearson, Langmore, Louis, & Zumwalt. (2012). Structural analysis of muscles elevating the hyolaryngeal complex. *Dysphagia*, 27(4), 445-451.
- Pearson, Taylor, Blair, & Martin-Harris. (2016). Computational analysis of swallowing mechanics underlying impaired epiglottic inversion. *The Laryngoscope*, 126(8), 1854-1858.
- Peng, Jost-Brinkmann, & Miethke. (1996). The cushion scanning technique: a method of dynamic tongue sonography and its comparison with the transducer-skin coupling scanning technique during swallowing. *Academic radiology*, 3(3), 239-244.
- Perlman, Booth, & Grayhack. (1994). Videofluoroscopic predictors of aspiration in patients with oropharyngeal dysphagia. *Dysphagia*, 9(2), 90-95.
- Perlman, Schultz, & VanDaele. (1993). Effects of age, gender, bolus volume, and bolus viscosity on oropharyngeal pressure during swallowing. *Journal of Applied Physiology*, 75(1), 33-37.
- Perlman, VanDaele, & Otterbacher. (1995). Quantitative assessment of hyoid bone displacement from video images during swallowing. *Journal of Speech, Language, and Hearing Research*, 38(3), 579-585.
- Perry, & Love. (2001). Screening for dysphagia and aspiration in acute stroke: a systematic review. *Dysphagia*, 16(1), 7-18.
- Perry, Miles, Fink, & Huckabee. (2019). The Dysphagia in Stroke Protocol reduces aspiration pneumonia in patients with dysphagia following acute stroke: a clinical audit. *Translational stroke research*, 10(1), 36-43.

- Perry, Winkelman, & Huckabee. (2016). Variability in Ultrasound Measurement of Hyoid Bone Displacement and Submental Muscle Size Using 2 Methods of Data Acquisition. *Folia Phoniatrica et Logopaedica*, 68(5), 205-210.
- Portney, & Watkins. (2000). Validity of measurements. *Foundations of clinical research: Applications to practice*, 2.
- R Core Team. (2017). R: A language and environment for statistical computing. Retrieved from <https://www.R-project.org/>
- Riley, Glasgow, Etheredge, & Abernethy. (2013). Rapid, responsive, relevant (R3) research: a call for a rapid learning health research enterprise. *Clinical and translational medicine*, 2(1), 10.
- Robbins, Hamilton, Lof, & Kempster. (1992). Oropharyngeal swallowing in normal adults of different ages. *Gastroenterology*, 103(3), 823-829.
- Rommel, & Hamdy. (2016). Oropharyngeal dysphagia: manifestations and diagnosis. *Nature Reviews Gastroenterology & Hepatology*, 13(1), 49.
- Sackett. (2000). The fall of " clinical research " and the rise of " clinical-practice research ". *Clinical and Investigative Medicine*, 23(6), 331-333.
- Sapir, Ramig, & Fox. (2008). Speech and swallowing disorders in Parkinson disease. *Current opinion in otolaryngology & head and neck surgery*, 16(3), 205-210.
- Scarborough, Waizenhofer, Siekemeyer, & Hughes. (2010). Sonographically measured hyoid bone displacement during swallow in preschool children: a preliminary study. *Journal of clinical ultrasound*, 38(8), 430-434.
- Schneider, Rasband, & Eliceiri. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature methods*, 9(7), 671.
- Scott, Perry, & Bench. (1998). A study of interrater reliability when using videofluoroscopy as an assessment of swallowing. *Dysphagia*, 13(4), 223-227.

- Seaman. (1976). Pharyngeal and upper esophageal dysphagia. *JAMA*, 235(24), 2643-2646.
- Selley, Flack, Ellis, & Brooks. (1989). Respiratory patterns associated with swallowing: Part 1. The normal adult pattern and changes with age. *Age and ageing*, 18(3), 168-172.
- Shaker, Dodds, Dantas, Hogan, & Arndorfer. (1990). Coordination of deglutitive glottic closure with oropharyngeal swallowing. *Gastroenterology*, 98(6), 1478-1484.
- Shaker, Easterling, Kern, Nitschke, Massey, Daniels, . . . Dikeman. (2002). Rehabilitation of swallowing by exercise in tube-fed patients with pharyngeal dysphagia secondary to abnormal UES opening. *Gastroenterology*, 122(5), 1314-1321.
- Shaw, Cook, Gabb, Holloway, Simula, Panagopoulos, & Dent. (1995). Influence of normal aging on oral-pharyngeal and upper esophageal sphincter function during swallowing. *American Journal of Physiology-Gastrointestinal and Liver Physiology*, 268(3), G389-G396.
- Shawker, Sonies, & Stone. (1984). Soft tissue anatomy of the tongue and floor of the mouth: an ultrasound demonstration. *Brain and language*, 21(2), 335-350.
- Sia, Carvajal, Carnaby-Mann, & Crary. (2012). Measurement of hyoid and laryngeal displacement in video fluoroscopic swallowing studies: variability, reliability, and measurement error. *Dysphagia*, 27(2), 192-197.
- Siebens, Trupe, Siebens, Cook, Anshen, Hanauer, & Oster. (1986). Correlates and consequences of eating dependency in institutionalized elderly. *Journal of the American Geriatrics Society*, 34(3), 192-198.
- Sivarao, & Goyal. (2000). Functional anatomy and physiology of the upper esophageal sphincter. *The American journal of medicine*, 108(4), 27-37.
- Skolnick, Zagzebski, & Watkin. (1975). Two dimensional ultrasonic demonstration of lateral pharyngeal wall movement in real time--a preliminary report. *The Cleft palate journal*, 12, 299-303.

