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Physiology and Lateralization of Swallowing: a Comparison Between Young and Old Adults.

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PHYSIOLOGY AND LATERALIZATION OF SWALLOWING: A COMPARISON BETWEEN YOUNG AND OLD ADULTS

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ABSTRACT

Age-related changes in discrete swallows have been well researched, but few studies have investigated sequential swallowing with little emphasis on age-related changes. It is also unclear whether the cortical representation of swallowing is lateralized to one hemisphere or is bilaterally represented. As such, the aims of this research were to examine deglutitive biomechanics of sequential straw swallowing (Experiment I), and study swallowing lateralization using a dual task paradigm in healthy, young and old adults (Experiment II).

Thirty-eight right-handed men (young = 20, old = 18) were studied. Experiment I: Videofluoroscopic swallow samples of two 10-second straw drinking trials were obtained. Hyolaryngeal complex (HLC) movement patterns, leading bolus edge location, airway invasion, number of swallows, and volume per swallow were determined. Experiment II: Subjects were examined at baseline and with interference. Baseline conditions were continuous straw drinking, finger tapping right and left hand, word repetition, and visuospatial processing. Interference tasks, including finger tapping right hand, finger tapping left hand, silent repetition, and silent visuospatial processing were completed with swallowing.

Experiment I: Three distinct patterns of HLC movement were identified during sequential straw drinking: 1) an opened laryngeal vestibule between swallows, 2) a closed laryngeal vestibule between swallows, and 3) a mixed movement pattern characterized by interchangeable opened and closed movements. The bolus was frequently in the distal pharynx at swallow onset during consecutive swallowing. This

location was strongly associated with a closed laryngeal vestibule. No age-related changes were identified with these patterns. Penetration appeared to be a normal variant in sequential straw swallowing and was associated with a closed laryngeal vestibule and hypopharyngeal bolus location. Penetration was uncommon in the younger adults but occurred more frequently in the older adults.

Experiment II: Findings indicated that both the right and left hemispheres contribute to swallowing. Right and left finger tapping, which selectively activates the left and right hemispheres respectively, interfered with swallowing. Silent repetition, which primarily activates the left hemisphere, and visuospatial processing, which primarily activates the right hemisphere, also interfered with swallowing when performed concurrently. Results suggest that bilateral cortical input is critical in the mediation of swallowing.

INTRODUCTION

The study of swallowing, particularly in humans, has increased exponentially over the last twenty years. Two areas of focus in deglutition research have been the neuroanatomical control of swallowing and more recently, the impact of normal aging on swallowing. Under normal conditions, the aging process results in morphological, chemosensory, somatosensory, and sensorimotor changes in the oropharyngeal swallowing system (Sonies, 1991). It is important to elucidate how these age-related changes impact swallowing in disease-free elderly in order to understand pathological deglutitive characteristics in the elder with disease. This is crucial as acute and chronic disease processes and structural changes resulting from head and neck cancer occur more frequently with aging.

Studies of swallowing in normal aging have identified subtle but important differences between the young and elderly. All of these studies have focused on the swallowing of discrete boluses and were crucial in providing a foundation to understanding deglutitive biomechanics. However, normal human ingestion is not comprised of a single calibrated bolus as healthy children and adults generally swallow consecutive boluses of foodstuffs and/or liquid. Research of normal ingestive patterns in healthy adults has been limited but has provided new insight into the understanding of the variability of the human deglutitive system. Results have demonstrated that there is considerable variation in the oropharyngeal swallowing mechanism. Thus, the concept of "normal" deglutitive physiology needs to be broadened, particularly in regard to ingestive mode. Baseline information on the physiology and biomechanics of various

ingestion modes in healthy adults is crucial in order to prevent misclassification of normal swallowing physiology as pathological, and initiation of inappropriate therapeutic or dietary management. Moreover, in studying the concept of normal ingestion patterns, one needs to discern the effects of normal aging. As the study of single swallows has indicated differences related to normal aging, one could suspect that normal aging may effect consecutive swallowing and that these changes may further expand our concept of normal biomechanical processes. Elucidation of the concept of "normal" biomechanical processes with varying ingestive patterns is crucial, particularly in regards to the elderly who are more apt to present with deglutitive disorders.

As previously indicated, another focus of deglutition research has been the study of the neuroanatomical control of swallowing. Swallowing involves an afferent system, central control, which includes higher cortical and brainstem centers, and an efferent system. Figure 1 provides a proposed model of swallowing based on empirical evidence from lesion studies. The role of the brainstem in deglutition is well understood, and until recently, it was thought that supratentorial regions had limited, if any influence on deglutition. Moreover, it was assumed that suprabulbar lesions must be bilateral to result in dysphagia. However, over the past 15 years, studies using the ablation paradigm and functional neuroimaging methodologies have shown that supratentorial regions do influence swallowing. While there is agreement that cortical and subcortical brain regions contribute to swallowing, controversy remains as to whether swallowing representation is predominately lateralized to the left or right cerebral hemisphere.

Dysphagia is common following acute stroke; therefore, a more precise elucidation of the cortical control and lateralization of swallowing can facilitate earlier detection of stroke patients who may be at greater risk for dysphagia and aspiration. In addition, dysphagia and the resultant complications are a major health problem in the elderly.

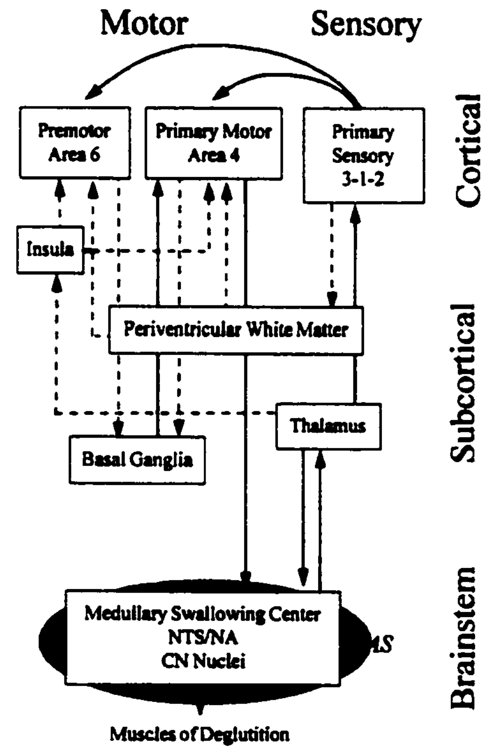


Figure 1. A proposed network for swallowing showing afferent and efferent connectivity of critical cortical, subcortical, and brainstem sites. The solid lines show known connections, and the hatched lines indicate proposed connections (Daniels & Foundas, 1999, © Lippincott Williams & Wilkins. Reprinted with permission. See Appendix A).

As presented above, the current understanding of biomechanical properties of particular modes of ingestion and lateralization of swallowing is limited, and the influence of normal aging on these factors is unknown. Further knowledge in these areas is crucial for conceptual and clinical reasons. Identifying an accurate and complete model for neuroanatomical functioning and biomechanical characteristics for various ingestion patterns, and the effects of aging on both, will contribute to a better understanding of the neuroanatomical control of swallowing. A clearer construct of normal aging and swallowing will facilitate research into the neural mechanism and risk factors of pathological aging. Moreover, increased insight into these areas will facilitate service delivery and may guide therapeutic intervention in that service providers can identify which neurologically impaired patients may have increased risk of dysphagia and aspiration. Furthermore, clinicians will have an increased concept of normal versus abnormal to guide in the diagnosis and management of deglutitive disorders. Thus, the major goals of this research were to examine and elucidate the deglutitive biomechanics of sequential straw swallowing and swallowing lateralization in normal, healthy young and old adults. This was accomplished through two experiments. The first experiment compared biomechanical features of consecutive straw drinking in young and elderly subjects. The second experiment employed a dual task paradigm to study the cortical control of swallowing and to learn whether specific swallowing behaviors are lateralized to the left verses the right hemisphere.

Overview of Normal Swallowing Physiology and Biomechanics

An overview of normal swallowing biomechanics is provided to characterize the complex nature of deglutition, and to provide a basis for interpreting the literature reviews of normal aging and ingestion patterns. Historically, deglutition has been subdivided into four phases: oral preparatory, oral transport, pharyngeal transfer, and esophageal transfer with the oropharyngeal swallowing mechanism composed of the first three stages. Some of the anatomical structures important in swallowing are shown in Figure 2. In addition, a complete listing of abbreviations used in this paper is found in Appendix B. As the focus of this study was the oropharyngeal swallowing mechanism in relation to normal aging, the esophageal stage of swallowing was not reviewed.

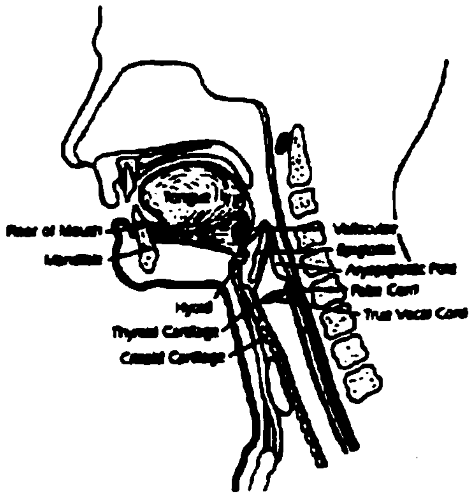


Figure 2. Lateral view of the oral cavity and the pharynx, showing critical structures in the oropharyngeal swallowing mechanism (Logemann, 1998, © Pro-Ed. Reprinted with permission. See Appendix A).

Oral Preparatory Phase

The primary purpose of the oral preparatory stage is to achieve an acceptable bolus consistency for swallowing. This phase involves coordination of lip closure, buccal and labial tension, rotary and lateral jaw movement, rotary and lateral tongue movement, and anterior velum movement. The oral preparatory stage concludes when a bolus is formed on the tongue. Conclusion of this stage is indicated by elevation of the sides of the tongue creating a groove in the center of the tongue to hold the bolus (Logemann, 1998). Recent studies, however, have indicated that numerous episodes of bolus preparation, i.e., mastication, and transfer to the oropharynx may occur prior to the actual swallow (Palmer, Rudin, Lara, & Crompton, 1992).

Oral Transport Phase

Initiation of the oral stage is generally indicated by a posterior lingual movement squeezing the bolus against the palate (Logemann, 1998). Coordinated posterior bolus transfer is critical for normal initiation and execution of pharyngeal events. Two types of oral placement may occur for a liquid bolus prior to transfer. An incisor-type (tipper) swallow is characterized by holding the bolus on the dorsal surface of the tongue before swallowing, whereas a dipper-type swallow is characterized by anterior sublingual position requiring inferior anterior tongue movement to move the bolus to a supralingual position (Cook et al., 1989; Dodds et al., 1989). The oral transfer stage concludes when the bolus head reaches any point between the anterior faucial arch and the ramus of the mandible, in which triggering of the pharyngeal swallow is observed.

The anterior faucial arch extends from the velum to the sides of the base of tongue, whereas the ramus of the mandible extends upward from horizontal body of the mandible. Duration of the oral stage is dependent on determination of the starting point (bolus versus tongue movement) and identification of the endpoint (faucial pillar versus ramus of the mandible). The duration of oral transport is generally one second (Logemann, 1998), regardless of parameters measured.

Evocation of the Pharyngeal Swallow

A critical and controversial part of deglutition has been defining the trigger point for evocation of the pharyngeal swallow, which is signaled by the onset of maximum hyolaryngeal excursion (Poudroux, Logemann, & Kahrilas, 1996). Before discrete swallows were studied in the elderly, it was posited that evocation of the pharyngeal swallow occurred when the bolus head reached the anterior faucial arches, and the pharyngeal swallow was considered "delayed" if the bolus progressed caudally before the onset of maximum hyolaryngeal excursion (Logemann, 1983). However, once deglutition was studied in healthy elderly adults, the trigger point for evocation of the pharyngeal swallow was extended caudally to the area where the ramus of the mandible bisects the base of the tongue (Robbins, Hamilton, Lof, & Kempster, 1992; Tracy et al., 1989). The time period from when the bolus head passes the ramus of the mandible until the initiation of maximum hyolaryngeal excursion is generally termed "pharyngeal swallow delay time" (Tracy et al., 1989) or "stage transition duration" (Robbins et al., 1992). In humans, progression of the bolus caudal to the ramus of the mandible prior to

the onset of maximum hyolaryngeal elevation has generally been considered dysfunctional and has resulted in implementation of therapeutic intervention. Perlman, Booth, and Grayhack (1994) noted that in patients with dysphagia the risk of aspiration parallels pharyngeal delay time. That is, the longer the delay in onset of the pharyngeal swallow, the greater the risk of aspiration. It has been suggested that location of the bolus at swallow onset predicts risk of aspiration (Murray, 1999). That is, aspiration risk is lowest if the bolus head is superior to the ramus of the mandible at onset of the pharyngeal swallow. Risk becomes moderate if the bolus is between the ramus of the mandible and the valleculae (the pharyngeal recess formed by the base of the tongue and the epiglottis), and aspiration risk is greatest if the bolus is inferior to the valleculae at swallow onset. The valleculae. However, some investigators have questioned whether inducement of the pharyngeal swallow caudal to the level of the ramus of the mandible is abnormal. A study of discrete swallows in healthy young adults found that pharyngeal swallow onset frequently occurred after the bolus head passed the anterior faucial arches (Linden, Tippet, Johnston, Siebens, & French, 1989). The authors, however, did not identify the exact location of the bolus at swallow onset. Furthermore, recent studies of normal sequential swallowing and feeding patterns have revealed that the bolus is frequently in the pharynx at pharyngeal swallow onset (Chi-Fishman & Sonies, 2000; Daniels & Foundas, 2001; Dua, Ren, Bardan, Xie, & Shaker, 1997; Palmer et al., 1992).

Pharyngeal Phase

The pharyngeal phase of swallowing involves the integration of respiration cessation and bolus transport. The pharyngeal stage of swallowing involves the complex coordination of six components: 1) velopharyngeal closure, 2) laryngeal closure, 3) hyoid and laryngeal elevation, 4) upper esophageal sphincter (UES) opening, 5) tongue base retraction, and 6) posterior pharyngeal wall contraction. As with oral transit, there are varying reference points used to measure pharyngeal transit duration. Arrival of the bolus head at the ramus of the mandible (Rademaker, Pauloski, Colango, & Logemann, 1998; Robbins et al., 1992), onset of laryngeal elevation as part of the swallow, i.e., triggering of the pharyngeal swallow, (Logemann, 1998), and arrival of the bolus tail at the posterior tonsillar pillar (Shaw et al., 1995) have been used to mark onset of pharyngeal transit. Passage of the bolus tail through the UES (Logemann, 1998; Rademaker et al., 1998; Robbins et al., 1992), UES closure (Shaw et al., 1995), and entry of the bolus head into the UES (Chi-Fishman & Sonies, 2000) have been used to denote conclusion of pharyngeal transit. Pharyngeal transit time is approximately one second (Logemann, 1998).

1) Velopharyngeal closure provides a seal between the nasopharynx and oropharynx, which prevents entry of the bolus into the nasal cavity. Velopharyngeal closure also contributes to the increase in pharyngeal pressure by closing off the nasopharynx (Perlman, Schultz, & Van Daele, 1993).

2) Superior and anterior movement of the hyoid bone and the larynx is achieved through contraction of the suprahyoid muscles and the thyrohyoid muscle. The superior movement of the hyolaryngeal complex facilitates supraglottic closure, and the anterior motion contributes to the opening of the UES (Jacob, Kahrilas, Logemann, Shah, & Ha, 1989).

3) Laryngeal valving involves three levels, from inferior to superior: true vocal cords (TVC), arytenoids, false vocal cords (FVC), aeryepiglottic folds, and epiglottis. The TVC are composed of the vocalis muscle and the vocal ligament and project from the lateral wall of the larynx. The FVC are parallel but superior to the TVC. The arytenoids are paired cartilages that form the posterior boundary of the laryngeal additus. The aeryepiglottic folds connect the epiglottis to the arytenoids and form the lateral boundary of the laryngeal additus. The epiglottis is a cartilage that provides the superior boundary of the laryngeal additus. Traditionally it was thought that TVC adduction was the initial event in valving; however, recent research has revealed that TVC closure is highly variable across subjects and swallows. Three patterns of glottic closure during swallowing have been identified (Shaker, Dodds, Dantas, Hogan, & Arndorfer, 1990) with TVC adduction frequently occurring after the onset of laryngeal elevation (Ohame, Logemann, Kaiser, Hanson, & Kahrilas, 1995). If the TVC are adducted prior to onset of the swallow, they often partially or fully abduct during laryngeal ascent. Arytenoid adduction and subsequent closure have been identified as initial events during normal swallowing; however, as timing is highly variable across

subjects, respiratory control may be an important influencing factor in arytenoid dynamics (Ohmae et al., 1995).

4) Opening of the UES, the sphincter separating the pharynx and the esophagus, requires relaxation of cricopharyngeal muscle and anterior movement of the hyolaryngeal complex. Bolus pressure contributes to obtaining the maximum sphincter diameter (Cook, 1993). Once the bolus passes through the UES, the esophageal phase of swallowing begins.

5) Base of tongue contact with the posterior pharyngeal wall is critical in order to create the dynamic pressure necessary to drive the bolus inferiorly through the pharynx (McConnel, 1988; Cerenko, McConnel, & Jackson, 1989).

6) As the tongue propels the bolus into the pharynx and the tongue base makes contact with the posterior pharyngeal wall, contraction of the pharyngeal constrictors occurs superiorly to inferiorly. This descending sequence aids in clearing pharyngeal residue but minimally facilitates bolus propulsion (Kahrilas, Logemann, Lin, & Ergun, 1992).

Dysfunction in any of the physiological or biomechanical events described above can yield dysphagia and airway invasion. Airway invasion can be in the form of supraglottic penetration or aspiration. Penetration is defined as entry of material into the laryngeal vestibule superior to or at the level of the TVC. Aspiration is defined as progression of material inferior to the TVC.

REVIEW OF THE LITERATURE

Discrete Swallowing: Effects of Normal Aging

The purpose of this section is to review the literature on the effects of normal aging on swallowing. The section has been divided in the same general fashion as the foregoing overview of normal biomechanics, as most of these studies examined aging effects on numerous temporal and spatial aspects of deglutition. Thus specific findings of each study will be discussed according to swallowing phase and biomechanical component. As such, Table 1 has been provided to detail the pertinent methodological information of each study.

Swallowing studies have frequently been conducted on young healthy subjects; however, recent research has concentrated on the effects of senescence on deglutition. It is important that researchers and clinicians understand the effects of normal aging on swallowing in order to discern what is within normal ranges and what is pathological for the aging adult. This is crucial, as aging populations are prone to diseases, which can affect deglutition. Previous research investigating age-related effects on discrete swallows has revealed changes in swallowing with increased age. These studies will be reviewed. Unless specified in the text, videofluoroscopy was the instrumentation used to evaluate swallowing. Videofluoroscopy, which is considered the "gold standard" in oropharyngeal deglutitive assessment, is a radiographic procedure that allows for the examination of duration and extent of biomechanical movement of all stages of swallowing. The clinical protocol generally consists of multiple swallowing trials of

Table 1. Previous Studies of Swallowing and Normal Aging. * M = males, F = females. Sex listed only when specified in the study. ** Single number represents mean age. Multiple numbers represent age range.