- Sonies, Parent, Morrish, & Baum. (1988). Durational aspects of the oral-pharyngeal phase of swallow in normal adults. *Dysphagia*, 3(1), 1-10.
- Sonies, Shawker, Hall, Gerber, & Leighton. (1981). Ultrasonic visualization of tongue motion during speech. *The Journal of The Acoustical Society of America*, 70(3), 683-686.
- Spechler. (1999). AGA technical review on treatment of patients with dysphagia caused by benign disorders of the distal esophagus. *Gastroenterology*, 117(1), 233-254.
- Splaingard, Hutchins, Sulton, & Chaudhuri. (1988). Aspiration in rehabilitation patients: videofluoroscopy vs bedside clinical assessment. *Archives of physical medicine and rehabilitation*, 69(8), 637-640.
- Steele, Bailey, Chau, Molfenter, Oshalla, Waito, & Zoratto. (2011). The relationship between hyoid and laryngeal displacement and swallowing impairment. *Clinical Otolaryngology*, 36(1), 30-36.
- Stone, & Davis. (1995). A head and transducer support system for making ultrasound images of tongue/jaw movement. *The Journal of The Acoustical Society of America*, 98(6), 3107-3112.
- Stone, Morrish, Sonies, & Shawker. (1987). Tongue curvature: A model of shape during vowel production. *Folia Phoniatica et Logopaedica*, 39(6), 302-315.
- Tamburrini, Solazzo, Sagnelli, Del Vecchio, Reginelli, Monsorro, & Grassi. (2010). Amyotrophic lateral sclerosis: sonographic evaluation of dysphagia. *La radiologia medica*, 115(5), 784-793.
- Tamura, Kikutani, Tohara, Yoshida, & Yaegaki. (2012). Tongue thickness relates to nutritional status in the elderly. *Dysphagia*, 27(4), 556-561.

- Thompson, Obeidin, Davidoff, Hightower, Johnson, Rice, . . . Pearson Jr. (2014). Coordinate mapping of hyolaryngeal mechanics in swallowing. *JoVE (Journal of Visualized Experiments)*(87), e51476.
- Thorsen, & Lakin. (2010). *Basic Physics of Ultrasonography*. Paper presented at the Seminars in Colon and Rectal Surgery.
- Torrico, Corazziari, & Habib. (2003). Barium studies for detecting esophagopharyngeal reflux events. *The American journal of medicine*, 115(3), 124-129.
- Udovičić, Baždarić, Bilić-Zulle, & Petrovečki. (2007). What we need to know when calculating the coefficient of correlation? *Biochemia medica: Biochemia medica*, 17(1), 10-15.
- Van Daele, McCulloch, Palmer, & Langmore. (2005). Timing of glottic closure during swallowing: a combined electromyographic and endoscopic analysis. *Annals of Otolaryngology, Rhinology & Laryngology*, 114(6), 478-487.
- Van den Engel-Hoek, Erasmus, Hendriks, Geurts, Klein, Pillen, . . . De Groot. (2013). Oral muscles are progressively affected in Duchenne muscular dystrophy: implications for dysphagia treatment. *Journal of neurology*, 260(5), 1295-1303.
- Vandaele, Perlman, & Cassell. (1995). Intrinsic fibre architecture and attachments of the human epiglottis and their contributions to the mechanism of deglutition. *Journal of anatomy*, 186(Pt 1), 1.
- Venables. (2011). How does ultrasound work? *Ultrasound*, 19(1), 44-49.
- Vose, & Humbert. (2018). “Hidden in plain sight”: a descriptive review of laryngeal vestibule closure. *Dysphagia*, 1-9.
- Wang, Chang, Chen, Lin, & Hsiao. (2010). Reduction in hyoid bone forward movement in irradiated nasopharyngeal carcinoma patients with dysphagia. *Archives of physical medicine and rehabilitation*, 91(6), 926-931.

- Warnecke, Teismann, Oelenberg, Hamacher, Ringelstein, Schäbitz, & Dziewas. (2009). The safety of fiberoptic endoscopic evaluation of swallowing in acute stroke patients. *stroke*, 40(2), 482-486.
- Watkin. (1999). Ultrasound and swallowing. *Folia Phoniatrica et Logopaedica*, 51(4-5), 183-198.
- Watkin, Diouf, Gallagher, Logemann, Rademaker, & Ettema. (2001). Ultrasonic quantification of geniohyoid cross-sectional area and tissue composition: A preliminary study of age and radiation effects. *Head & Neck*, 23(6), 467-474.
- Watkin, & Zagzebski. (1973). On-line ultrasonic technique for monitoring tongue displacements. *The Journal of The Acoustical Society of America*, 54(2), 544-547.
- Watts. (2013). Measurement of hyolaryngeal muscle activation using surface electromyography for comparison of two rehabilitative dysphagia exercises. *Archives of physical medicine and rehabilitation*, 94(12), 2542-2548.
- Widdicombe, Addington, Fontana, & Stephens. (2011). Voluntary and reflex cough and the expiration reflex; implications for aspiration after stroke. *Pulmonary pharmacology & therapeutics*, 24(3), 312-317.
- Wilcox, Liss, & Siegel. (1996). Interjudge agreement in videofluoroscopic studies of swallowing. *Journal of Speech, Language, and Hearing Research*, 39(1), 144-152.
- Yabunaka, Konishi, Nakagami, Sanada, Iizaka, Sanada, & Ohue. (2012). Ultrasonographic evaluation of geniohyoid muscle movement during swallowing: a study on healthy adults of various ages. *Radiological physics and technology*, 5(1), 34-39.
- Yabunaka, Sanada, Sanada, Konishi, Hashimoto, Yatake, . . . Ohue. (2011). Sonographic assessment of hyoid bone movement during swallowing: a study of normal adults with advancing age. *Radiological physics and technology*, 4(1), 73-77.

Yasumoto, Nakagawa, Shibuya, Suzuki, & Satoh. (1993). Ultrasonography of the sublingual space. *Journal of ultrasound in medicine*, 12(12), 723-729.

Yoon, Khoo, & Liow. (2014). Chin tuck against resistance (CTAR): new method for enhancing suprahyoid muscle activity using a Shaker-type exercise. *Dysphagia*, 29(2), 243-248.

Young, Macrae, Anderson, Taylor-Kamara, & Humbert. (2015). The sequence of swallowing events during the chin-down posture. *American Journal of Speech-Language Pathology*, 24(4), 659-670.

Appendix 1: Participant Information Sheet

ETHICS NO: 17/STH/230

Version 6: 02/03/2018

Participant NO: _____



Participant Information sheet

Study Title: Use of ultrasound to assess swallowing and swallowing safety

Coordinating investigator: Rebecca Hammond **Contact:** 021 223 8132

Supporting investigator: Alice Dimmock **Contact:** 021 815 295

Supervising investigator: Maggie-Lee Huckabee **Contact:** 021 324 616

You are invited to take part in a study that evaluates a small ultrasound device to assess swallowing and swallowing safety.

What is the study for?

Swallowing problems are difficult to evaluate by watching someone eat. Our main tool for evaluating swallowing is a motion picture X-ray or videofluoroscopy (VFSS). You have been referred for a videofluoroscopy as part of your standard care. Depending on the results of your x-ray, you may be invited participate in a research project to evaluate a new tool for swallowing assessment. This would require a small amount of extra testing using an ultrasound device to measure your swallowing at the same time as the x-ray.

Ultrasound is non-invasive, it is the same test as used on pregnant women; in this case an ultrasound transducer will be placed on the skin surface below your chin and above the larynx (Adam's apple).

Results from this study will give us more information on whether we can identify the type of swallowing problems people have and whether they can protect their lungs from food and fluid going the wrong way, using a small portable ultrasound device. This could offer more options for patients with swallowing problems, which don't require transport to an x-ray department.

Should I participate in the study?

- Whether or not you take part is your choice.
- If you don't want to take part, you don't have to give a reason. It won't affect the care you receive.

- If you do want to take part now, but change your mind later, you can pull out of the study at any time.

What will I need to do?