Authors	Subjects*	Age**	Trials/Stimuli	Techniques
Cook et al., 1994	7M, 2F	28	two 5,10 ml water	scintigraphy
	11M, 10F	68		
Dodds et al., 1989	118	<60	three10 ml liquid barium	videofluoroscopy
	42	>60		
Kobayashi et al., 1997	10M,10F	20-29	one 1ml pharyngeal water injection	submental surface EMG
	10M, 10F	30-39		
	10M, 10F	40-49		
	10M, 10F	50-59		
	10M, 10F	60-69		
	10M, 10F	70-79		
	5M, 5F	80-89		
Logemann et al., 2000	8M	21-29	two 1,10 ml liquid barium	videofluoroscopy
	8M	80-94		
Nilsson et al., 1996	22M, 31F	76	one 200 ml water	suction pressure detector piezo-electric movement sensor thermodector

(table continued)

Authors	Subjects*	Age**	Trials/Stimuli	Techniques
Perlman et al., 1993	10M, 10F	23	three dry swallows	manometry
	10M, 10F	68	three 5,10 ml water	
			three 5,10 ml applesauce	
Rademaker et al., 1998	61F	20-39	two 1,3,5,10 ml	videofluoroscopy
	45F	40-59	liquid barium	
	38F	60-79		
	23F	80-89		
Ren et al., 1993	10	23	0-20ml water (tepid)	videoendoscopy
	10	73	5,10 ml water (0°/60°C)	manometry
				respirography
				submental surface EMG
Robbins et al., 1999	25	23	three 3 ml liquid barium	videofluoroscopy
	20	40		
	53	68		
Robbins et al., 1995	10M	25	three isometric tasks	Iowa Oral
	14M	75	three saliva swallows	Performance Instrument
Robbins et al., 1992	10M, 10F	25	three 2 ml liquid barium	videofluoroscopy
	10M, 10F	45	three 2 ml barium paste	manometry
	10M, 10F	65		
	10M, 10F	72		

(table continued)

Authors	Subjects*	Age**	Trials/Stimuli	Techniques
Shaker et al., 1994	8	24	rapid pulse and continuous	manometry
	9	74	pharyngeal water infusion	
Shaker et al., 1993	7M, 7F	25	0-20 ml water (tepid)	manometry
	6M, 6F	76	5,10 ml water (0°/60°C)	
			5,10 ml mashed potatoes	
Shaker et al., 1992	10	18-34	resting saliva swallow	surface EMG
	11	63-83	respiratory rate	respirography
Shaw et al., 1995	11M	21	two 2,5,10,20 ml	videofluoroscopy
	5M, 7F	75	liquid barium	manometry
Sonies et al., 1988	7M, 8F	18-34	three saliva swallows	ultrasound
	6M, 7F	35-54	three 10 ml water	
	9M, 10F	55-75	continuous saliva swallows	
Tracy et al., 1989	6	20-29	three 1,5,10,20 ml	videofluoroscopy
	12	30-59	liquid barium	manometry
	6	60-79		
Zamir et al., 1996	10	76	three saliva swallows	videofluoroscopy
			three 5 ml water	videoendoscopy
			three 5 ml liquid barium	manometry
				submental surface EMG

calibrated volumes of liquid barium. Other viscosities such as barium pudding and a barium-coated solid bolus are also evaluated. Liquid swallows are typically initiated with a small volume (1 to 3 ml) in order to control for possible aspiration. Typically the largest calibrated volume is 20 ml, which has been determined to be the approximate amount of an average liquid bolus swallowed from a cup (Anderhill, Ekberg, & Groher, 1989). However, studies of sequential straw drinking revealed an average of 12 ml per swallow with the range being 4-26 ml in a group of healthy young males (Daniels & Foundas, 2001). Videotaping the fluoroscopic procedure allows for multiple slow motion and frame-by-frame analyses.

Oral Stage Effects

Robbins, Levine, Wood, Roecker, and Luschei (1995) evaluated lingual pressure during a maximum isometric task and during saliva swallows using The Iowa Oral Performance Instrument (IOPI) in two age groups: young (age range 22-33 years) and old (age range 67-83 years). The IOPI was initially designed to examine the relationship between tongue strength and motor speech control (Robin, Goel, Somodi, & Luschei, 1992). It consists of pressure sensor connected to a battery-operated amplifier that displays pressure. Three sites were tested: tip, blade, and dorsum. Younger subjects had significantly greater maximum lingual pressures for the tongue blade location. Lingual pressure for swallowing was equivocal between groups among the three tongue sites. Of notable importance was the identification of differences in pressure reserve for old and young subjects. Pressure reserve is the difference between needed force and

actual applied pressure. There was a positive correlation for swallowing pressure and isometric pressure in the older subjects, whereas there was no correlation between swallowing and isometric pressures in younger subjects. This indicated that older adults might be using more effort to achieve adequate lingual pressure needed for swallowing. From these results, one would be concerned that with increasing age there may be fatigue over the course of a meal, and an increase in oral transfer duration or oral stasis after the swallow. Additionally, magnetic resonance imaging (MRI) of the brain was completed on all subjects. Increased periventricular white matter (PVWM) disease was identified in the elderly. However, the investigators did not rigidly control for medical conditions such as hypertension or diabetes mellitus, which are associated with PVWM disease.

Nilsson, Ekberg, Olsson, and Hindfelt (1996) used the Repetitive Oral Suction Swallow test to assess oral and pharyngeal aspects of deglutition in a group of healthy elderly subjects (mean age 76 years). Subjects sucked water through a specially modified straw designed to register lip pressure. From a 200 ml bolus, subjects initially sucked and swallowed a single volume. Then subjects sucked/swallowed the remainder of the bolus as quickly as possible. Results were compared with those of young subjects (mean age 37 years) from a previous study (Nilsson, Olsson, Ekberg, & Hindfelt, 1996). The older subjects demonstrated decreased straw suction duration and pressure, multiple swallows to clear the oral cavity, and increased inspiratory frequency after swallowing.

When comparing the oral containment patterns for liquid barium boluses, Dodds et al. (1989) found that sublingual bolus positioning (dipper swallow) was significantly

more prevalent in subjects over the age of 60, whereas supralingual positioning (tipper swallow) was evident in subjects under the age of 60. Older subjects could readily convert to the tipper swallow upon request. When measuring duration of oral transit in young subjects, the dipper swallow generally doubled the overall transfer time as compared to the tipper swallow (Cook et al., 1989).

Numerous studies have measured age effects on duration of oral transfer; however, contradictory findings have been reported. In measuring oral transfer from contact of the tongue tip with the central incisors to arrival of the bolus tail at the posterior faucial arch, Shaw et al. (1995) found oral transit durations significantly longer for older subjects (mean age 76 years). Tracy et al. (1989) and Rademaker et al. (1998) found no difference in oral transit times across age groups. Shaw et al. (1995) indicated that the different findings between their study and Tracy et al. (1989) might have resulted from the use of different temporal references to denote initiation of oral transit. These differences in termination of both onset and offset of oral transport may also have resulted in differences with Rademaker et al. (1998). However, it is difficult to make comparisons of oral transit durations between the three studies as anatomical and bolus reference points varied for each study. Shaw et al. (1995) measured onset of oral transfer as the initiation of anterior tongue motion against the maxillary incisors and termination as the point when the bolus tail reached the posterior tonsillar pillar. Rademaker et al. (1998) defined oral transit duration from the onset of posterior tongue movement to the point when the bolus head passed the ramus of the mandible. Tracy et al. (1989) did not define onset of oral bolus transfer but used movement of both the

bolus head and tail past the posterior edge of the ramus of the mandible to determine two measures of oral stage duration.

Cook et al. (1994) also found longer oral transit for older subjects (mean age 68 years) when evaluating swallowing with scintigraphy. Scintigraphy is a nuclear medicine evaluation that involves the ingestion of water labeled with radionuclide, generally technetium-99m (^{99m}Tc). The bolus is then imaged with a gamma camera (Hamlet, Muz, Patterson, & Jones, 1989; Silver & Van Nostrand, 1992). This technique can be used to objectively quantify the amount of oropharyngeal retention and aspiration as well as to calculate temporal bolus measurements. To demarcate the oral phase, the investigators used external radioactive skin markers (tubing filled with ^{99m}Tc) to identify the superior margin of the hyoid bone and the posterior tonsillar pillar, with the region of interest anterior to the line joining these two markers. Boundaries to demarcate the onset and termination of the oral stage were the same as those used by Shaw et al. (1995), thus explaining the similarity in results. With scintigraphy, Cook et al. (1994) did not identify an age-effect for oral retention. However, using the subjective measure of percent of stasis after the swallow, Rademaker et al. (1998) noted oral residue to be two times greater in the oldest subjects compared to the youngest group.

Ultrasound has also been used to study oral transport. This technique involves the placement of a transducer on the skin overlying the soft tissue to be imaged. The transducer sends bursts of sound into the tissue and in turn, receives the reflected sound. The reflected sound appears as dots and forms an image; images can be obtained in

multiple planes (Brown & Sonies, 1997). Using ultrasound to study water and saliva swallows in three age groups (18-34 years, 35-54 years, 55-75 years), Sonies, Parent, Morrish, and Baum (1988) noted that multiple lingual gestures, i.e., tongue pumping or rocking, were required by the older subjects to achieve anterior hyoid positioning. Of interest, the authors noted that the older subjects did not complain of increased time to consume meals, thus concluding that the older subjects apparently perceived their swallowing as normal.

Elicitation of the Pharyngeal Swallow

Robbins et al. (1992) investigated the effects of age (group age means 25, 45, 65, >70 years) and bolus viscosity (thick, thin) on swallowing using manometry and videofluoroscopy. (Refer to Table 1 for further subject information). Manometry involves the measurement of pressure changes in the pharynx using solid state pressure sensors, which are housed in flexible tubing and inserted transnasally into the pharynx. Generally, concurrent videofluoroscopy is needed to determine bolus position in relation to pressure changes. A significantly longer duration of stage transition (delay time in triggering the pharyngeal swallow) was evident for the oldest group as compared with the two youngest groups. Increased frequency of supraglottic penetration was observed in the oldest group with the manometric tube in place.

Further videofluoroscopic studies investigating the effects of age and bolus volume support the above finding. Tracy et al. (1989) and Logemann et al. (2000) also noted significantly longer durations for elicitation of the pharyngeal swallow in the oldest group. Moreover, Rademaker et al. (1998) identified significant variations by age

for duration of stage transition. Although systematic increases were not evident as age advanced, the oldest group (ages 80-89) did demonstrate the longest pharyngeal delay time.

For these four studies, bolus progression inferior to the ramus of the mandible was used to mark a delay in the pharyngeal swallow. In the youngest group, triggering of the pharyngeal swallow occurred prior to arrival of the bolus at the ramus of the mandible and ranged from -0.15 seconds (Logemann et al., 2000) or slightly after the head of the bolus reached the ramus, approximately 0.08 seconds (Tracy et al., 1989). Whereas in the oldest group, triggering of the pharyngeal swallow occurred as the bolus head progressed inferior to the ramus, > .6 seconds in some older subjects (Tracy et al., 1989). In all studies, the swallow delay was less than 1 second. Although bolus location at swallow onset was not specified, the results of these studies suggest that the bolus was superior to the level of the valleculae for younger subjects and either superior to or at the level of the valleculae for older subjects.

Using submental surface electromyography (EMG), Kobayashi, Sekizawa, and Sasaki (1997) did not find any significant age-related effect on delay time for elicitation of the pharyngeal swallow. Surface EMG involves the placement of electrodes to the skin surface, in this case under the chin, to record information on the timing and amplitude of designated muscle contraction. While this study bypassed the oral stage and infused the water into the pharynx, only 1 ml was injected into the pharynx, which is a negligible amount and may not have been enough to stimulate a swallow. One milliliter of water is generally equal to a saliva swallow. Furthermore, the authors did

not indicate the infusion location of the bolus. If the valleculae were the infusion point, this limited amount may have been too small to stimulate a swallow. Previous research of infused boluses has revealed that the valleculae are not a trigger point for evocation of the pharyngeal swallow in that a bolus must overflow the valleculae in order to induce a swallow (Poudroux et al., 1996). With such a small bolus amount used to stimulate the swallow and without visualization of the bolus location, it is impossible to determine if the water had any effects on swallow initiation. Thus, the Kobayashi et al. study (1997) may have inadvertently been testing initiation of the resting saliva swallow rather than a stimulus evoked swallow.

In another study of direct stimulation of pharyngeal structures with water infusion directly into the pharynx, Shaker et al. (1994) found that a significantly larger volume of water was required for the older subjects (mean age 74 years) to evoke a swallow as compared to younger subject (mean age 24 years). The injection port was situated 2 cm above the UES high pressure zone with the port situated posteriorly. Water was infused in two speeds: rapid-pulse and slow continuous. The average volume difference between age groups to stimulate a swallow was one milliliter. Moreover, the volume required to elicit a swallow was the same in the elderly regardless of speed of presentation, whereas in the younger subjects, the volume for rapid-pulse injection was significant smaller than slow-continuous presentation to evoke a swallow.

Pharyngeal Stage Effects

Velopharyngeal Closure

Only one study has evaluated age effects on velopharyngeal closure. Using videofluoroscopy, duration of velopharyngeal closure was found to significantly and systematically increase with advancing age (Rademaker et al., 1998). The authors suggested that this prolonged valve closure was in response to increased pharyngeal transit time.

Hyolaryngeal Elevation

Shaw et al. (1995) found that age did not effect onset of hyolaryngeal excursion, extent of hyoid excursion or duration of hyolaryngeal excursion. Robbins et al. (1992) reported no age-related changes in duration of maximum hyolaryngeal elevation. Conversely, in a study of only female subjects, Rademaker et al. (1998) found age effects for duration of hyoid elevation with the 60-79 year old age group having the longest duration of the four age groups including the 80-89 group. Furthermore, they identified an interaction between bolus volume and age for duration of laryngeal elevation. The 60-79 year old group again had the longest duration. Concerning extent of movement of the hyolaryngeal complex, Logemann et al. (2000) identified significantly reduced anterior hyoid, superior laryngeal, and superior hyoid movements for the older men as compared to the younger men. Differences for temporal measurements may be explained by the fact that Shaw et al. (1995) specified the anatomical points measured but did not indicate the specific onset and offset reference points used to calculate durations, whereas Rademaker et al. (1998) defined onset (start

of hyoid and laryngeal movement) and offset (return to rest of the hyoid and larynx). Methods of data analyses also differed for spatial measurements in the studies and may account for discrepancies in results.

Using ultrasound to study hyoid movement patterns in three age groups of normal subjects, Sonies et al. (1988) found that the oldest group's total swallow duration increased. For women, the difference was noted in the phase of initiation of maximum hyoid excursion, whereas for men, the difference was evident in the return to rest phase of hyoid movement.

Laryngeal Closure/Respiratory Pattern

Ren et al. (1993) and Tracy et al. (1989) identified no age-related changes in duration of glottic or supraglottic closure. Rademaker et al. (1998) found a significant interaction between age group and bolus volume for duration of laryngeal closure. Results between the studies varied perhaps because two different activities were measured. While Rademaker et al. (1998) measured duration of contact of the arytenoids with the base of the epiglottis and used videofluoroscopy, Ren et al. (1993) measured TVC adduction using videoendoscopy. Videoendoscopy involves the transnasal passage of a flexible fiberoptic scope to examine the pharynx and larynx. The oral stage of swallowing cannot be evaluated with this technique and the point of the actual swallow cannot be imaged as apposition of tissue obstructs the view. Differences between the Rademaker et al. (1998) study and the Tracy et al. (1989) study may be related to unequal subject numbers and variance in designation of age groups (Table 1).

Comparing the order of temporal relationships to previously studied young controls (Shaker et al., 1990); the overall coordination of TVC closure and bolus transfer was similar in the elderly (Zamir, Ren, Hogan, & Shaker, 1996). Whereas the young subjects initiated posterior bolus movement after the occurrence of maximum TVC adduction, the elderly demonstrated intersubject variability for this parameter. Other than this subtle difference, temporal relationships were preserved for the elderly. Concurrent videoendoscopic, videofluoroscopic, manometric, and surface EMG measurements were made to compare sequencing of events.

In a study of normal saliva swallowing and respiratory rate using submental surface EMG and respirography, Shaker et al. (1992) identified age-related changes over a 30-minute time span. Respirography, which is composed of a pneumobelt that is wrapped around the chest and a polygraph, records the phases of respiration by recording the respiration-induced movement of the thorax. The older subjects initiated swallowing in the inspiratory phase of respiration, whereas the younger subject initiated swallowing in the expiratory phase. Nilsson, Ekberg et al. (1996) identified increased respiratory frequency for older subjects during continuous swallowing.

UES Parameters

Using videofluoroscopy to measure UES dimensions, Shaw et al. (1995) noted decreased UES diameter with increased age. On manometric readings, they found that increased proximal sphincter intrabolus pressure increased with age and concluded that this resulted from decreased UES diameter. Logemann et al. (2000) identified significantly smaller width of UES opening during ingestion of the 10ml volume in the

older men. The diameter of UES opening was also smaller for the 1ml volume in the older men, but this was not statistically significant.

Shaw et al. (1995) and Robbins et al. (1992) found no age-related changes in duration of UES opening, whereas Tracy et al. (1989) noted shorter UES opening durations with increasing age. Conversely, Rademaker et al. (1998) identified longer durations in UES opening with advancing age. All durations were measured with videofluoroscopy. When related to initiation of bolus movement in the oral cavity, increased durations in onset to UES relaxation, opening, and closure were noted with increased age (Shaw et al., 1995; Robbins et al., 1992).

UES resting pressure decreased in the elderly (Shaker et al., 1993). Shaw et al. (1995) reported no age-related differences in basal UES pressure and indicated that discrepancies in the studies may be related to varying adaptation periods and control of hypopharyngeal stimulation.

Base of Tongue Retraction

Perlman et al. (1993) found no difference in tongue driving pressure among the two age groups studied. Robbins et al. (1995) identified no age changes related to "oral" tongue pressures during swallowing; however, a decrease in pressure reserve was identified in the older subjects. When comparing results of the two studies, it is important to remember that different lingual points were measured and different measurement techniques were used. Manometry was used in the Perlman et al. (1993) study and the IOPI was used in the Robbins et al. (1995) study.

Posterior Pharyngeal Wall Contraction

Using manometry, analyses across all water volumes revealed that duration of the pharyngeal pressure wave was age dependent with older subjects having a longer duration than younger subjects (Perlman et al., 1993). Moreover, they found that these age variations occurred during muscle contraction as well as during muscle relaxation. Older subjects demonstrated longer rise time to obtain peak contraction as well as longer durations to achieve baseline relaxation. The authors posited that these differences might be related to age-related changes in the viscoelastic properties of pharyngeal tissue. They also noted a trend toward significance in age-related peak pharyngeal pressure with elderly subjects having higher pressure values than younger subjects.