- After you have considered what is involved and discussed with family/whanau (if you like), you will need to sign a consent form.
- We will need to know some information about you, for example, your age, ethnicity and medical diagnosis.
- If we find that your type of swallowing problem would be useful to ultrasound during your x-ray test, we will ask you to swallow an additional 4 -8 mouthfuls of food and fluid under x ray at the end as part of the research.
- Whilst having the x-ray of these extra mouthfuls, a Speech-language therapist will place a small ultrasound device under your chin to measure your swallowing at the same time as the x-ray.
- This means it will take a small amount of additional x-rays (approximately 1-2 minutes). It will also take about 25 minutes of your time.
- For some participants after the x-ray study is complete, another speech-language therapist will need to complete 20 more minutes of ultrasound testing without x-ray. We will be able to tell you before you begin on the day if you are one of these people.

What happens after this?

- After the study, your clinical care will be managed as usual.
- Your x-rays and ultrasound for this study will be stored and analysed at Waitemata District Health Board.
- For the purposes of research your name will be removed from all paperwork and you will be assigned a code number.
- Copies of your X-rays and ultrasound images will be securely transferred to the Rose Centre for Stroke Recovery and Research, St Georges Medical Centre, Christchurch.
- All information will be kept safely on a password protected computer.
- The data will be stored for 10 years; after that it will be deleted.
- The results of the study will be included in the researcher's MSc thesis and may be submitted for publication in a peer reviewed journal. If you would like a copy of the study when it's complete, please indicate this on the consent form. You should understand that it may be quite a long time before the study is complete and the summary is available.

What are the possible risks of this study?

- There are minimal risks in taking part in the study. Ultrasound is completely non-invasive.
- There will be a small amount of additional x-ray time required, which involves radiation exposure. We will take great care to limit the exposure you receive but it

is estimated that the additional time required would be the equivalent to the natural radiation exposure you receive in 1-2 months or that which you would receive from 2 return flights to Europe. Sources of natural radiation are for example the ground and in building materials around us.

- Your participation will not affect your care in any way.
- You will have the opportunity to ask questions and to find out more information from the researcher.
- If you were injured in this study, which is very unlikely, you would be eligible to apply for compensation from ACC just as you would be if you were injured in an accident at work or at home. This does not mean that your claim will automatically be accepted. You will have to lodge a claim with ACC, which may take some time to assess. If your claim is accepted, you will receive funding to assist in your recovery. If you have private health or life insurance, you may wish to check with your insurer that taking part in this study won't affect your cover.

Who pays for the study?

The Health Research Council of New Zealand has provided a grant to cover the majority of the study costs. There is no cost to you.

What if I change my mind and decide I no longer want to be involved in the study?

- You can withdraw from the study or withdraw your data from the study up to the point the analysis is completed by contacting the primary investigator.
- If you do not wish to contact the primary investigator, you can contact your speech-language therapist who can inform the primary investigator on your behalf.
- You do not have to decide immediately whether or not you will participate in this study. Before you decide you may want to talk about the study with other people, such as family, whānau, friends, or healthcare providers. Feel free to do this.
- If you agree to participate in the study, please sign the consent form that comes with this information leaflet and bring it with you to your x-ray swallowing study.

What if I have more questions?

- Principal Investigator and Waitemata DHB contact: Rebecca Hammond (email Becca.hammond@waitematadhb.govt.nz Phone : 021 2238232)
- Supervisor: Prof Maggie-Lee Huckabee.
maggie-lee.huckabee@canterbury.ac.nz
- Maori Health Support: **Maori Health Support:** If you require Māori cultural support, talk to your whānau in the first instance. Alternatively, you may contact the administrator for He Kamaka Waiora (Māori Health Team) by telephoning 09 486 8324 ext. 42324
- If you have any questions or complaints about the study you may contact the Auckland and Waitematā District Health Boards Maori Research Committee or Maori Research Advisor by telephoning 09 4868920 ext. 43204

Appendix 2: Consent Form

ETHICS NO: 17/STH/230

Version 6: 02/03/2018

Participant NO: _____



Consent Form

Study title: use of ultrasound to assess swallowing and swallowing safety

- I have been given a full explanation of this project and have had the opportunity to ask questions.
- I understand what is required of me if I agree to take part in the research.
- I understand that participation is voluntary and I may withdraw at any time without penalty.
- Withdrawal of participation will also include the withdrawal of any information I have provided, if this is still possible.
- I understand that any information or opinions I provide will be kept confidential to the researcher and supervisors, and that any published or reported results will not identify the participants.
- I understand that a thesis is a public document and will be available through the University of Canterbury and Waitemata DHB libraries.
- I understand that all data collected for the study will be kept in locked and secure facilities and/or in password-protected electronic form and will be destroyed after ten years.
- I understand that I can contact the researcher Rebecca Hammond (Becca.hammond@waitematadhb.govt.nz) or her supervisor Maggie-Lee Huckabee (maggie-lee.huckabee@canterbury.ac.nz) for further information.