Tracy et al. (1989) found that amplitude and velocity of pharyngeal contraction significantly decreased with age. Conversely, Shaker et al. (1993) found that the amplitude and duration of pharyngeal contraction increased with age. Discrepancies in results may be due to sample size and age (Table 1) as well as to differing areas measured. Shaker et al. (1993) and Shaw et al. (1995) indicate that this increase in muscle contraction was directly related to narrowed UES opening with a greater pressure wave necessary to drive the bolus through into the esophagus. While this may partially explain the increase in elderly pharyngeal pressure, other explanations may be plausible. First, previous research indicates that pharyngeal constriction minimally facilitates bolus propulsion (Kahrilas et al., 1992), whereas base of tongue contact with the posterior pharyngeal wall is the driving force that moves the bolus through the

pharynx (McConnel, 1988). Thus, if reduced UES diameter with aging affects pharyngeal contraction, it would follow that tongue driving pressure should also increase with age. Perlman et al. (1993), however, did not find an increase in lingual pressure with advanced age. Second, it is unclear whether the pharyngeal constrictors have to exert more amplitude for longer durations to clear pharyngeal residue. This situation implies that the muscles may be weaker. This factor may explain the age-related increases in pharyngeal retention identified with scintigraphy (Cook et al., 1994).

Age-related differences were not found for onset of pharyngeal contraction nor duration to onset of peak contraction (Robbins et al., 1992). Logemann et al. (2000) identified significantly earlier onset of posterior pharyngeal wall movement in relation to UES opening for the older subjects. Varying sites of manometric measurement may have resulted in some of the discrepancies in these studies.

Pharyngeal Transit Time

Varying results have been shown with regard to the impact of age on pharyngeal transit time. Using videofluoroscopy, Robbins et al. (1992) and Rademaker et al. (1998) identified longer durations for aged subjects, whereas Shaw et al. (1995) found no differences. Using scintigraphy, Cook et al. (1994), found age-related differences for pharyngeal transit duration. The use of different reference points between the first two studies (bolus head) and the latter two studies (bolus tail) to identify onset of pharyngeal transfer may explain some of the variances in the results. Nevertheless, this factor cannot explain the different results obtained by Shaw et al. (1995) and Cook et al. (1994) as the same reference points were used. Varying viscosities, however, may

explain the differing results as water was used in the study by Cook et al. (1994) and barium was used in the investigation by Shaw et al. (1995). Furthermore, as regions of interest are derived in different manners, valid comparison between scintigraphy and videofluoroscopy are uncertain. That is, anatomical boundaries can easily be identified on videofluoroscopy, whereas with scintigraphy, regions of interest must be externally identified with radiopaque skin markers and approximate durations calculated using flow of the bolus in relation to these external markers.

Pharyngeal Retention

Cook et al. (1994) identified greater pharyngeal stasis in the elderly. Scintigraphy was used to measure residual isotope counts in the regions of interest. Rademaker and colleagues (1998) found oropharyngeal swallowing efficiency (OPSE) to significantly decrease with age. OPSE was obtained from videofluoroscopy and was calculated by dividing the combined times of oral and pharyngeal transit duration by the percent of bolus entering the esophagus (Rademaker, Pauloski, Logemann, & Shanahan, 1994). Estimated amounts of bolus residue and aspiration are used to calculate the estimated percent of the bolus swallowed. Rademaker et al. (1998) noted a marked increase in the percent of pharyngeal residue for the oldest group (80-89 years) as compared to the youngest group (20-39 years). However, there were no significant differences in OPSE in the intermediate age groups (40-59, 60-79). OPSE is a very subjective measure as percents of bolus swallowed, retained in the oropharynx, and aspirated are estimated; thus, these results must be interpreted cautiously.

Supraglottic Penetration and Aspiration

Previous studies support the notion of reduced laryngeal sensation with advancing age. Post-mortem studies of the superior laryngeal nerve (SLN) have revealed a significant decline in the number of myelinated nerve fibers in older adults (Mortelliti, Malmgren, & Gracek, 1990). Specifically, age-related loss affected primarily the small myelinated fibers. It was posited that these fibers were afferent, tonic and low threshold mechanoreceptors.

Using chemical stimulation and air puffs, it has been demonstrated that sensation decreases in the aging larynx (Aviv et al., 1994; Pontoppidan & Beecher, 1960). With increasing age, increased thresholds of inhalation of ammonia gas were required before respiratory inhibition was observed. The most dramatic increase was found in the 70-90 year old group (Pontoppidan & Beecher, 1960). Aviv et al. (1994) examined sensory discrimination thresholds using air pulse stimulation of the anterior wall of the pyriform sinus. Sensation for the hypopharynx and the supraglottic region is supplied by the internal branch of the superior laryngeal nerve (SLN_{ib}). Advancing age correlated with increased pressure threshold suggesting that sensory discrimination thresholds were significantly higher for the oldest age group. The authors posited that this decrease in sensitivity might be associated with an increased risk of aspiration in the elderly. However, association between sensory response to air puff stimulation and response to airway invasion with food or liquid has not been empirically studied. Varying intensity and type of stimulation may prove to evoke different responses and thresholds. For example, supraglottic penetration of liquid barium without evocation of a cough

response has been demonstrated in healthy young and old adults (Robbins, Coyle, Rosenbek, Roecker, & Wood, 1999).

Tracy et al. (1989) did not find age-related differences in the occurrence of supraglottic and subglottic penetration. One subject aspirated, and four subjects penetrated; none of the older subjects demonstrated airway invasion. Robbins et al. (1992) found no instances of aspiration in any age group but did report age-related effects based on the frequency of supraglottic penetration. Whereas there were seven and four occurrences of supraglottic penetration, respectively, for the two younger groups, the instances of penetration in the older groups were 12 and 22, respectively. Increased frequency of penetration in the oldest group may have been due to the presence of the manometry tube because penetration frequencies were similar across all age groups with the tube out (25 years-4 occurrences, 45 year-4 occurrences, 65 years-7 occurrences, and >70 years-5 occurrences). Thus, under normal conditions, penetration did not increase with age. Of note, however was the observation that the oldest group decompensated with internal, invasive instrumentation (17 occurrences of penetration), whereas the younger groups did not. It remains to be determined if varying invasive states (e.g. nasogastric tube) may produce dysphagia in the sick or frail elderly, even those without a primary swallowing deficit. It is also unclear whether invasive instrumentation can increase the severity of deglutitive dysfunction in patients with dysphagia.

Robbins et al. (1999) studied the effects of aging on airway invasion using a previously designed Penetration-Aspiration Scale (Rosenbek, Robbins, Roecker, Coyle,

& Wood, 1996). Scale scores range from 1 (no entry of the bolus into the airway) to 8 (passage of a bolus inferior to the TVC without elicitation of a cough). Most subjects in all age groups (21-32 years, 43-47 years, 63-84 years) received a score of 1 or 2 (supraglottic penetration with clearing). Only one subject aspirated and obtained a score of 6 (aspiration with clearance of the aspirate out of the trachea); that subject was in the oldest group. From these results, the authors concluded that the aged population might have difficulty swallowing repeatedly over the course of a meal thus increasing risk of aspiration. This conclusion must be interpreted cautiously as only one subject (6%) in the elderly group aspirated. Moreover, percentages for a score of 3 (supraglottic penetration with laryngeal vestibule stasis) were similar for all age groups.

Summary

Results of these studies indicate a general slowing of swallowing with aging. That is, increased duration of biomechanical movement, increased transit times, and decreased extent of structural movement are evident in healthy elderly adults. Muscle movement may not be as robust or may require additional effort, thus negating any effects of muscular reserve. It is important to note that none of the studies incorporated neuropsychological testing to ensure that the subjects were neurologically intact without signs of dementia. This information is critical in the study of normal aging.

While this literature review demonstrates that there may be age-related changes in deglutition, swallowing of discrete volumes remains fully functional in normal aging without increased risk of airway invasion. Age-related changes, however, may result in dysfunction when there are additional demands placed on this system. As muscular

reserve is limited with aging, fatigue or general medical illnesses may impact the senescent swallow. Sequential swallowing may stress or fatigue the senescent swallow. The effects of normal aging on the biomechanical features of sequential swallowing have not been addressed.

Sequential Swallowing

The following section reviews literature on normal ingestion patterns. Two models are presented, animal and human, both of which provide strong evidence of substantial variability in deglutitive biomechanics. Moreover, they provide support that human deglutitive biomechanics may be more related to animal models than initially realized.

Animal Model

Ingestion is composed of a series of events involving transportation of a bolus from the teeth to the stomach with swallowing being part of this continuous series, not an isolated act (Thexton & Crompton, 1998). Normal eating and drinking involve multiple repetitions of this continuous action; however, human swallowing has been studied as an isolated event during a single swallow completed upon command. The study of animals provides the best source, thus far, in the understanding of the dynamic series of events of ingestion. It was previously suggested that an animal model was difficult to apply to human adult swallowing. In a study of deglutition in three cats, it was noted that morphological and physiological features of cat ingestion were more closely related to that of the human infant than the human adult (Kobara-Mates, Logemann, Larson, & Kahrilas, 1995). The authors noted several differences in the

anatomy and physiology of swallowing in the cat model as compared to the human model. Cats have a high intranarial positioning of the larynx, which reduces distances of structures. During swallowing, cats demonstrate multiple lingual propulsive gestures per pharyngeal swallow, vallecular collection of the bolus prior to swallowing, a longer oral stage and shorter pharyngeal stage duration. Thus, Kobara et al. (1995) concluded that these differences made comparisons with human adult swallowing difficult. While no species provides homologous oral and pharyngeal morphology with humans, an understanding of phylogenetic stages can aid in clarifying the events of food and liquid intake in order to make appropriate application to human ingestion during eating during the course of a meal and sequential drinking.

Ingestion pattern has been studied for mastication in a variety of species. Two stages of bolus transport have been identified prior to the swallow. Stage I transport involves the movement of food to molar region. During processing of the food, stage II transport occurs which involves the movement of triturated food past the fauces into the oropharynx, where it accumulates until swallowed (for review, Hiiemae & Crompton, 1985). Animals, such as the macaque, transport food during tongue/hyoid protraction with food squeezed posteriorly by contact between the dorsal tongue surface and the soft palate, whereas other animals, such as the opossum, pig, and cat, transport food during tongue retraction (Franks, Crompton, & German, 1984).

Various animals have been used to study liquid ingestive patterns. In all of these species, the larynx is in an intranarial position with the epiglottis overlapping the velum. The valleculae and pyriform sinuses are relatively close together as compared to human

adults. Adult animals may either suck (pig) or lap (cat, opossum) liquids. In the adult pig, the tongue forces liquid posteriorly with collection in the valleculae. Swallowing occurs only after accumulation the bolus in the vallecular recess (Herring & Scapino, 1974). For cats and opossums, liquid is transported posteriorly into the valleculae during coordinated movement of the jaw, tongue, and hyoid (for review, Thexton, Crompton, & German, 1998). In the opossum, the valleculae are continuous with the pyriform sinuses, and liquids progress into this recess which expands to accommodate bolus accumulation prior to the swallow. Thexton and Crompton (1998) noted that it was difficult to distinguish between stage I and stage II transport during lapping because during the time one bolus was being transported posteriorly another bolus was entering the oral cavity.

When drinking from a cup with a drinking spout, the adult macaque has the tongue depressed so that liquid flows posteriorly into the valleculae. The tongue then elevates to contact the palate, anteriorly to posteriorly, to transport the liquid into the esophagus. Depression of the anterior tongue then occurs to allow entry of another bolus into the oral cavity (Thexton & Crompton, 1998). Confluency of bolus movement makes is difficult to distinguish stage I and stage II transport as separate phases. In primates, liquid is transported into the valleculae and is swallowed within one cycle and never more than 2 to 3 cycles (German, Crompton, Levitch, & Thexton, 1992). However, in other animals such as the opossum or the cat, 20 and 7 cycles, respectively, of liquid transport and storage may be completed prior to swallowing (Thexton & Crompton, 1998; Thexton & McGarrick, 1988). These variations are due to

morphological differences because primates have reduced vallecular space as compared to other mammals such as the cat. The extended number of transport cycles in the opossum is also due to differences in pyriform sinus anatomy (Thexton & Crompton, 1998).

Studies in Healthy Adults

While the physiology of evocation of the pharyngeal swallow and deglutitive biomechanics have been studied extensively in the discrete swallow, only a few studies have investigated consecutive swallows, and these studies have generally been limited to healthy young adults. When comparing ingestion of varying foodstuffs across subjects (n = 4, mean age 36 years), Palmer et al. (1992) identified preswallow pharyngeal bolus accumulation of triturated food prior to swallow onset. Specifically, during mastication subjects would transfer the triturated bolus into the valleculae while continuing to chew the remainder of the bolus with subsequent transfer of the remaining bolus yielding elicitation of the pharyngeal swallow. This observation was termed Stage II transport, as it was not unlike transfer observed in animal feeding. These results have been supported by further studies of mastication (Hiiemae & Palmer, 1999; Palmer, 1998). Radiographic studies have shown that a triturated bolus may accumulate in the valleculae for several seconds prior to initiation of the swallow and that stage II transport is not a product of gravity but is dependent upon tongue palate contact (Palmer, 1998). Palmer et al. (1992) also evaluated liquid swallows, but the study was limited to three consecutive swallows of liquid through a straw. Bolus aggregation into the pharynx was not evident with the three liquid swallows. Dua et al. (1997) studied

swallowing during ingestion of a meal (n = 15, age range 21-40 years). Detailed analyses were completed during swallows of masticated material and with the saliva generated from gum chewing, but the swallows of liquids ingested during the course of the meal were not analyzed. As with Palmer et al. (1992), Dua and colleagues (1997) identified pharyngeal dwell time prior to the onset of the pharyngeal swallow and found the epiglottic edge to be the most sensitive area for inducement of the pharyngeal swallow.

Chi-Fishman and Sonies (2000) have further challenged the concept of normal ingestion patterns in healthy adults and have questioned the use of pharyngeal delay time as a marker for abnormal swallowing physiology during sequential swallowing. As discussed earlier, traditionally, evocation of the pharyngeal swallow has been considered normal only when it is triggered at the level of the ramus of the mandible or rostral to this point (Robbins et al., 1992; Tracy et al., 1989). Progression of the bolus caudal to the ramus of the mandible prior to the onset of maximum hyolaryngeal elevation has generally been considered abnormal. However, when comparing discrete swallows with continuous cup drinking across healthy subjects (n = 10, age range 31-55 years), Chi-Fishman & Sonies (2000) reported longer durations of stage transition with sequential swallowing, indicating that the bolus was caudal to the ramus. In addition, unlike Palmer et al. (1992) who did not identify bolus aggregation with liquids, Chi-Fishman and Sonies (2000) noted this occurrence. That is, in three subjects the first bolus was retained in the hypopharynx while the second bolus was loaded and

transferred into the pharynx with both boluses swallowed together. This characteristic was termed "pharyngeal bolus merging" and occurred with only two successive boluses.

Martin, Logemann, Shaker, and Dodds (1994) evaluated respiratory patterns in healthy young subjects (n = 10, mean age 23 years) as they ingested 100 ml of water through a straw. They identified prolongation of laryngeal elevation with extended durations of apnea during consecutive straw drinking; however, respiration during the sequence was identified in some subjects. Duration of apnea was positively correlated with duration of laryngeal excursion.

Only one study has examined the effects of aging on sequential swallowing; however, the researchers did not investigate bolus transport. Rather, Nilsson, Ekberg et al. (1996) studied straw suction pressure, respiration and laryngeal movement patterns in older subjects (n =53, mean age 76 years) as they repetitively swallowed water as rapidly as possible through a straw. The straw was equipped with a solid state pressure detector to determine sucking pressure and duration. A piezo-electric movement sensor recorded laryngeal movement, and a thermodector recorded respiration. Results were compared with young subjects from a previous study (Nilsson, Olsson et al., 1996). Respiration during sequential swallowing was significantly more common for older subjects. Older subjects also demonstrated significantly more polyphasic laryngeal movements, which were defined as more than two directional changes in laryngeal movement during the swallow sequence. Larger bolus volumes were associated with the polyphasic laryngeal movements. As sensory perception does not significantly change with advancing age (Weiffenbach, Tylenda, & Baum, 1990), it was unclear why

the older subjects tended to attempt ingestion of larger volumes during the polyphasic laryngeal movements.

In a pilot study for the present dissertation, Daniels and Foundas (2001) examined deglutitive physiology during sequential straw drinking in healthy young adults (n = 15, mean age 30 years) to learn how sequential swallowing differed from single swallows. Analysis across subjects revealed three distinct patterns of hyolaryngeal complex (HLC) movement during sequential straw swallows: opening of the laryngeal vestibule after each swallow (53%), continued vestibule closure after each swallow (27%), and interchangeable vestibule opening and closing during the swallow sequence (20%). The majority of subjects consistently demonstrated onset of the pharyngeal swallow when the bolus was inferior to the valleculae. Analysis of all swallows across all subjects (n = 305 total swallows) revealed position of the leading edge of the bolus at onset of maximum hyolaryngeal excursion to be significantly associated with HLC movement pattern. When the laryngeal vestibule remained closed between swallows, the leading bolus edge was inferior to the valleculae at swallow onset, whereas position of the leading edge was randomly placed when the vestibule opened between swallows. Preswallow pharyngeal bolus accumulation was evident and was significantly associated with the HLC pattern of opened laryngeal vestibule after each swallow.

Summary

The application of animal models can facilitate our understanding of normal ingestion patterns for mastication as well as consecutive liquid swallows in healthy

adults. Recent studies in healthy young adults suggest that sequential swallows are physiologically different from discrete swallows, and substantial variability in deglutitive biomechanics exists in healthy young adults. However, it is unclear whether swallowing dynamics for sequential straw drinking changes with increasing age, particularly for HLC movement patterns and bolus location at swallow onset. It is also unclear whether there is a relationship between these different movement patterns and airway safety. Further research is indicated to discern age-related effects on normal ingestion patterns.

Neuroanatomy of Swallowing

While an understanding of the biomechanical properties of swallowing is critical, the elucidation of neuroanatomical control of swallowing is equally crucial. This section reviews literature on the neuroanatomical control and laterality controversy of swallowing. As in the previous section, research of animal and human models will be reviewed, with focus on anatomical and functional imaging in human research.