Optional: I would like to receive a summary of the findings. If so, please provide postal/ email address:

By signing below, I agree with the statements above, and to participate in this research project.

Print name of participant: _____

Signature of participant: _____ Date: _____

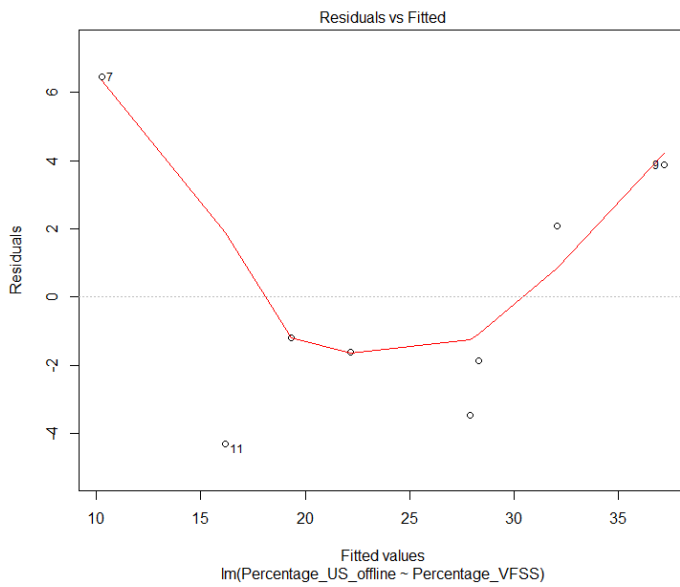
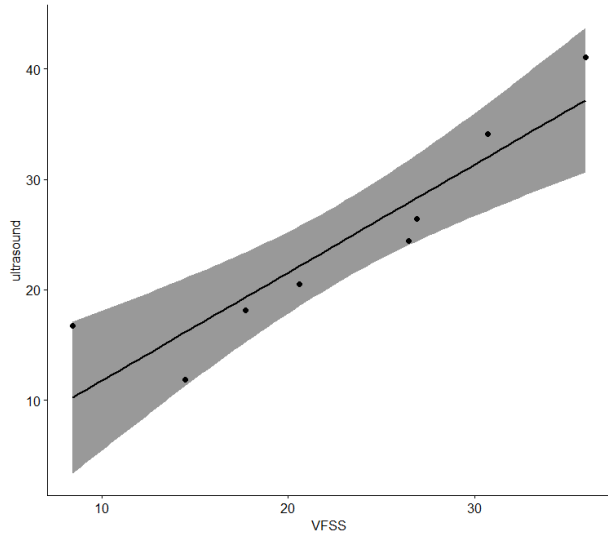
Appendix 3: Data Collection Protocol

NHI: Participant ID:	
DOB:.....	Age:..... Handedness:.....
Date	Time.....
Participant: <input type="checkbox"/> has read the information sheet and understood the information <input type="checkbox"/> meets inclusion criteria and <input type="checkbox"/> not pregnant <input type="checkbox"/> not allergic to food provided <input type="checkbox"/> has provided consent	
Further participant information: <input type="checkbox"/> New Zealand European <input type="checkbox"/> Other European <input type="checkbox"/> NZ Maori <input type="checkbox"/> Samoan <input type="checkbox"/> Fijian <input type="checkbox"/> Cook Island Maori <input type="checkbox"/> Tongan <input type="checkbox"/> Tokelauan <input type="checkbox"/> Other pacific peoples	<input type="checkbox"/> Niuean <input type="checkbox"/> Southeast Asian <input type="checkbox"/> Chinese <input type="checkbox"/> Indian <input type="checkbox"/> Other Asian please state..... <input type="checkbox"/> Middle Eastern <input type="checkbox"/> Latin American/Hispanic <input type="checkbox"/> African <input type="checkbox"/> Other:
Medical Diagnosis: 	
Post standard VFSS checklist:	
Signs of reduced hyolaryngeal excursion?	Yes/No
Signs of reduced pharyngeal shortening?	Yes/No
Completion of ultrasound analysis?	Yes/No
Participant required to have reliability measures completed (every 5 th participant who completes US analysis)	Yes/No