Animal Models

Initially, identification of cerebral organization of swallowing has been through the study of animal models. Using various electrophysiological techniques such as electrical stimulation and neural recordings, the synergistic control of swallowing has been localized to bilateral neural networks in the medulla (the medullary swallowing center). Specifically, the medullary swallowing center has been identified as involving the dorsal region of the nucleus tractus solitarius (NTS) and adjacent reticular formation, and the ventral nucleus ambiguus and adjacent reticular formation (Jean,

1984). The dorsal component plays the leading role in generating the swallowing pattern, while the ventral component transmits the swallowing drive to motoneuron pools. While swallowing is a time-locked sequence (Doty & Bosma, 1956), meaning that the sequence of pharyngeal muscular contraction is fixed, sensory input can modify swallowing. For example, afferent input from the oropharyngeal region can modify the magnitude and duration of hyolaryngeal excursion (Dodds et al., 1988; Rademaker et al., 1998) and onset, magnitude, and duration of UES opening (Dantas et al., 1990; Jacob et al., 1989). Numerous studies have suggested that certain cortical regions integrate with the brainstem to activate and modulate swallowing. Swallowing, in isolation or with concomitant chewing motions, has been evoked in various species during repetitive electrical stimulation of the anteriolateral frontal and lateral pericentral cortex (Miller & Bowman, 1977; Sumi, 1969). Sumi (1969) noted in rabbits that stimulation of either the left or right cortex could induce swallowing with bilateral stimulation enhancing the swallowing response. Severing the corpus collusum did not impact swallowing suggesting that each hemisphere has an independent descending pathway to the brainstem. Furthermore, intracortical microstimulation evoked swallowing from four discrete cortical regions: the lateral region of the face primary motor cortex, the lateral face primary somatosensory cortex, the cortical masticatory area, which is anteriolateral to the face motor cortex, and an area inferior to the frontal operculum (Martin et al., 1999). Neuroanatomical tracing studies in primates have documented direct projections from the most lateral part of the precentral cortex to the rostral region of the NTS (Kuypers, 1958a,b). Paralimbic and limbic cortices and

portions of the pons and cerebellum have been documented to facilitate swallowing (for review, Hockman, Bieger, & Weerasuriya, 1979). While animal studies have identified supratentorial substrates involved in swallowing, they have not addressed the issue of swallowing laterality.

Anatomical Imaging

In humans, the localization of swallowing has primarily been based on ablation paradigms, which utilize computed tomography (CT) scan or MRI of focal lesions in stroke patients. Until the advent and application of these neuroimaging techniques to the study of swallowing, it was generally assumed that dysphagia resulted from either brainstem or bilateral hemispheric lesions. Furthermore, specific cytoarchitectonic sites contributing to dysphagia could not be determined in vivo in humans until CT/MRI application. Two early reports without the benefit of precise neuroimaging studies noted the occurrence of dysphagia following unilateral lesions. Tuch and Nielsen (1941) described a patient with the sudden inability to speak or swallow. Although dynamic swallowing tests were not completed, the authors reported a complete inability to swallow, even saliva; they defined the condition as “apraxia of swallowing.” (See Daniels, 2000 for a recent assessment of the notion “apraxia of swallowing”). Postmortem evaluation revealed infarction of the left lower portion of the pre- and post-central gyri (Brodmann’s areas 4 and 3-1-2). Meadows (1973) reported three cases in which the patients presented with dysphagia following unilateral cerebral lesions. Dysphagia was confirmed using cineradiography. Carotid angiography revealed right hemispheric involvement in all three patients: two patients presented with tumors and

one with an abscess. Of the two surviving patients, swallowing returned to normal after surgical intervention. Adding further support to the notion of cortical input in swallowing, sterotaxic surgery in awake human subjects with epilepsy revealed that stimulation of the lateral pericentral and superior Sylvian cortex evoked swallowing (Penfield & Rasmussen, 1950), and stimulation of the insular cortex evoked alteration of gastrointestinal motility and sensations associated with digestion (Penfield & Faulk, 1955).

Only recently has dysphagia been confirmed to be associated with unilateral hemispheric lesions; however, few of these studies have focused on identifying specific cytoarchitectonic sites contributing to dysphagia. In a provocative study, Robbins and Levine (1988) documented that dysphagia can result from unilateral ischemic stroke. Confirmation of a single stoke was obtained using CT scan, and they identified particular dysmotility patterns that differed based on the hemisphere lesioned. Specifically, patients with left hemispheric damage (LHD, n = 8) demonstrated greater oral stage dysfunction, while patients with right hemispheric damage (RHD, n = 8) demonstrated greater pharyngeal stage dysfunction and aspiration. Additional support for the concept of hemispheric contributions to swallowing was provided by another study from Robbins, Levine, Maser, Rosenbek, and Kempster (1993) who confirmed their previous results in a larger sample (n = 40). Patients in both studies were evaluated in the post-acute stage of stroke (21 days post-stroke) rather than in the acute stage. The concept of hemisphere specialization in swallowing was further supported, in part, by Daniels, Foundas, Iglesia, and Sullivan (1996). In a retrospective study of 16

unilateral stroke patients, they found that pharyngeal dysfunction was more common with RHD stroke patients, yet they did not find that the left hemisphere was more commonly associated with oral stage dysfunction than the right hemisphere. Furthermore, the insula was identified as a common lesion site in these dysphagic patients, irregardless of which hemisphere was involved. Conversely, Irie and Lu (1995) found a greater incidence of isolated oral stage dysfunction in LHD patients in their study of stroke patients (n = 74). The persistence of dysphagia following RHD was supported in a recent investigation that evaluated swallowing in the acute phase (3 days after admission) and post-acutely (29 days following admission) (Smithard, O'Neill, Martin, & England, 1997). In the acute phase, hemisphere did not distinguish between subjects with and without aspiration; however, significantly more post-acute patients with aspiration had RHD. Patients (n = 87) with single and multiple strokes were entered into this study, but the authors did not indicate whether bilateral lesions were more common in the patients with persistent dysphagia. Another limitation of this study was that the authors did not discuss whether patients with a premorbid history of dysphagia were excluded. Furthermore, due to the limited number of post-acute stroke patients with only a single lesion and aspiration (n = 5), statistical analysis could not be completed, yielding inadequate power to support their conclusions.

Using this ablation model, other investigators have not identified lateralization of swallowing. Most of these investigations have studied patients in the post-acute phase of stroke. In a study of 46 patients with cerebrovascular disease, Chen, Ott, Peele, and Gelfand (1990) found that dysfunction in the oral or pharyngeal stage of swallowing

was not associated with specific hemisphere of infarction nor could they attribute swallowing severity to a specific hemisphere. Johnson, McKenzie, Rosenquist, Lieverman, and Sievers (1992) found no differences between hemisphere and pharyngeal transit times in a study of 40 stroke patients. Daniels, Brailey, and Foundas (1999) found no association between lingual discoordination during swallowing and hemisphere of stroke, suggesting that both the right and left hemispheres contribute to oral swallowing coordination. In a study of 91 unilateral stroke patients, Shanahan, Logemann, Colangelo, and Halper (1995) also found no association between hemisphere of stroke and specific patterns of swallowing dysfunction or aspiration. In a retrospective study of 330 subjects with oropharyngeal dysphagia including 101 stroke patients (LHD = 39, RHD = 26), Perlman et al. (1994) found no significant difference in the incidence of aspiration, oral stage dysfunction, or pharyngeal abnormalities between the LHD and the RHD patients. They did report a high incidence of dysphagia and aspiration in patients with subcortical lesions. In a retrospective study which included both acute and chronic stroke patients (n = 47), Alberts, Horner, Gray, and Brazer (1992) found that neither lesion site nor hemisphere consistently predicted aspiration. In a study of 54 consecutive acute stroke patient (studied within 5 days of admission), Daniels and Foundas (1999) did not find an association between aspiration, dysmotility pattern, and hemisphere. Lesion analyses revealed that location appeared to be more critical than hemisphere in predicting patients as risk of aspiration. Specifically, anterior locations as well as subcortical periventricular sites were commonly lesioned in patients with risk of aspiration, whereas patients without risk of aspiration were more

likely to have posterior lesions and small lesions limited to subcortical gray matter structures. Involvement of the anterior PVWM, both in isolation and with cortical extension, was found to be significantly associated with risk of aspiration. The PVWM, which is the white matter adjacent to the body of the lateral ventricles, is comprised of ascending somatosensory and descending motor fibers as well as intrahemispheric cortico-cortical connections (Schulz, 1993). Given the distribution of various fiber systems within the PVWM (Barnes, Van Hoesen, & Yeterian, 1980; Jurgens, 1984; Petrides & Pandya, 1984; Schulz, 1993), lesions to the anterior PVWM may interrupt anterior and/or posterior cortical connections, thereby disconnecting critical cortical swallowing regions from cortical and subcortical projection sites. In addition, the premotor cortex (Brodmann's area 6) was frequently lesioned in the patients with risk of aspiration. The premotor cortex provides inputs both to the pyramidal tract and to extrapyramidal pathways and is critical in the selection of appropriate movements (Passingham, 1993). Lastly, while insular lesions of either hemisphere did not predict aspiration, they did appear to be strongly associated with dysphagia in that 12 of 14 patients with insular lesions had dysphagia. The association of insular lesions, particularly the anterior insula, with dysphagia has previously been documented in stroke studies (Daniels et al., 1996; Daniels & Foundas, 1997). It has been posited that the anterior insula may be an important cortical substrate in swallowing due to its connectivity with the primary and supplementary motor cortices, ventroposterior medial nucleus of the thalamus, and to the NTS, all of which are important regions in the mediation of oropharyngeal swallowing.

Functional Imaging

Functional imaging studies and transcranial magnetic stimulation (TMS) have been used to investigate swallowing laterality in vivo in healthy adults. Functional neuroimaging studies have allowed for correlation of brain structures with function. Functional neuroimaging methodologies study changes in cerebral blood flow that reflect neuronal metabolic activity associated with the performance of a specific task like swallowing. Cortical and subcortical maps of cerebral function are derived from statistical parametric maps of increased or decreased neuronal activity. It is important to remember that neuronal activity may be excitatory or inhibitory, thus metabolically active regions may serve to excite or inhibit function. The two types of functional imaging techniques that have been used in the study of swallowing are positron emission tomography (PET) and functional magnetic resonance imaging (fMRI).

Positron Emission Tomography

PET uses radiotracers that circulate within the cerebral blood and diffuse into cerebral tissue. Advantages of PET are: low susceptibility to motion artifact, short half-life of the radiotracer which allows for brief task and scan times, ability to perform multiple experiments in one sitting, and no degradation by adjacent air spaces. Disadvantages of PET include radiation exposure, difficulty in achieving accurate region of interest placement, and limited spatial resolution (Nadeau & Crosson, 1995). With PET, block design paradigms can easily be conducted due to low susceptibility to motion artifact. In a block design, an activity, "on" condition (e.g., consecutive swallows performed fairly rapidly) is alternated with rest periods, "off" condition. In a

specific task, like swallowing, multiple on-off blocks are completed with averaging of activation over trials. Two PET studies of swallowing have been completed. In one study, subjects (n = 8) continuously completed saliva swallows over a 90-second period (Zald & Pardo, 1999). In the other study, water infused swallows were completed in eight subjects over a 90-second period with the onset of swallowing visually cued and monitored with mylohyoid EMG (Hamdy, Rothwell et al., 1999). Similar areas of activation were found in these studies and included the inferior precentral cortex, right insula, and left cerebellum. Interhemispheric asymmetry, that is, bilateral but asymmetric activation within the sensorimotor cortex was noted in one study (Hamdy, Rothwell et al., 1999) but not in the other study (Zald & Pardo, 1999). Zald and Pardo (1999) also reported significant activation of various subcortical structures, the right temporal cortex, and the right supramarginal gyrus. Hamdy, Rothwell et al. (1999) noted significant activation of limbic and paralimbic structures and the dorsal brainstem. They reported significant deactivation of the left superior prefrontal cortex, superior temporal gyrus, and precuneus.

Functional Magnetic Resonance Imaging

With fMRI, blood oxygen level dependent (BOLD) effects are mapped on MRI scans. BOLD effects are based on the principle that disproportionate increases in blood flow over metabolic demands yields reduced deoxyhemoglobin levels in regions of high neuronal activity. For fMRI, advantages include no radiation exposure, excellent image registration, and excellent spatial resolution. In addition, an unlimited number of studies can be performed because radioactive tracers and x-ray beams are not used.

Disadvantages include high susceptibility to motion artifact, low signal to noise ratio, extremely noisy environment, and degraded images adjacent to air spaces (Nadeau & Crosson, 1995). Block design and event-related paradigms have been conducted. The timing of tasks in event-related fMRI may be advantageous in experiments that study swallowing, as this type of acquisition sequence reduces motion artifact. That is, the use of an event-related paradigm can significantly reduce motion artifact in that hemodynamic responses are delayed in onset but prolonged in duration (Birn, Bandettini, Cox, & Shaker, 1999). The other fMRI experimental method involves the block design, which evaluates swallowing in an on-off (experiment-control) paradigm. Movement artifact and magnetic field drift need to be corrected in this type of fMRI acquisition. Two fMRI studies of swallowing have been completed. One used an event-related paradigm with water infusion boluses in 10 subjects (Hamdy, Mikulis et al., 1999). The other study used a block design paradigm consisting of swallows (bolus and duration variables) alternated with rest periods in eight subjects (Mosier, Liu, Maldjian, Shah, & Modi, 1999; Mosier, Patal et al., 1999). Similar activation areas were identified in these studies and included motor and premotor cortices, cingulate, insula, temporal and somatosensory association cortices, and pars opercularis. Hamdy, Mikulis et al. (1999) also noted activation of the superior premotor cortex, prefrontal cortex, subcortical structures, and precuneus. Bilateral activation was found in all of these regions except the insula, frontal operculum, and premotor cortex. Asymmetric activation was evident with these regions, with the right insula more activated than the left. This finding is consistent with studies of gustation, which have found that the right

insula may be more important than the left insula in taste sensation-perception (for review, Small, Jones-Gotman, Zatorre, Petrides, & Evans, 1997). Mosier, Patal et al. (1999) noted additional activation of the primary somatosensory cortex and the supramarginal gyrus. There were more sites activated for saliva swallows compared to water swallows, and more sites were active with longer swallow durations. Laterality effects were identified but were not consistently observed within subjects or across regions (Mosier, Liu et al., 1999).

Transcranial Magnetic Stimulation

TMS uses a magnetic pulse generated from a conducting coil to stimulate neural tissue. Stimulation of a particular area can be correlated with a measured external response (e.g., EMG). Using this technique, cortical areas that project to corresponding muscles of deglutition can be identified, and inter- and intra-hemispheric differences in cortical responsiveness can be studied. This method has two major limitations: 1) TMS may also stimulate subcortical and/or adjacent cortical sites and 2) the level of magnetic pulse cannot evoke a complete swallow. Despite these limitations, TMS studies have found discrete somatotopic organization of swallowing musculature on the motor and premotor cortices with an asymmetric representation of swallowing within subjects (Hamdy et al., 1996; Hamdy et al., 1997). That is, as with Hamdy, Rothwell et al. (1999), swallowing was not localized to one specific hemisphere across subjects, but within each subject one hemisphere tended to be more important than the other in mediating swallowing.

Dual Task Paradigm

Lateralization of language functions has been extensively studied using the ablation paradigm, cortical stimulation, Wada testing, and functional neuroimaging methodologies (for review, Beaton, 1997). It is well established that the left cerebral hemisphere is dominant for language functions in 95% of right-handed individuals, while 5% have bilateral or right hemisphere dominance. In left-handed individuals, language is lateralized to the left hemisphere in 70%, whereas 30% demonstrate either bilateral or right hemisphere lateralization (Benson & Geschwind, 1968). The dual task paradigm has been used extensively in neuropsychology to investigate lateralized functions. This paradigm indirectly evaluates lateralized cortical systems by comparing performance on tasks at baseline and with a concurrent or competitive condition. The most common paradigm is the verbal-manual interference paradigm. In this paradigm the subject performs a motor task, such as finger tapping, with the dominant and nondominant hands at baseline (without interference), and with interference. The interference task consists of a verbal output such as repeating a series of words. Because distal hand movements are mediated by the contralateral primary motor cortex, right handers will be activating the left primary motor cortex when tapping with the right hand and vice versa when tapping with the left hand (Rao et al., 1995). In the baseline condition, right handers tap faster with the right than left hand. Concurrent verbalization (verbal-manual interference condition) typically yields a decrement in right hand finger tapping rate as compared to baseline finger tapping rate (Kee, Bathurst, & Hellige, 1983; Dalen & Hugdahl, 1986). There are several theories that have been

proposed to explain this verbal-manual interference. The most widely accepted theory is the "functional cerebral space model" which indicates that co-activation of functionally overlapping neural substrates will yield a decline in response in one of the two concurrent activities (Kinsbourne & Hicks, 1978). Others have posited that "hemispheric overload" (Dalby, 1980) or "competition of resources" (Kee, Bathurst, & Hellige, 1984) produces a decrement in response. That is, allocation of attentional or processing resources is compromised due to two tasks sharing resources within the same hemisphere. The dual task paradigm can be used to study swallowing laterality.

Daniels et al. (2000) employed a modified dual task paradigm to investigate swallowing lateralization in a pilot study for this research project. Using this paradigm, one may hypothesize that if language or motor systems share neural substrates or overlap with neural systems that impact swallowing, then a decremental response would occur in the dual task (motor-swallowing, language-swallowing). Fifteen healthy consistently right-handed young males (age 30 ± 3 years) completed two 10-second trials of four tasks. Tasks were performed at baseline (without a simultaneously performed task) and with interference (with a simultaneously performed task); task order was counterbalanced. Baseline (without interference) conditions included: 1) continuous swallowing, 2) left hand finger tapping, 3) right hand finger tapping, and 4) verbal repetition. Baseline conditions with interference involved verbal-manual competition (repetition-right finger tap, repetition-left finger tap). Experimental conditions to investigate the effects of interference on swallowing included motor tasks (finger tap right, finger tap left) and a language task (silent repetition). For the

swallowing with silent repetition interference task, subjects were instructed to repeatedly think, not vocalize, a three-word series. The experimental condition also studied the effects of interference on the motor tasks produced by swallowing. The number of swallows and the volume per swallow (total volume swallowed/number of swallows) were calculated as well as number of finger taps with each hand, and the baseline total number of word repetition sets. Paired t-tests revealed that interference tasks without swallowing demonstrated the expected decrease in right hand finger tapping with repetition ($p = 0.01$) and no significant change in left hand finger tapping ($p = 0.41$). There was a significant decrease in the volume per swallow with silent repetition interference (M = 9.7 ml, SD = 5.1, $p = 0.049$) as compared to baseline (M = 11.5 ml, SD = 5.9), but there was no change with right or left hand finger tapping. Compared to baseline tapping rate (M = 54.9, SD = 4.6), there was a significant decrease in right hand finger tapping with continuous swallowing (M = 51.3, SD = 7.7, $p = 0.042$). Left hand finger tapping with continuous swallowing interference approached significance ($p = 0.06$). These data suggest that left hemispheric motor and language systems have an impact on swallowing with the right hemispheric motor influence less prominent.

The mouth, hand, pharynx, and larynx are closely positioned anatomically along the length of the primary motor strip. This anatomical relationship and the data from the dual task paradigm support the cerebral space model explanation for the decrement in response with competing tasks. It remains unclear whether right hemisphere dominant systems impact swallowing, as these functions were not directly tested.