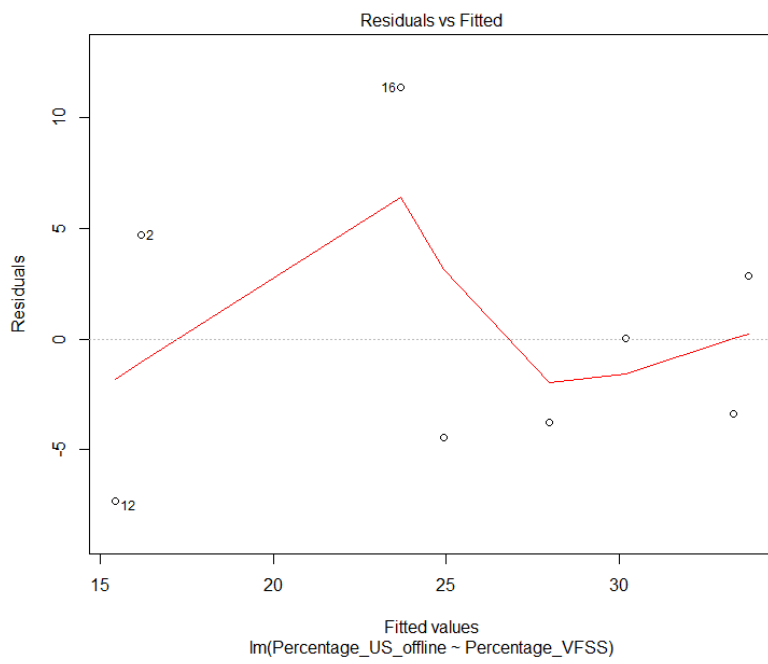
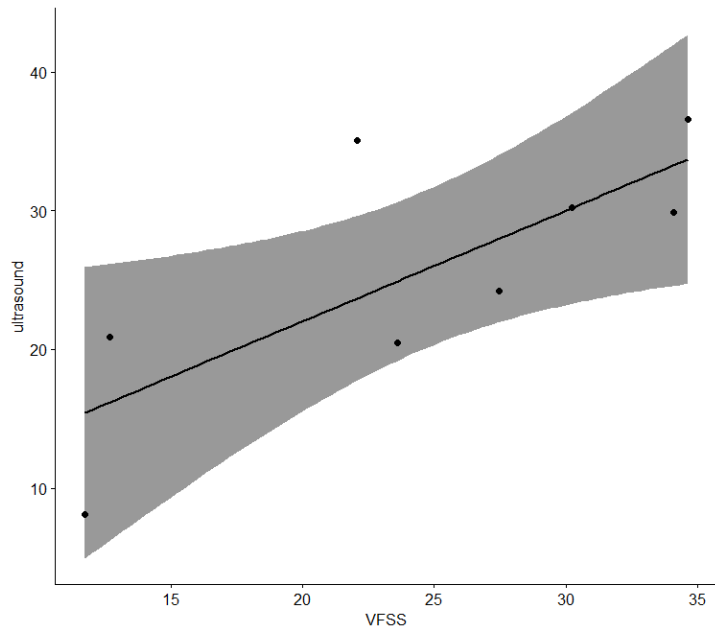
US assessment concurrent with VFSS	
Date: Time: BH acquires all swallows	
<input type="checkbox"/> Instruction: "Please sit with your hips as far back as comfortably possible. Keep your head in a natural position throughout the study. Please take this sip/spoon of... and keep it <u>on</u> your tongue until I tell you to swallow. Swallow as naturally as possible, whenever you are ready."	
Hyoid displacement (curvilinear transducer - Abdomen setting) Thin Barium (5ml) Hyoid Rest..... Hyoid Max.....	Hyoid displacement (curvilinear transducer - Abdomen setting) Apple sauce mixed with barium (5ml) Hyoid Rest..... Hyoid Max.....
Thyrohyoid approximation (curvilinear transducer - Superficial setting) Thin Barium (5ml) Thyrohyoid Rest..... Thyrohyoid Max.....	Thyrohyoid approximation (curvilinear transducer - Superficial setting) Apple sauce mixed with barium (5ml) Thyrohyoid Rest..... Thyrohyoid Max.....
US assessment post VFSS : Floor of mouth (linear transducer - Breast setting)	
Geniohyoid..... Left anterior belly of digastric muscle..... Right anterior belly of digastric muscle.....	
Tongue thickness (curvilinear transducer - Abdomen setting) Tongue Thickness	

Appendix 4: Correlation – Assumption Plots:

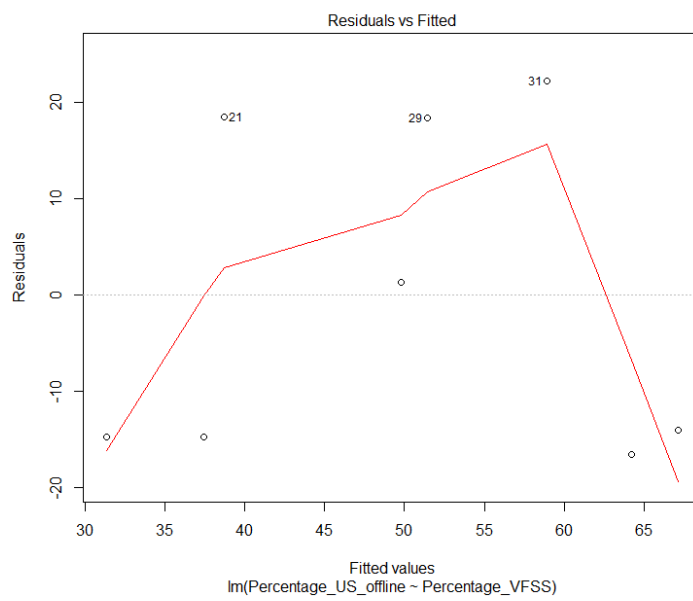
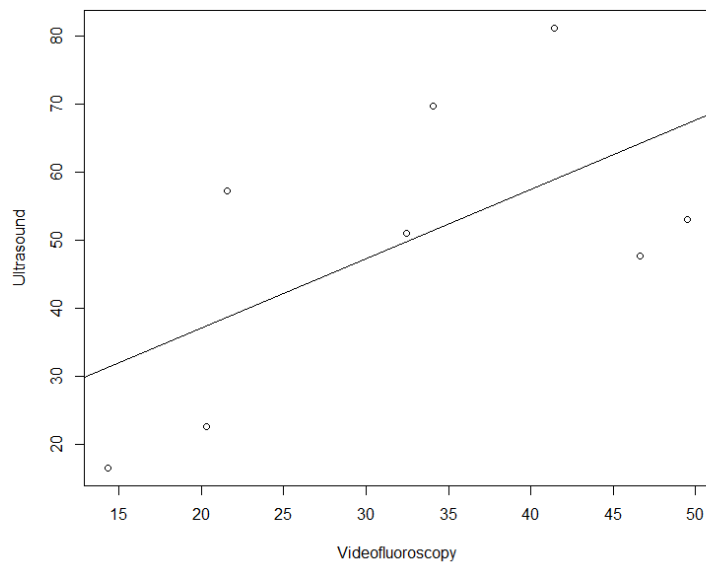
Hyoid, Liquid, VFSS-US Offline



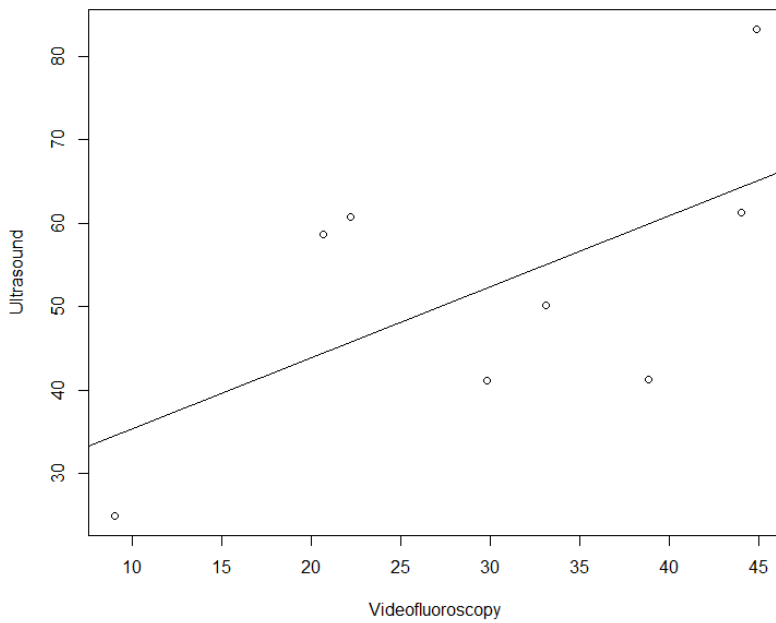
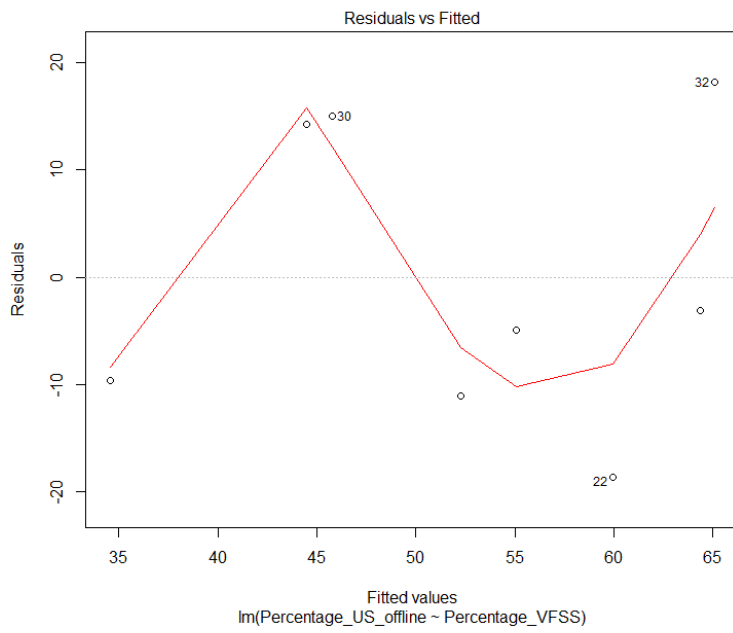
Hyoid, Puree, VFSS-Ultasound Offline