Although these data suggest that the left hemisphere motor and language systems have an impact on some swallowing behaviors, other processes such as attentional demands and allocation of resources may be contributing to the observed interference in the dual task paradigm. Furthermore, the effect of a higher order right hemisphere activating task on swallowing was not investigated, thus right hemisphere contributions to swallowing behavior needs to be further elucidated.

Summary

While studies have confirmed that the cerebral cortex is part of the neural network that mediates swallowing in humans, it remains unclear whether the right or the left cerebral hemisphere is more critical or "dominant" for swallowing. Two competing hypotheses have been put forth: lateralization of function versus a bilateral representation of swallowing. The control of swallowing may be lateralized exclusively to the right or left cerebral hemisphere, although there may not be a consistent pattern of lateralization across individuals. Conversely, swallowing may not be strongly lateralized. It may be that there is bilateral control of swallowing with or without some lateralized aspects. Empirical studies have provided partial support for each of these hypotheses. Continued research exploring right and left hemisphere contributions to swallowing behavior is warranted.

RESEARCH PLAN

Hypotheses and Specific Aims

The first aim of this investigation was to study the effects of normal aging on specific biomechanical features in sequential straw drinking. According to the detailed literature review, dysphagia research thus far suggests that the impact of normal aging on swallowing is multifaceted. It can increase the duration of oropharyngeal events, limit the extent of movement of particular muscle groups, and decrease muscular reserve (for example, Rademaker et al., 1998; Robbins et al., 1995). However, two important features are lacking from these earlier studies. First, neuropsychological testing was not completed to ascertain if the subjects, particularly the elderly, were cognitively intact. This information is crucial, as cognitive decline, unrelated to normal aging, may be an indicator of subtle neurological deficits, which can impact swallowing. Second, all of the studies were completed with calibrated volumes. While these studies were important in establishing normative temporal and spatial features of deglutition, research concerning aging effects on swallowing needs to be expanded to include the impact of aging on sequential swallowing. Consecutive swallowing represents a more natural pattern of liquid ingestion, as opposed to a single swallow. Investigation of more typical patterns of ingestion has recently been completed. However, none has focused specifically on the liquid bolus location at swallow onset, movement patterns of the hyolaryngeal complex, or how normal aging may impact these dynamic and biomechanical features. It is important to study these factors in sequential swallowing

in healthy young and elderly adults in order to learn more about natural patterns of swallowing and potential age-related effects on deglutition.

As the concepts of "normal" deglutition are broadened, it is critical that we expand basic physiological knowledge to the healthy elderly population in order to distinguish between normal aging and pathological aging. In undertaking a study of normal aging, it is crucial that neuropsychological testing be completed to ensure that cognitive decline is controlled, as neuropsychological deficits may be a marker of subtle cognitive deficits that may impact function. Subtle cognitive deficits will not be evident in the subjects unless directly assessed.

Pilot data identified differences in swallowing physiology based on mode of ingestion (Daniels & Foundas, 2001). It is unclear whether these biomechanical differences are maintained with aging or whether different biomechanical patterns or different distributions of these patterns emerge with normal aging. If differences are indeed evident with aging, it is unknown if a particular pattern, e.g., laryngeal vestibule opened between swallows, increases risk of airway invasion.

The second aim of this research was to continue the study of swallowing lateralization using a dual task paradigm. As the foregoing literature review has also indicated, cortical regions integrate with the brainstem to mediate swallowing; however, it is still unclear if swallowing is lateralized to a particular cerebral hemisphere. The two competing theories concerning swallowing laterality have been reviewed. One hypothesis asserts that there is bilateral control of swallowing with, perhaps, some lateralized aspects of deglutition. The other hypothesis suggests that there is a dominant

hemisphere for swallowing, although the pattern of lateralization may not be consistent across individuals. Empirical studies have supported each hypothesis. Using a dual task paradigm, pilot data in young right-handed subjects demonstrated that the left hemisphere contributes to swallowing (Daniels et al., 2000). However, right hemisphere contribution to swallowing was not fully studied, as a comparable higher order right hemisphere task was not administered to participants.

Thus, the current investigation expanded these pilot data to include a higher cortical right hemisphere task. The research also investigated the effects of aging on swallowing laterality. Knowledge of lateralization of the cortical representation of swallowing is critical to fully understand the role of supratentorial regions in deglutition and how neurological disease, in particular, stroke, may affect swallowing. This information can impact service delivery provided to neurologically impaired patients.

To achieve these two goals, two experiments were conducted to investigate the relationship of swallowing physiology and aging, and to study swallowing lateralization. In Experiment I, the effects of aging on specific biomechanical features of swallowing were investigated. Specifically, location of the leading edge of the bolus at swallow onset, HLC movement pattern, bolus aggregation, and airway invasion were examined in a group of healthy young and old subjects as they sequentially drank from a straw. In Experiment II, lateralization of swallowing was investigated in a cohort of old and young subjects using a dual task paradigm. The effects of both higher cortical tasks and a motor task on swallowing were measured, as well as the effects of swallowing on the motor task. The following questions were considered, with the a priori hypotheses

generated based on the literature to date. Appendix C provides a summary of the research questions.

Experiment I: Swallowing Physiology of Continuous Straw Drinking

Question 1: What HLC movement patterns are observed during sequential straw swallowing across individuals, and are there age-related effects? Based on pilot data, the a priori hypothesis was that subjects would demonstrate one of the following three patterns of HLC movement: 1) opening of the laryngeal vestibule (return of the epiglottis to upright) between each swallow, 2) continued laryngeal vestibule closure (maintenance of epiglottic inversion) between each swallow, or 3) a mixed pattern (interchangeable opened and closed HLC patterns between swallows). HLC movement patterns were defined as either open or closed if more than 60% of the total swallows for a subject was classified as one of these two patterns. A subject was designated with a mixed HLC movement pattern if the two patterns were interchangeable, with no one pattern constituting more than 60% of the swallows. It was posited that the older adults would demonstrate greater opened or mixed type of HLC movement pattern, as opposed to a closed pattern. The rationale for this was that fatigue may decrease muscular reserve (Robbins et al., 1995) thus, not allowing the older subjects to maintain laryngeal elevation for the 10-second swallowing period.

Question 2: What are the patterns of leading bolus edge location at swallow onset across subjects, and are there age-related differences? Initiation of maximum hyolaryngeal excursion was the biomechanical marker used to identify pharyngeal swallow onset (Pouderoux et al., 1996). Based on the pilot data, three variables were

used to designate the location of the leading edge of the bolus at swallow onset: anterior to the valleculae, level with the valleculae, and inferior to the valleculae. In this manner, differences between individuals could be addressed, as in Question 1. For each subject, a pattern of bolus placement was identified. An overall placement pattern of superior to the valleculae, level with the valleculae, or inferior to the valleculae was designated if a ratio of ≥ 3:2 was identified for one of the locations. If no one cell compromised the majority, that is, the ratio was < 3:2, then the placement pattern was designated as random. Based on pilot data and previous data concerning the senescent swallow, it was hypothesized that the primary location of the leading bolus edge at swallow onset would be inferior to the valleculae, with no differences between groups. Pilot data indicated that young adults evoked a swallow inferior to the valleculae; moreover, research has indicated that increased sensory input is needed to induce a pharyngeal swallow in elderly adults (Shaker et al., 1994). Given these data, one may posit that, regardless of age, multiple receptor sites within the oropharynx must be stimulated in order to achieve the threshold necessary to evoke a pharyngeal swallow during sequential straw drinking.

Question 3: Across all swallows, what is the location of the leading bolus edge at swallow onset, and is it related to HLC movement pattern? Are there age-related differences? Whereas Questions 1 and 2 addressed individual differences, this question analyzed differences across the total number of swallows across subjects. Based on pilot data, it was suggested that the bolus would be in the distal pharynx at swallow onset. It was hypothesized that in the older subjects, this distal leading edge would be

observed with all HLC movement patterns, as larger volumes during pharyngeal infusion have been required to evoke a swallow in elderly adults (Shaker et al., 1994).

Question 4: Is bolus aggregation observed, and if so, is it related to HLC movement pattern? Are there effects of aging related to bolus aggregation? Bolus aggregation was operationally defined as two or more episodes of oral filling, in which the first bolus was volitionally propelled into the pharynx while the oral cavity was reloading the second bolus. The pharyngeal swallow was evoked only after the multiple episodes of bolus loading and transfer processes. It was hypothesized that bolus aggregation would occur more often in the elderly regardless of HLC movement pattern. This notion was posited as it was suspected that the elderly would swallow a smaller volume of liquid per swallow as compared to younger subjects (see Experiment II, Question 1). Given that the elderly require increased sensory input to evoke a swallow (Shaker et al., 1994), it was hypothesized that the propulsion of subsequent boluses would be required to achieve a volume large enough to induce a pharyngeal swallow. In contrast, pilot data have indicated that in young subjects, bolus aggregation occurs more frequently with an opened laryngeal vestibule movement pattern.

Question 5: Across all swallows, what are the occurrences of penetration (entry of material into the laryngeal vestibule above the level of the glottis) and aspiration (entry of bolus into the trachea), and are they related to HLC movement pattern, to location of the leading bolus edge at swallow onset, or to age. The Penetration-Aspiration Scale (Rosenbek et al., 1996) was used to score airway invasion for each swallow (Table 2). This scale is ordinal and focuses on depth of airway invasion,

clearance, and sensory response to determine a score. A score of 1 indicates no airway invasion. Scores 2-5 indicate penetration. Scores 6-8 indicate aspiration. It was hypothesized that penetration and aspiration would occur more frequently in the elderly and would be associated with an opened laryngeal vestibule and distal bolus placement.

Table 2. The Penetration-Aspiration Scale (Rosenbek et al., 1996)

Score	Classification	Description
1	None	No airway invasion
2	Penetration	Entry of the bolus into the airway with clearing
3	Penetration	Entry of the bolus into the airway without clearing
4	Penetration	Bolus contacts the vocal cords followed by airway clearing
5	Penetration	Bolus contacts the vocal cords without airway clearing
6	Aspiration	Bolus enter the trachea and is cleared wither into the larynx or out of the airway
7	Aspiration	Bolus enters the trachea but is not cleared despite attempt
8	Aspiration	Bolus enters the trachea and no attempt is made to clear

Robbins et al. (1995, 1999) have suggested that the elderly may be at risk of dysphagia and airway invasion when swallowing repeatedly. Conventional wisdom suggests that ingestion with the laryngeal vestibule opened between swallows and with the leading bolus edge in the hypopharynx would yield greater risk of airway invasion. When these features are present, rapid movement of the laryngopharyngeal structures would be required to prevent penetration and aspiration. Studies of single swallows in the elderly have revealed increased durations of transfer and decreased amplitude of movements (for example, Logemann et al., 2000). Thus, the elderly may not achieve

rapid airway protection with the bolus in the distal pharynx or with an opened airway at swallow onset, and as such, would be at increased risk for penetration and aspiration.

Experiment II: Swallowing Lateralization Using a Dual Task Paradigm

Question 1: Are baseline motor, language and swallowing performances significantly reduced in the elderly compared to their young counterparts? Given that increasing age is associated with a decrease in cognitive processing speed and motor slowing, for both skilled movement and gait (for review, Alberts, 1984), it was hypothesized that motor and language performances would differ significantly between groups, with the older group demonstrating slower response rates on the language and motor tasks. Based on data indicating increased duration of bolus transfer with increasing age (for example, Robbins et al., 1992; Tracy et al., 1989) and decreased muscular reserve with increasing age (Robbins et al., 1995), the a priori hypothesis was that significant age differences would be apparent for all swallowing parameters. Specifically, the older adults would swallow fewer times and would ingest smaller volumes per swallow, as compared to the younger adults during the 10-second sequence.

Question 2: Does baseline motor performance differ with concurrent repetition? If so, are there effects of hand and age? It was hypothesized that motor responses would be slower with concurrent repetition and that there would be a significant right hand effect. Neural regions activated for speech and manual motor tasks are anatomically close and functionally overlapping. As such, a decrement in response would result from the competition of two activities that require access to the same functional units that

may be anatomically close or overlapping (Kinsbourne & Hicks, 1978). While finger tapping rates would be slower in the elderly as compared to the young, asymmetry patterns with language interference would be similar across the two age groups.

Question 3: Are baseline averages of number of swallows and volume per swallow significantly influenced by a competing language or motor task, and are there age effects? Given the results of the pilot study, the a priori hypothesis was that there would be a significant decline in the number of swallows and the volume per swallow with the silent repetition task, but no significant difference with finger tapping. Neural regions activated for swallowing and speech are anatomically close and functionally overlapping. The cerebral space model suggests that co-activation of functionally overlapping neural substrates will yield a decline in response in one of the two concurrent activities (Kinsbourne & Hicks, 1978). Similar lateralization results would be observed across age groups. If age differences were observed, then one must consider the effects of allocation of resources as research has shown that parallel processing declines with age (Tsang & Shaner, 1998).

Question 4: Are baseline averages of number of swallows and volume per swallow significantly influenced by a simultaneous cognitive right hemisphere activating task (visuospatial processing), and are there age-related effects? The question could not be addressed in the pilot study because a higher order right hemisphere activating task was not included in the paradigm. However, data was collected for the newly recruited subjects (young = 6, old = 17) in the current study. It was predicted that there would not be significant differences between baseline averages and averages with

a concurrent visuospatial task, and that there would not be effects of aging. Based on the cerebral space model, frontal lobe motor neural regions for speech and swallowing are anatomically close and functionally overlapping in the left hemisphere; however, this is not true for swallowing and visuospatial processing, which is predominately an occipitoparietal right hemisphere function. Hence, differences between baseline averages and those assessed with the right hemisphere interference task were not anticipated. If differences were evident, attentional or processing compromise might be suspected, as suggested by the attentional model (Kee et al., 1984).

Question 5: Does baseline motor performance differ with concurrent swallowing? If so, are there effects of hand and age? It was hypothesized that finger tapping rates would be slower with concurrent swallowing as compared to baseline tapping rates. It was also posited that there would be no hand effect; that is, tapping rates would decline similarly for the two hands with swallowing interference. While motor responses would be slower in the elderly as compared to the young, lateralization patterns would be similar across the two age groups. These hypotheses were based on the results from the pilot study, which showed decrements in right and left finger tapping responses with concurrent swallowing. Swallowing and finger tapping are driven predominately by the motor cortices. Whereas unilateral distal hand movements are mediated by the contralateral motor hand representation, greater bilateral sensorimotor activation is required for swallowing. Thus, it was predicted that there would be a reduction of finger tapping rates across both hands with concurrent swallowing.

METHODS

Subjects

Thirty-eight healthy adults were studied including 20 right-handed younger males between the ages of 25 and 35 years and 18 right-handed elderly males above the age of 60 years (range 60-83 years). In previous studies of aging and swallowing, the ages for the youngest group have ranged from 20-29 years of age and the ages for elderly subjects have ranged from 60-79 years of age (e.g., Tracy et al., 1989). Thus, the age range determined for the current study adequately reflected senescent deglutition. While 15 young adults and one older adult were tested in the pilot study, an additional 6 young subjects were recruited to achieve the appropriate cell size. One subject from the pilot study was excluded as the handedness questionnaire suggested a mixed hand preference. Subjects were recruited from Veterans Affairs Medical Center (VAMC) patients and employees, students and employees from Tulane University Medical Center and Louisiana State University Medical Center, and from outside the local medical community. Inclusion criteria included right handedness as determined by self-report and confirmed with a handedness inventory, no history of left hand preference in immediate family members (parents and siblings), and intact cognitive functioning confirmed by the Mini-Mental Status Examination (MMSE, Folstein, Folstein, & McHugh, 1975). Exclusion criteria included a history of dysphagia, neurological disorders, oropharyngeal structural damage, psychiatric disturbance, alcohol or drug abuse, pulmonary disease, arthritis or cervical spine disease affecting upper extremity

movement, developmental disorders (stuttering, dysphasia, dyslexia, dyspraxia), and a family history of dementia or Parkinson's disease. Given the exclusion criteria, particularly for the elderly subjects, 40 was selected as the sample size that could be recruited in a reasonable time frame. Analysis revealed that 20 subjects per cell, with an alpha of .05 and power of .80, would detect a difference of .894 standard deviations between the means. Previous deglutitive research has identified large effects (range .90-2.0) when comparing pharyngeal delay time in old and young subjects (Tracy et al., 1989), and thus supports the proposed sample size. The study protocol was approved by the Institutional Review Boards at Tulane University Medical Center and the VAMC in New Orleans and Louisiana State University in Baton Rouge. Informed consent was obtained from each qualified subject.

Procedures

Neurobehavioral Measures

Confirmation of handedness was determined by the Briggs and Nebes (1974) handedness inventory, which consists of 12 unimanual tasks adapted from Annett's (1970) 120-item questionnaire. Consistent right hand performance for a task was scored as +2 while consistent left hand performance was scored as –2. A score of +24 indicated a strong right hand preference for all tasks, whereas a score of –24 was indicative of stong left handedness. Schachter, Ransil, and Geschwind (1987) identified scores ≥ +.70 to be representative of consistent right handedness and scores ≤ –.70 to be representative of consistent left handedness. This cut-off score, which translates to a raw score ≥ 17, was adapted for this study to identify subjects with a strong right hand

preference. Thus for this investigation, only those subjects with a raw score ≥ 17 of 24, which is indicative of a strong right hand preference, participated in the study. This procedure was followed in order to control for the effect of hand preference, because there is evidence that "mixed" right handers and left handers are less lateralized for language and motors systems than consistent right handers who are more strongly lateralized for these functions (Benson & Geschwind, 1968). Medical and current medication histories were obtained from a questionnaire that was completed by each prospective subject to assess for the presence of exclusionary criteria. All subjects underwent a detailed neuropsychological assessment prior to the swallowing assessment (Table 3). The MMSE (Folstein et al., 1975) was administered to screen cognition. Subjects who achieved a score of ≥ 26 were recruited to participate in the study. This baseline criterion was selected because normative data indicates that healthy adults obtained a mean of 27.6 ± 1.7 (Folstein et al., 1975). Moreover, in a recent study with a cohort of healthy elderly subjects (n = 30, mean age 60.3 years) recruited from the VAMC, the average MMSE score was 27.8 ± 2.15 (Foundas, Daniels, Vasterling, Otto, & Roberts, 1998). For this reason, a cutoff score of ≥ 26 was adequate to identify cognitively intact subjects. Clock drawing to command and reproduction (Goodglass & Kaplan, 1983) was used to screen visuospatial and construction skills. Clock drawings were scored using the Libon, Swenson, Barnoski, and Sands (1993) adaptation of the Sunderland et al. (1989) scoring system (range 1-10), in which scores lower than 7 indicate cognitive decline. All subjects scored at or above 7 on spontaneous and reproduction clock drawing.

Normative data based on age and education was used to interpret results of the semantic word fluency task that was used to screen language skills (Tombaugh, Kozak, & Rees, 1999). All subjects scored within the average range for their age and education level. The <u>Test of Limb and Oral Apraxia</u> <u>(TOLA)</u> was used to evaluate oral and limb praxis on gesture-to-command and imitation tasks (Helm-Estabrooks, 1992). The <u>TOLA</u> provides standard scores, with a mean of 10 and a standard deviation of 3. All subjects scored ≥ 10 for limb and oral scores. An oromotor examination was completed to assess the integrity of oral musculature strength and movement. Neither facial asymmetry nor orofacial musculature weakness was observed in any of the subjects.

Table 3. Demographic and neuropsychological assessment data presented as means and (standard deviations).

	Group			
	Young		Old	
	Means (SD)	Range	Means (SD)	Range
Age	29.10 (2.95)	25-35	69.44 (7.05)	60-83
Education	17.30 (2.92)	12-23	12.39 (3.74)	6-22
MMS	29.95 (1.21)	26-30	28.72 (1.49)	26-30
Handedness	21.45 (2.74)	17-24	22.72 (1.93)	18-24
Clock-Free	9.50 (.55)	9-10	8.71 (.99)	7-10
Clock-Copy	9.83 (.41)	9-10	9.06 (.75)	8-10
Fluency	18.83 (1.36)	12-26	17.35 (4.11)	11-26
TOLA-Right	12.95 (1.36)	10-16	13.61 (1.58)	11-16
TOLA-Left	12.74 (1.10)	11-16	13.83 (1.47)	11-16
TOLA-Oral	13.70 (1.38)	12-15	13.61 (1.38)	11-15

<u>Radiographic Procedure</u>

Subjects were tested in the radiology fluoroscopy suite at the VAMC, New Orleans. Videofluoroscopic swallowing samples were performed in conjunction with a board-certified radiologist and were recorded on a Super-VHS videocassette recorder

that was coupled to a counter timer that encoded digital time in the hundredths of a second on each video frame. Lateral radiographic views of swallowing were obtained with the fluoroscopic tube focus encompassing the oral cavity (rostral to the lips) and the pharynx (caudal to the UES). On all swallowing trials, 300 ml of diluted liquid barium (60% w/v, diluted 2:1 sugar-free juice to barium) were placed in a cup and were ingested through a straw (19 cm length, ½ cm diameter) with the examiner holding the cup and straw.

Study Design

Baseline and competition tasks were completed by each subject. Baseline conditions were 1) continuous swallowing, 2) finger tapping (right hand and left hand), and 3) verbal repetition of a 3-word series. In addition, the newly recruited subjects (n = 23) completed a line orientation task. This higher order right hemisphere task was not included in the pilot study. The interference task without swallowing involved verbal-manual interference (finger tapping right hand, finger tapping left hand, verbal repetition). The interference with swallowing tasks included 1) motor interference (finger tapping right hand, finger tapping left hand), 2) language interference (silent repetition), and 3) visuospatial interference (nonverbal line orientation). Young and old groups completed each condition except for the visuospatial interference task, which was performed by six younger subjects and 17 older subjects. Each condition consisted of a 10-second trial that was measured with a stopwatch. Two trials of each condition were completed. Order of presentation of task was counterbalanced across groups, and

order of hand for the finger tapping section was randomized within task. A practice trial was completed for each task before experimental trials for each condition began.

Baseline Tasks

Swallowing

Subjects continually ingested diluted liquid barium (maximum volume of 300 ml) through a straw. Instructions were: "When I say go, start drinking. Continually drink until I say to stop." Each subject completed two 10-second periods of continual ingestion. A 15-second rest period was provided between trials. The amount of liquid ingested during each swallowing period was computed by measuring the amount not swallowed and subtracting this from the initial total volume (300 ml). The number of swallows during continual ingestion was totaled using the video recordings and was averaged across the two trials. The volume per swallow was calculated for each trial by dividing the total amount ingested during each 10-second period by the number of swallows and the average across the two trials was computed. HLC movement pattern, location of the leading bolus edge of swallow onset, bolus aggregation occurrences, airway invasion, and Penetration-Aspiration Scale scores were identified for each swallow across the two trials and were derived from slow motion and frame by frame analyses of the video recordings.

Finger Tapping

Using their index finger, subjects tapped on a board that had an attached counter to register the number of taps. Subjects were instructed to tap as quickly as possible. Each subject completed two 10-second trials with a 15-second rest period between each

trial. The number of finger taps was obtained from the counter and averaged across the two trials. Finger tapping averages were compared across the baseline and swallowing competition conditions. fMRI studies have demonstrated that finger tapping activates motor regions contralateral to the performing hand (Rao et al., 1995).

Repetition

Subjects continually, verbally repeated a three-word set "wolf-butterfly-duck." Subjects were instructed to repeat the word set as fast as possible. An audiocassette recorder was used to tape the baseline repetition task. Two 10-second trials were completed with a 15-second rest period between each trial. The number of repetition series was computed from the audiocassette recording. The total number of word sets was obtained for each 10-second period and averaged across the trials. It was expected that repetition would activate the left hemisphere in strongly right-handed individuals. Functional imaging studies have identified activation of the left dorsolateral prefrontal cortex and the left supplementary motor cortex in "silent" verb generation (Wise et al., 1991), and activation of the left primary motor cortex during "silent" repetition (Warburton et al., 1996).

Line Orientation

The Judgement of Line Orientation test, Form H (Benton, Hamsher, Varney, & Spreen, 1983) was administered. This test evaluated spatial discrimination of line orientation. The subtest consisted of pictured lines in various orientations. Subjects verbally matched the stimuli to the identical slope in a "sun ray" of lines (Figure 3).

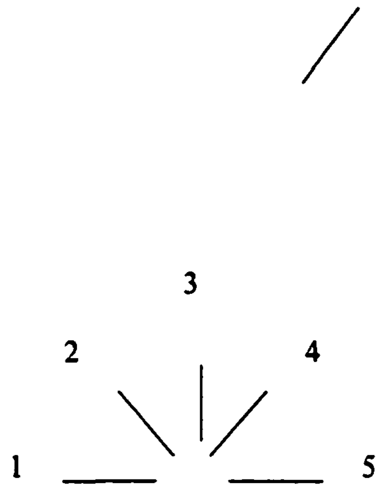


Figure 3. An example of the type of used in the visuospatial processing task.

Subjects were instructed to complete as many items as possible in 10-seconds. Two trials were completed. A binary system (correct, incorrect) was used to calculate response accuracy. The number of correct responses was tallied and averaged across the two trials. For this research study, speed was incorporated into the baseline task in order to match testing procedures with swallowing competition. However, when the test is administered in the standardized manner, speed is not a factor. As results might be compromised with the incorporation of a speed factor, results were not analyzed. Research has shown that the right hemisphere processes spatial orientation with impairments in judging line orientation associated with right hemispheric lesions (Benton, Hannay, & Varney, 1975; Warrington & Rabin, 1970).

Competition Tasks

Manual-Verbal Competition Paradigm

Subjects continuously repeated the three-word set (wolf-butterfly-duck) as they repetitively tapped with their finger. Two 10-second trials were completed with each hand. A 15-second rest period was provided between trials. The number of finger taps for each hand was obtained from the counter and averaged across the two trials. The verbal repetition was taped on an audiocassette recorder. The total number of word sets was obtained for each trial and averaged across the two trials.

Swallowing-Manual Competition Paradigm

Subjects continuously ingested diluted liquid barium through a straw (300 ml maximum volume) as they repetitively tapped with their finger. Two 10-second trials were completed with each hand. A 15-second rest period was given between each trial. The amount of liquid ingested during each swallowing period was obtained by measuring the amount not swallowed and subtracting this from the initial total (300 ml). The number of swallows during continual ingestion across all conditions was analyzed using the video recordings and was averaged across trials. The volume per swallow was calculated by dividing the total amount ingested during each 10-second period by the number of swallows with averaging across the two trials. The number of finger taps for each hand was obtained from the counter and averaged across trials.

Swallowing-Language Competition Paradigm

Subjects simultaneously silently repeated the three-word set (wolf-butterfly-duck) continuously as they ingested diluted liquid barium (maximum volume, 300 ml).

That is, the subjects did not vocalize the words during this condition; rather, they were instructed to rapidly and repeated think the three word set. Two 10-second trials were completed with a 15-second rest period between trials. Confirmation of silent repetition was ascertained after each trial. The amount of liquid ingested during each swallowing period was obtained by measuring the amount not swallowed and subtracting this from the initial total (300 ml). The number of swallows during continual ingestion across all conditions was analyzed using the video recordings and was averaged across trials. The volume per swallow was calculated by dividing the total amount ingested during each 10-second period by the number of swallows with averaging across the two trials.

Swallowing-Line Orientation Competition Paradigm

The newly recruited subjects (old = 17, young = 6) continually ingested diluted liquid barium through a straw (maximum volume, 300 ml) as they simultaneously silently matched line stimuli to the identical slope in a "sun ray" of lines. Subjects were instructed to think of the answer but not vocalize it. Stimuli were presented at a rate of every three seconds for a total of four stimuli presented in each of the two 10-second trials. A 15-second rest period was provided between trials. Confirmation of the visuospatial task performance was ascertained after each trial. The amount of liquid ingested during each swallowing period was obtained by measuring the amount not swallowed and subtracting this from the initial total (300 ml). The number of swallows during continual ingestion across all conditions was analyzed using the video recordings and was averaged across trials. The volume per swallow was calculated by dividing the

total amount ingested during each 10-second period by the number of swallows with averaging across the two trials.

Reliability

Inter- and intrarater reliabilities were completed for patterns of movement of the HLC, location of the leading edge of the bolus at onset of maximum hyolaryngeal excursion, and scoring of airway invasion using the Penetration-Aspiration Scale. Reliability was assessed for each swallow across the two 10-second trials in 12 randomly selected subjects (young = 6, old = 6) for a total of 223 analyzed swallows. For airway position and bolus placement, rules for scoring were established with a speech pathologist with extensive research experience in examining movement patterns. She then completed interrater reliability measures on the pilot data. These methods were then taught to a graduate student who completed interrater reliability measures for the newly recruited subjects. Interrater reliability for the airway invasion using Penetration-Aspiration Scale scores was completed by an expert speech pathologist who designed the scale.

Intrarater reliability was assessed at a later date for the same subjects originally selected for interrater reliability by having the investigator rescore the same three swallowing parameters. Kappa coefficients were completed between the investigator's initial scores and the interraters scores and between the investigator's initial scores and the second scores for all swallows across the two trials for the 12 subjects. A kappa of .60 was the minimal acceptance for inter- and intrarater reliabilities (Gelfand & Hartmann, 1975), with a kappa of .80 indicating good reliability (Landis & Koch, 1977).

RESULTS

All values are reported as estimated marginal means ± standard error unless otherwise stated. An alpha level of .05 was required for significance on all analyses.

Experiment I: Swallowing Physiology of Continuous Straw Drinking

Reliability

Kappa coefficients of agreement between raters on measures of HLC movement patterns, location of the leading edge of the bolus at swallow onset, and scoring of airway invasion using the Penetration-Aspiration Scale are shown in Table 4. All measures met the a priori criteria of $\kappa > .60$. The only reliability measure that did not reach the desired level of $\kappa > .80$ ($\kappa = .685$ for Penetration-Aspiration Scale interrater reliability) corresponded to 94.6% agreement between raters and was better than the reliability reported by Rosenbek et al. (1996) in their original paper.

Table 4. Interrater and intrarater reliability data using kappa coefficients.

Parameter	Interrater Reliability	Intrarater Reliability
HLC movement pattern	1.000*	1.000*
Bolus location	.968*	.968*
Penetration-Aspiration Score	.685**	.853*

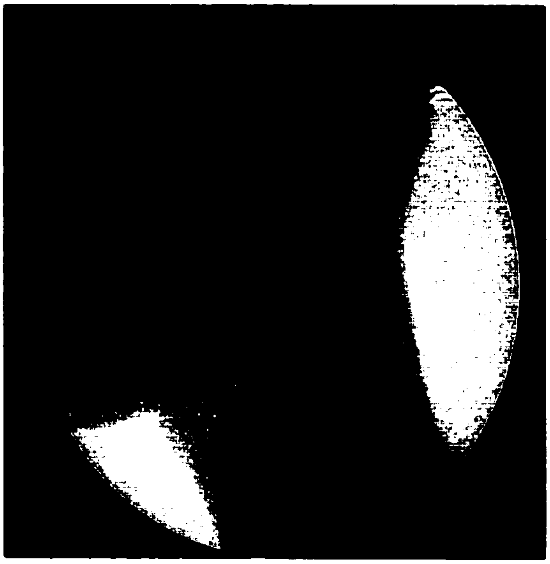
*Reliability exceeded $\kappa = .80$. **Reliability met the minimal acceptance of $\kappa = .60$

HLC Movement Patterns

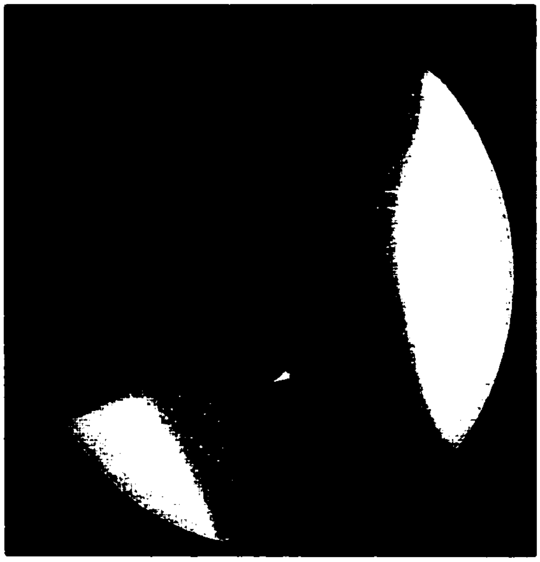
This question addressed the movement patterns of the HLC and the relationship of age on these movement patterns. Analysis of HLC movement characteristics revealed three distinct patterns of movement during sequential straw swallowing: 1) an opened laryngeal vestibule between swallows, 2) a closed laryngeal vestibule between

swallows, and 3) variable opening and closing of the laryngeal vestibule between swallows. Opening of the laryngeal vestibule between swallows with the epiglottis returning to upright was observed in 19 of 38 (50%) subjects (Figure 4). Continued closure of the laryngeal vestibule between swallows with the epiglottis remaining inverted was observed in 17 of 38 (45%) subjects (Figure 5). A mixed movement pattern, characterized by interchangeable opened and closed patterns, was observed in 2 of 38 (5%) subjects. None of the older subjects demonstrated a mixed movement pattern. HLC movement pattern was not significantly related to age group ($\chi^2(2) = 2.91$, $p = .234$; Figure 6).

To determine if the number of swallows and the volume per swallow were related to HLC movement pattern and age, a multivariate analysis of variance (MANOVA) was completed with Age (old, young) and HLC Movement Pattern (opened, closed, mixed) as the between subjects factors and Number of Swallows and and Volume per Swallow as the dependent variables. The MANOVA indicated that there were significant multivariate main effects of Age (Wilks' Lamda = .76, $F[2,32] = 4.93$, $p = .014$) and HLC Movement Pattern (Wilks' Lamda = .62, $F[4,64] = 4.35$, $p = .004$). The Age by HLC Movement Pattern interaction was not significant ($p > .05$). Univariate tests on the independent variables revealed significant differences for Number of Swallows but not Volume per Swallow. The young subjects swallowed significantly more frequently than did the old ($F[1,33] = 9.03$, $p = .005$); however, there was no significant difference between age groups in the volume per swallow ($p > .05$; Table 5).



Picture A



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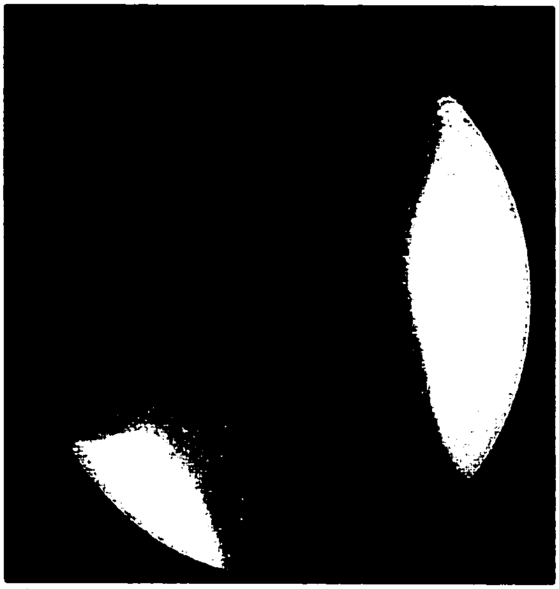
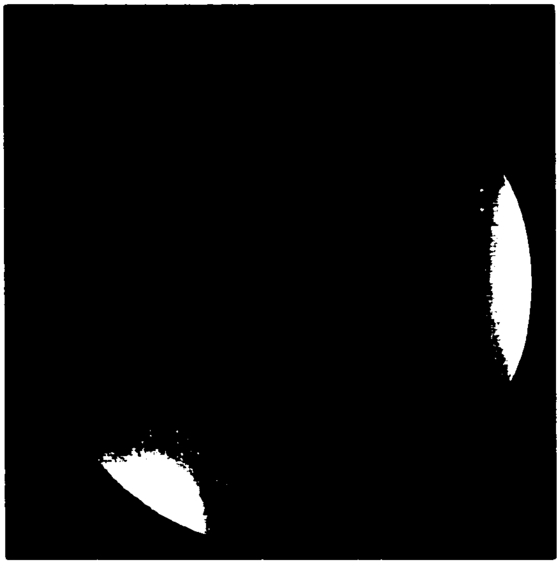
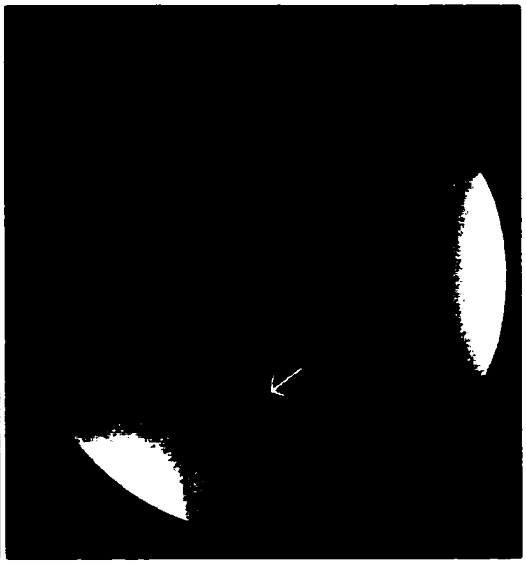


Picture C

Figure 4. Opened hyolaryngeal complex movement pattern. A. During the 10-second swallow sequence. A bolus of barium is in the oral cavity with the laryngeal vestibule opened and the epiglottis upright. B. Onset of the pharyngeal swallow. The leading bolus edge (arrow) is inferior to the valleculae with continued opening of the laryngeal vestibule. C. After the swallow. The next bolus of barium is in the oral cavity with return of the epiglottis to upright and opening of the laryngeal vestibule.