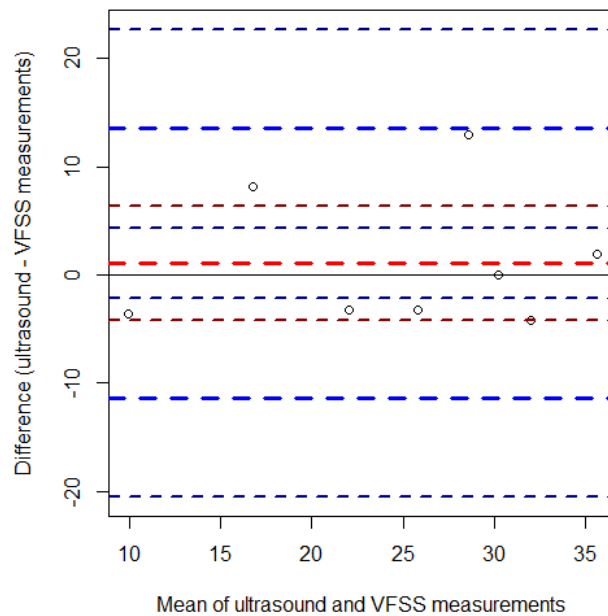
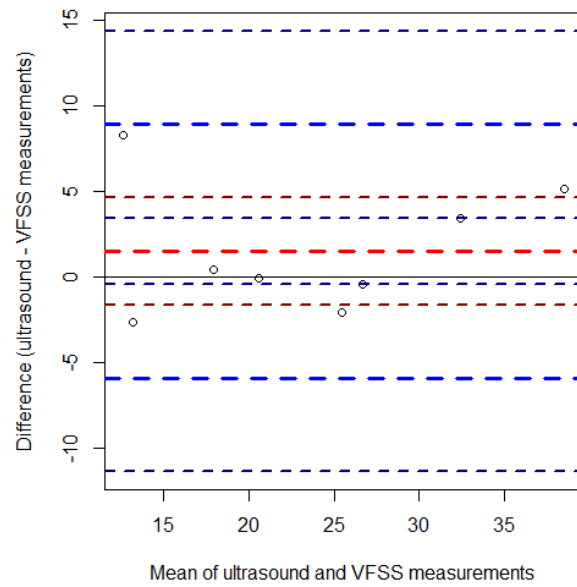
Thyrohyoid Liquid:



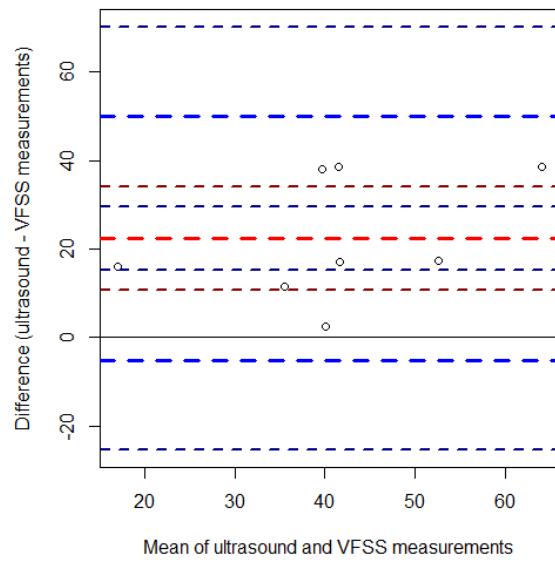
Thyrohyoid Puree



Appendix 5: Bland-Altman Plots for Validity Results



Bland Altman plot for hyoid excursion during liquid (a), and puree swallowing (b) assessed using ultrasound and VFSS. The unit of the X- and Y-axis is percentage change. The thick dashed red line represents the mean difference between ultrasound and VFSS measurements; the thin dashed red lines represent the 95% confidence interval of the mean difference.



Bland Altman plot for thyrohyoid approximation during puree swallowing (a) assessed using ultrasound and VFSS.