Picture A



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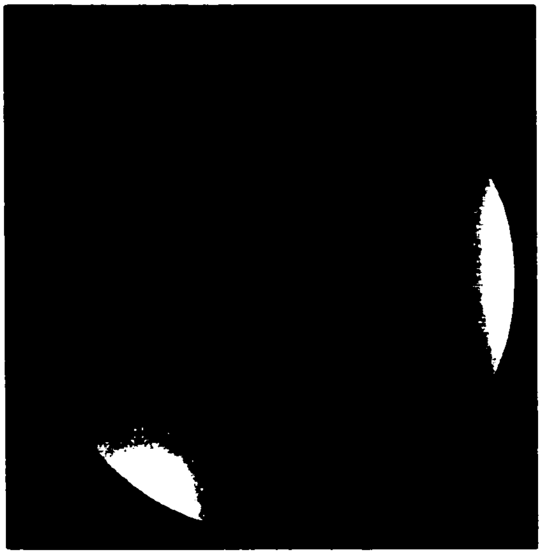


Picture C

Figure 5. Closed hyolaryngeal complex movement pattern. A. During the 10-second swallow sequence. A bolus of barium is in the oral cavity with closure of the laryngeal vestibule and the epiglottis remaining inverted. B. Onset of the pharyngeal swallow. The leading bolus edge (arrow) is in the hypopharynx with continued closure of the airway entrance. C. After the swallow. The next barium bolus is in the oral cavity with continued epiglottic inversion and closure of the laryngeal vestibule.

Significantly fewer swallows occurred with an opened laryngeal vestibule, as compared to a closed or mixed HLC movement pattern ($F[2,33] = 7.08$, $p = .003$). Volume per Swallow did not vary significantly across HLC movement patterns ($p > .05$, Table 6).

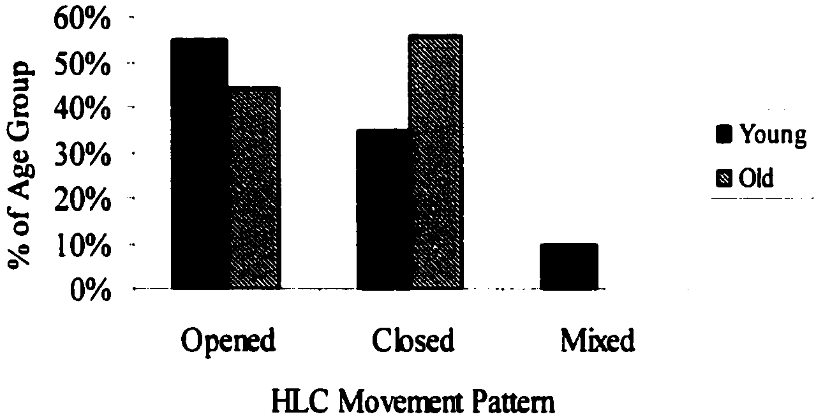


Figure 6. Percent of subjects in each age group (young, old) demonstrating one of the three hyolaryngeal complex (HLC) movement patterns (opened, closed, mixed).

Table 5. Estimated marginal means (standard errors) for swallowing measures (number of swallows and volume [V] per swallow) across the two age groups (old, young). Volume is expressed in milliliters.

Swallowing Measure	Age Group	
	Young	Old
Number	10.12 (.57)	8.02 (.47)
V/Swallow	12.42 (1.70)	12.87 (1.41)

Table 6. Estimated marginal means (standard errors) for swallowing measures (number of swallows and volume [V] per swallow) across the three HLC movement patterns (opened, closed, mixed). Volume is expressed in milliliters.

Swallow Measure	HLC Movement Pattern		
	Opened	Closed	Mixed
Number	7.73 (.46)	10.31 (.49)	10.25 (1.41)
V/Swallow	10.33 (1.38)	12.61 (1.47)	17.11 (4.21)

Leading Bolus Edge Location at Swallow Onset

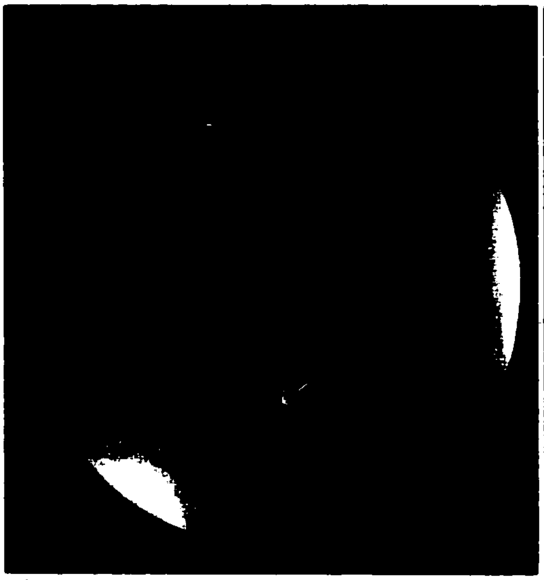
This question was addressed to determine the location of the leading bolus edge (superior to the valleculae, level with the valleculae, inferior to the valleculae) at onset of maximum HLC movement during sequential drinking and to determine the relationship of age on the bolus location.

Twenty-five of the 38 subjects (66%) consistently demonstrated initiation of maximum hyolaryngeal excursion with the leading bolus edge inferior to the valleculae (Figure 7A), and 7 of the 38 subjects (18%) consistently demonstrated the leading bolus edge to be superior to the valleculae at swallow onset (Figure 7B). Of the remaining 6 subjects, 2 of 38 (5%) demonstrated bolus placement to be at the level of the valleculae (Figure 7C) and 4 of 38 (11%) demonstrated an inconsistent leading edge location at swallow onset. Age group was not significantly related to location of the leading edge of the bolus at swallow onset ($\chi^2(3) = 2.55$, $p = .467$) (Figure 8).

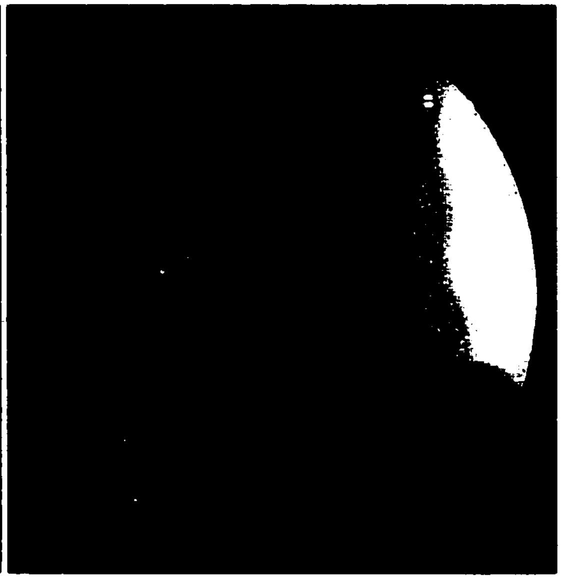
Relationship between Age, HLC Movement Patterns, and Bolus Locations

Hierarchical loglinear analysis was used to evaluate the relationships among HLC movement pattern (opened, closed), leading bolus edge location at swallow onset (superior to the valleculae, level with the valleculae, inferior to the valleculae), and age group (young, old). Swallow frequencies are shown in Table 7.

A backward elimination method was used to identify the independent variables and the relationships among the independent variables that significantly participated in the model. The generated model included the association between age and HLC



Picture A



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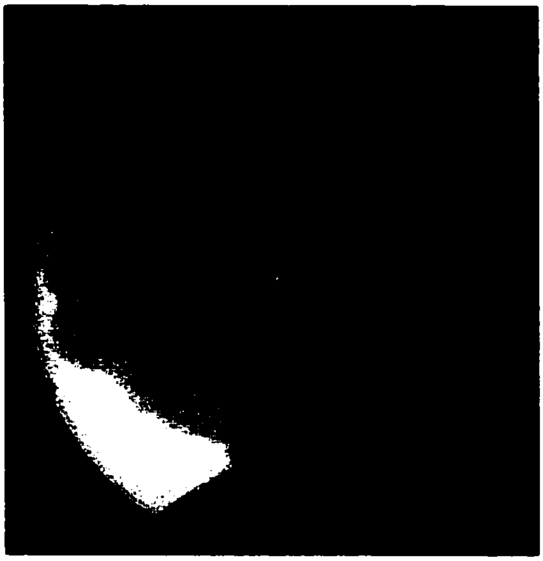


Picture C

Figure 7. Leading bolus edge location at onset of maximum hyolaryngeal elevation. A. The leading edge (arrow) is inferior to the valleculae at swallow onset. B. The leading edge (arrow) is superior to the valleculae at swallow onset. The bolus in the hypopharynx is stasis from the previous swallow. C. The leading edge (arrow) is level with the valleculae at swallow onset.

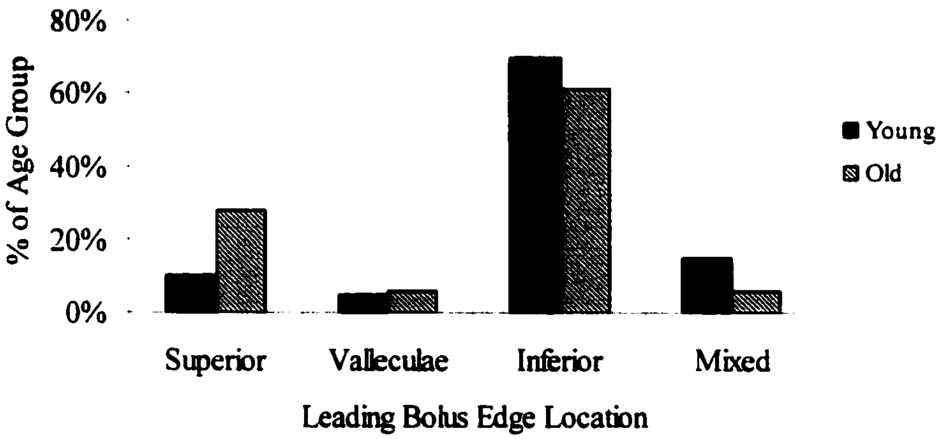


Figure 8. Percent of subjects in each age group (young, old) demonstrating one of the four leading bolus edge locations (superior to the valleculae, level with the valleculae, inferior to the valleculae, mixed location pattern).

Table 7. Number of swallows (% of age group) are shown across levels of HLC movement pattern (opened, closed), location of leading bolus edge at swallow onset (superior, valleculae, inferior), and age group (old, young).

	Age Group			
	Young		Old	
Bolus Location	Opened	Closed	Opened	Closed
	n (%)	n (%)	n (%)	n (%)
Superior	67 (30)	2 (1)	84 (59)	1 (1)
Valleculae	51 (22)	6 (4)	25 (18)	7 (5)
Inferior	108 (48)	155 (95)	33 (23)	141 (94)

movement pattern, the association between age and bolus location, and the association between HLC movement pattern and bolus location. The predicted cell frequencies did not differ significantly from the observed frequencies (Likelihood ratio $\chi^2(2) = 2.79$, p = .248), and removal of any of the three associations significantly reduced the fit of the model. These associations can be characterized as follows:

For HLC movement pattern, the odds ratio of the young having an opened laryngeal vestibule at the start of each swallow, as opposed to a closed laryngeal

vestibule, was 1.39:1. For the old, the odds ratio of having an opened laryngeal vestibule, as opposed to a closed vestibule, was .95:1. Thus, the young were more than 1.46 times more likely to have an opened versus closed laryngeal vestibule at the start of each swallow as compared to the old (Table 8).

Table 8. Number of swallows (% of age group) are shown across levels of HLC movement pattern (opened, closed) and age (old, young).

HLC Movement Pattern	Age Group	
	Young	Old
	n (%)	n (%)
Opened	226 (58)	142 (49)
Closed	163 (42)	149 (51)

For leading bolus edge location at swallow onset, the odds ratio of the young having the bolus inferior to the valleculae as opposed to level with the valleculae or superior to the valleculae was 2.09:1. In the elderly, the odds ratio of having the bolus inferior to the valleculae as opposed to level with or rostral to the valleculae was 1.49:1. Thus, at the onset of the pharyngeal swallow, the young were 1.40 times more likely to have the bolus in the hypopharynx at swallow onset as compared to the old (Table 9).

When examining the relationship between HLC movement pattern and bolus location, for an opened laryngeal vestibule, the odds ratio of the leading bolus edge being in the hypopharynx as opposed to rostral to this location was .62:1. For a closed laryngeal vestibule, the odds ratio of the leading edge being in the hypopharynx as opposed to rostral to this level was 18.5:1. Thus, when the laryngeal vestibule was closed at the start of each swallow, the leading bolus edge was 29.84 times more likely to be in the hypopharynx as compared to an opened laryngeal vestibule (Table 10).

Table 9. Number of swallows (% of age group) is shown across levels of leading bolus edge location (superior, valleculae, inferior) and age (old, young).

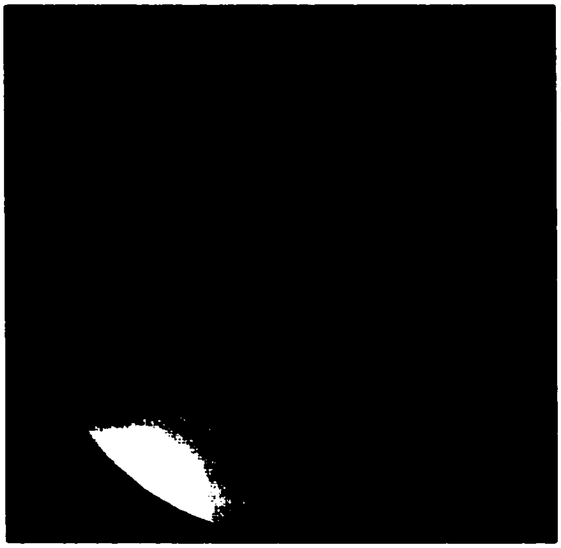
Bolus Location	Age Group: Young	Age Group: Old
	n (%)	n (%)
Superior	69 (18)	85 (29)
Valleculae	57 (15)	32 (11)
Inferior	263 (67)	174 (60)

Table 10. Number of swallows (% of HLC movement pattern) is shown across levels of leading bolus edge location (superior, valleculae, inferior) and HLC pattern (opened, closed).

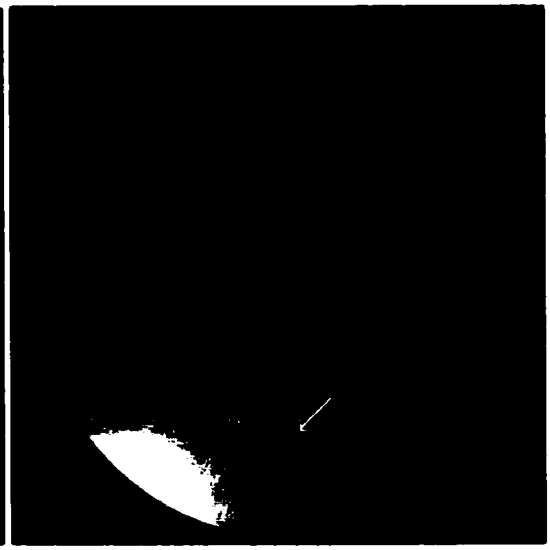
Bolus Location	HLC Movement Pattern: Opened	HLC Movement Pattern: Closed
	n (%)	n (%)
Superior	151 (41)	3 (1)
Valleculae	76 (21)	13 (4)
Inferior	141 (38)	296 (95)

Relationship between Age, Bolus Aggregation, and HLC Movement Pattern

Bolus aggregation was evident in a total of 11 of 38 (29%) subjects (Table 11) for a total of 42 (6%) swallows out of 680 total swallows (Figure 9). Hierarchical loglinear analysis was used to evaluate the relationship among bolus aggregation, HLC movement pattern, and age group. A backward elimination method was used to determine the independent variables and relationships among the independent variables that significantly participated in the model. The generated model included the association between bolus aggregation and age. Cell frequencies predicted using this model did not differ significantly from the observed frequencies (Likelihood $\chi^2(4) = 2.34$, $p = .673$), and removal of this association significantly reduced the fit of the model. The odds ratio of bolus aggregation occurring in the young was .82:1, while the



Picture A



Picture B

Picture C

Picture D

Figure 9. A. The barium bolus is in the oral cavity. B. The bolus has been transferred into the pharynx (arrow) as more barium is being reloaded into the oral cavity. C. The next bolus is propelled into the pharynx (arrow) as another bolus is loaded into the oral cavity. D. The pharyngeal swallow is triggered after the multiple occurrences of oral filling and pharyngeal transfer.

odds of bolus aggregation occurring in the old was .12:1. Thus, the young were 4.67 times more likely to demonstrate bolus aggregation as compared to the old.

Table 11. Number of subject (% of age group) demonstrating bolus aggregation.

Bolus Aggregation	Age Group: Young	Age Group: Old
	n (%)	n (%)
Yes	9 (45)	2 (11)
No	11 (55)	16 (89)

Relationship between Age, Swallowing Parameters and Airway Invasion

The frequency of Penetration-Aspiration Scale scores across all swallows (n = 680) between the two age groups is shown in Table 12. Airway invasion occurred in 103 of the total 680 swallows (15%). Of the 389 swallows completed by the young subjects, 27 (7%) were penetrated. For the older subjects, 75 of 291 total swallows (26%) were penetrated and only one (< 1%) was aspirated.

Seven of 20 (35%) of the young subjects received a score of 2 (penetration with clearing) on some swallows, with only one of these subject also receiving a score of 3 (penetration without clearing) for some swallows. The remaining young subjects received a score of 1 on all swallows across the two 10-second trials. In contrast, 12 of 18 (67%) of the older subjects demonstrated airway invasion. Ten older subjects scored 2 on some swallows, eight subjects received a score of 3 on some swallows, two subjects demonstrated TVC contact of contrast (scores 4-5), and one subject aspirated (score 7, unsuccessful attempts to clear the aspirate) on one swallow (Figure 10).

Table 12. The frequency of occurrence (% of swallows) by age group for each score on the Penetration-Aspiration Scale.

Scale Score	Age Group: Young n (%)	Age Group: Old n (%)
1	362 (93)	215 (74)
2	21 (5)	33 (11)
3	6 (2)	32 (11)
4		3 (1)
5		7 (2)
7		1 (<1)

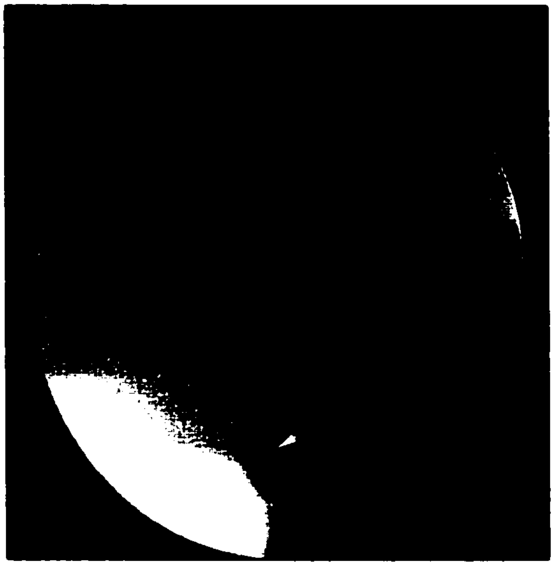


Figure 10. An example of aspiration. The arrow designates the bolus in the trachea.

Scores were averaged across trials and swallows for each subject to determine each subject's average score. Correlation analysis revealed a significant relationship between age and the average Penetration-Aspiration Scale score ($\underline{r}$ = .460, $\underline{p}$ = .004, Figure 11). Thirteen of 20 young subjects (65%) obtained an average score of 1 on the Penetration-Aspiration Scale, whereas six of 18 older subjects (33%) obtained an average score of 1. Note that none of the 8 subjects ≥ 70 years of age obtained an

average score of 1 across all trials. This indicates that there was at least one instance, if not more, of airway invasion during the two 10-second swallowing trials for all subjects ≥ 70 years of age.

To test the relationship among airway invasion, HLC movement pattern, leading bolus edge location at swallow onset, and age on these variables, a hierarchical loglinear analysis was completed. Penetration-Aspiration Scale scores of 2-5 were classified as penetration, and scores 6-8 were classified as aspiration. A backward elimination method was used to determine which independent variable and relationships among the independent variable significantly participated in the model. The best model generated consisted of three associations: 1) age, bolus location, and airway invasion, 2) age, HLC movement pattern, and airway invasion, and 3) bolus location and HLC movement pattern (Likelihood ratio $\chi^2(10) = 6.32$, $p = .788$).

For the first association among age, bolus location, and airway invasion, the young subjects had an odds ratio of .09:1 of penetrating with the bolus in the hypopharynx at swallow onset and an odds ratio of .05:1 of penetrating with the bolus superior to this location. In the older subjects, the odds ratio of penetrating when the bolus was in the hypopharynx increased to .52:1, with an odds ratio of .16:1 for penetrating when the bolus was superior to this location. When comparing the odds of airway invasion between groups, the old were 5.78 times more likely to penetrate as compared to the young when the bolus was in the hypopharynx, and 3.2 times more likely to penetrate as compared to the young when the bolus was level to or above the valleculae (Table 13). There was only one instance of aspiration; thus; an odds ratio

was not generated. The aspiration occurred in an elderly subject, with the leading bolus edge in the hypopharynx at swallow onset.

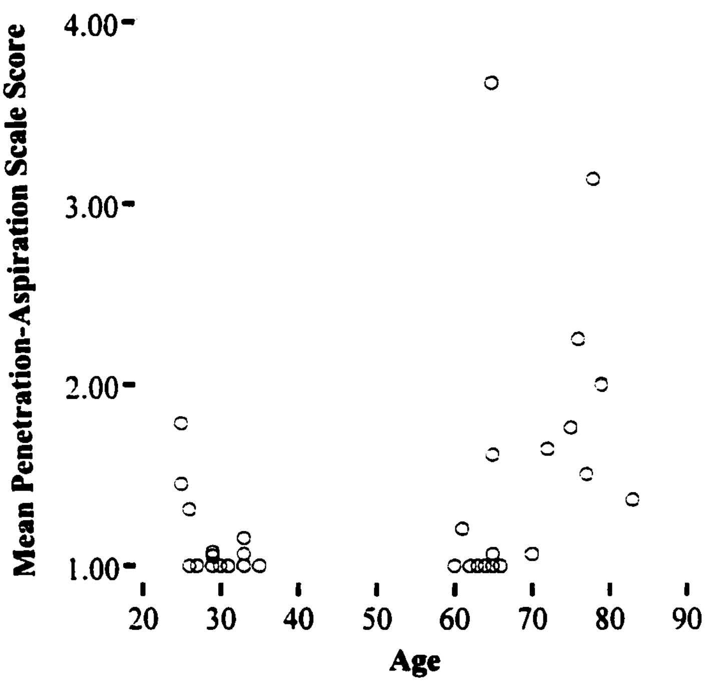


Figure 11. The scatterplot shows Penetration-Aspiration Scale scores averaged across all swallows and trials for each subject in the two age groups.

Table 13. The frequency of occurrences (% of age group) is shown across levels of bolus location (superior, valleculae, inferior), penetration (yes, no), and age group (old, young).

	Bolus Location					
	Superior		Valleculae		Inferior	
Penetration	Young	Old	Young	Old	Young	Old
	n (%)	n (%)	n (%)	n (%)	n (%)	n (%)
No	63 (91)	71 (84)	57 (100)	30 (94)	242 (92)	114 (66)
Yes	6 (9)	14 (16)	0	2 (6)	21 (8)	59 (34)

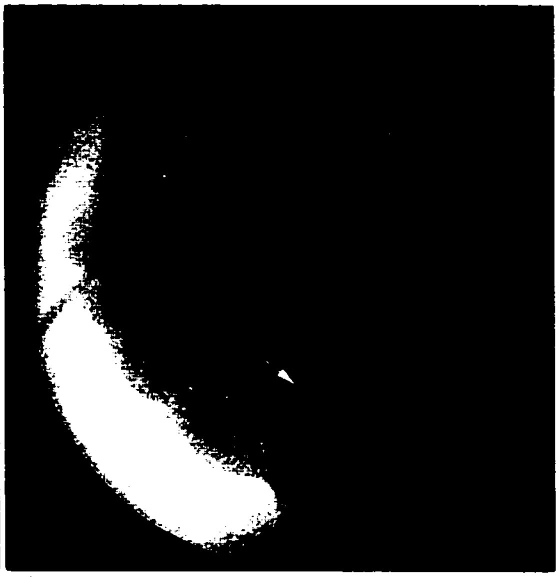
When examining the association of age, HLC movement pattern, and airway invasion, the odds ratio of the young demonstrating penetration with an opened laryngeal vestibule between swallows was .05:1, with the odds ratio increasing to .12:1

with a closed laryngeal vestibule between swallows. For the elderly, the odds ratio of penetration occurring with an opened laryngeal vestibule was .33:1, whereas the odds of penetration occurring with a closed vestibule were .37:1. Thus the old were 3.08 times more likely to demonstrate penetration with a closed laryngeal vestibule as compared to the young and were 6.6 times more likely to demonstrate penetration with an opened laryngeal vestibule as compared to the young (Table 14). The single instance of aspiration occurred in an elderly subject with an opened HLC movement pattern. (See Figure 12 for an example of a penetration with a closed laryngeal vestibule between swallows). The association of HLC movement pattern and bolus location variables was discussed previously with results under the section Relationship of HLC Movement Pattern and Bolus Location, but briefly, when the laryngeal vestibule was closed at the start of each swallow, the leading bolus edge was 29.84 times more likely to be in the hypopharynx as compared to an opened laryngeal vestibule.

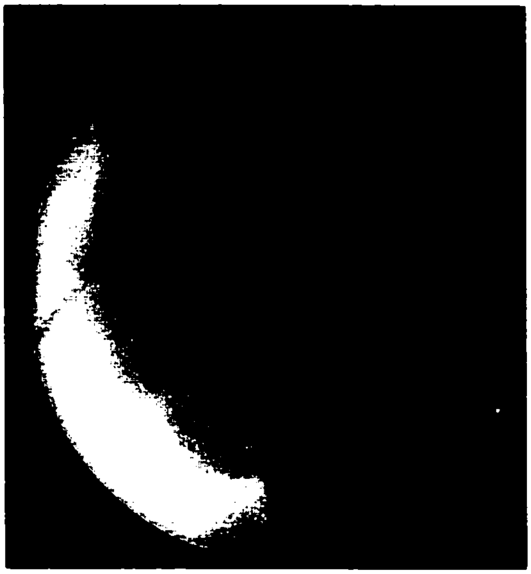
Table 14. The frequency of occurrences (% of age group) is shown across levels of HLC movement pattern (opened, closed), penetration (yes, no), and age group (old, young).

	Group			
	Young		Old	
Penetration	Opened	Closed	Opened	Closed
	n (%)	n (%)	n (%)	n (%)
No	216 (96)	146 (90)	106 (75)	109 (73)
Yes	10 (4)	17 (10)	35 (25)	40 (27)

Picture A



Picture B



Picture C

Figure 12. An example of penetration with a closed laryngeal vestibule. A. The laryngeal vestibule is closed without any visible air space. B. Contrast enters the laryngeal vestibule (arrow). C. The contrast is cleared as the laryngeal vestibule remains closed and the epiglottis remains inverted.

Experiment II: Swallowing Lateralization Using a Dual Task Paradigm

Age Effects on Baseline Tasks

Mean rates and volumes for each of the baseline tasks (finger tapping right hand, finger tapping left hand, word repetition series, number of swallows, and volume per swallow) for both age groups are shown in Table 15. A MANOVA was completed to determine if performances on baseline motor, language and swallowing tasks varied across age groups. Age (old, young) was the between subjects independent variable. The baseline tasks of Finger Tap Right, Finger Tap Left, Repetition, Number of Swallows, and Volume per Swallow were the dependent variables. The MANOVA indicated that there was a significant multivariate main effect of Age (Wilks' Lamda = .49, $\underline{F}[5,32] = 6.69$, $\underline{p} = .000$). At the univariate level, significant differences between the age groups were identified for Finger Tap Right ($\underline{F}[1,36] = 8.78$, $\underline{p} = .000$), Finger Tap Left ($\underline{F}[1,36] = .5.4$, $\underline{p} = .024$, Repetition ($\underline{F}[1,36] = 31.90$, $\underline{p} = .000$) and Number of Swallows ($\underline{F}[1,36] = 5.04$, $\underline{p} = .031$). The rate for these tasks significantly decreased for the elderly subjects as compared to their young counterparts.

Table 15. Estimated marginal means (standard errors) for average rates and volumes across groups.

	Age Group	
Condition	Young (n=20)	Old (n=18)
Right Hand Tapping**	54.95 (1.76)	47.36 (1.86)
Left Hand Tapping*	47.52 (1.57)	42.17 (1.65)
Repetition**	11.50 (.31)	8.94 (.33)
Number of Swallows*	9.87 (.51)	8.19 (.54)
Volume Per Swallow	10.91 (1.40)	13.20 (1.48)

*p < .05, **p < .01

There was no statistically significant difference for Volume per Swallow ($F[1,36] = 1.26$, $p = .270$), although the older subjects averaged approximately 2 ml more per swallow than the younger subjects. Overall, the average total volume swallowed across the two 10-second trials was similar across the two groups (young = 105.38 ± 14.17; old = 112.36 ± 14.93).

Data was further inspected within subject by group to determine if all older subjects increased their volume per swallow. Scatterplots for individual averages of the number of swallows and the volume per swallow across the two 10-second trials are shown in Figures 13 and 14. Inspection of the volume per swallow data (Figure 14) revealed two clusters of volume intake for the older group: ≥ 15 ml and ≤ 10 ml. These two clusters were identified as: 1) higher volume per swallow group and 2) lower volume per swallow group. As evident by the scatterplot, 8 of 18 (44%) older subjects and 3 of 20 (15%) younger subjects were in the higher volume per swallow group. In contrast, 10 of 18 (56%) old and 17 of 20 (85%) young subjects were in the lower volume per swallow group. To identify patterns of intake within the groups, post hoc analysis was completed to determine the number of swallows to volume per swallow ratio within subject. Three intake patterns were identified: 1) increased number of swallows relative to volume per swallow, 2) equal number of swallows relative to volume per swallow, and 3) increased volume per swallow relative to number of swallows (Table 16). All three intake patterns were evident in the young subjects in the lower volume per swallow group. The old subjects in the lower volume per swallow group demonstrated only two of the intake patterns. None of these old subjects

displayed an increased number of swallows relative to the volume per swallow. The increased volume per swallow relative to the number of swallows was the only pattern of intake evident for young and old subjects in the higher volume per swallow group.

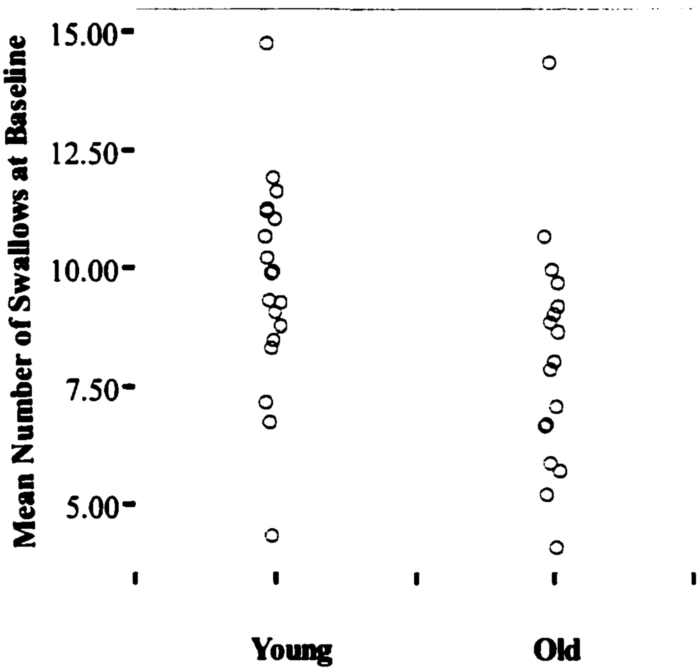


Figure 13. The scatterplot shows the number of swallows averaged across the two trials for each subject in the two age groups.

Table 16. Number of subjects (% of age) are shown across intake pattern (increased number of swallows relative to volume per swallow, equal number of swallows and volume per swallow, increased volume per swallow relative to number of swallows), group (low volume per swallow, high volume per swallow), and age (young, old).

	Intake Patterns		
Group	↑Number/Volume	Number=Volume	↑Volume/Number
Low Volume			
Young	9 (53)	2 (12)	6 (35)
Old	0	7 (70)	3 (30)
High Volume			
Young	0	0	3 (100)
Old	0	0	8 (100)

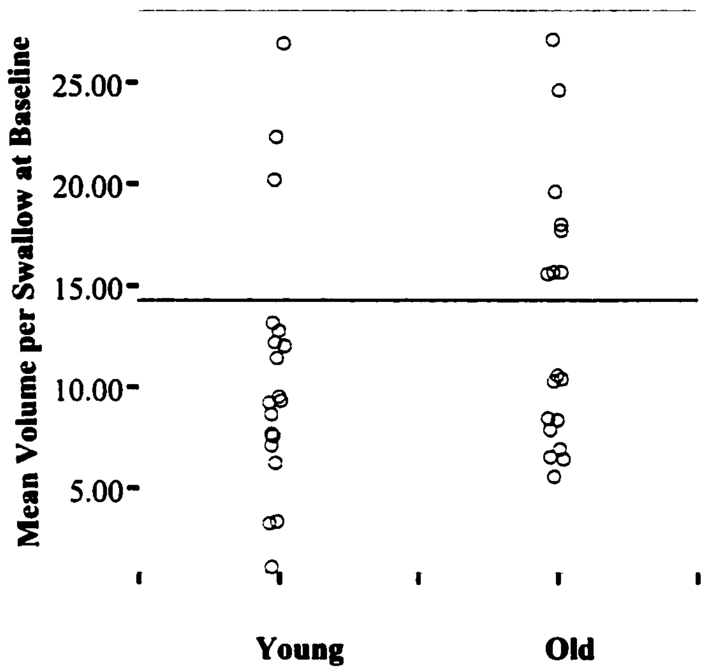


Figure 14. The scatterplot shows the volume per swallow averaged across all swallows and trials for each subject in the two age groups. The line separates the clusters identified in the group of older subjects.

Verbal-Manual Interference

Mean rates of the motor tasks (finger tapping right, finger tapping left) at baseline and with verbal competition for both age groups are shown in Table 17.

Table 17. Estimated marginal means (standard errors) for finger tapping rates at baseline and with language interference across age groups.

	Young (n=20)		Old (n=18)	
Hand	Baseline	Interference	Baseline	Interference
Right	54.95 (1.76)	50.63 (1.58)	47.36 (1.86)	43.14 (1.66)
Left	47.53 (1.57)	43.80 (1.67)	42.17 (1.65)	41.06 (1.76)

A three-way mixed analysis of variance (ANOVA) was completed to determine if concurrent repetition impacted motor performance and if the interference effect varied

across hands and across age groups. Age (old, young) served as the between subjects factor. Finger Tapping Hand (right, left) and Interference (baseline, repetition) were the repeated measures factors. Overall, participants tapped significantly faster with the right hand (49.02 ± 1.07) than the left hand (43.64 ± 1.04; $F[1,36] = 40.78$, $p = .000$). Finger tapping rates significantly decreased with the interference task of repetition (44.65 ± 1.08) as compared to baseline tapping rates (48.00 ± 1.07; $F[1,36] = 12.69$, $p = .001$). The Hand by Interference interaction was not significant ($p > .05$, Table 18).

Table 18. Estimated marginal means (standard errors) for tapping rate at baseline and with language interference.

	Interference	
	Baseline	Repetition
Right	51.16 (1.28)	46.88 (1.15)
Left	44.85 (1.14)	42.43 (1.21)

The younger subjects (49.22 ± 1.33) tapped significantly faster than the older subjects (43.43 ± 1.40; $F[1,36] = 8.99$, $p = .005$). However, this hand asymmetry varied significantly across age groups, as evidenced by a significant Hand by Age interaction ($F[1,36] = 4.28$, $p = .046$). Specifically, tapping asymmetry was greater for young than old (Table 19). The Age by Interference interaction was not significant ($p > .05$).

Table 19. Estimated marginal means (standard errors) for tapping rate.

	Age Group	
	Young	Old
Right	52.79 (1.47)	45.25 (1.55)
Left	45.66 (1.43)	41.61 (1.51)

The effect of motor interference on language performance was also analyzed. Mean rates of repetition of the three-word set (wolf, butterfly, duck) at baseline and with motor interference (finger tap right, finger tap left) are shown in Table 20.

Table 20. Estimated marginal means (standard errors) for the repetition at baseline and with motor interference.

	Age Group	
Interference	Young	Old
Baseline	11.50 (1.49)	8.94 (1.27)
Finger Tap Right	11.83 (1.21)	9.06 (1.37)
Finger Tap Left	11.29 (1.17)	9.22 (1.27)

A two-way mixed ANOVA was completed to determine if the concurrent motor task impacted repetition and if the interference effect varied across age groups. Age (old, young) served as the between subjects factor. Interference (baseline, finger tapping right, finger tapping left) was the repeated measures factor. The main effect of Age was significant ($F[1,36] = 44.39$, $p = .000$), with the young ($11.54 \pm .25$) repeating more three-word sets than the old ($9.07 \pm .27$). The main effect of Interference and the Interference by Age interaction were not significant ($p > .05$).

<u>Effects of Interference on Swallowing</u>

Mean rates and volumes for swallowing at baseline and with motor and language interference for both age groups are shown in Table 21. To determine the effects of competing tasks on swallowing across age groups, a mixed MANOVA was completed. Swallowing Measure (number of swallows, volume per swallow) was the dependent variable. Age (old, young) was a between subjects factor, and Interference (baseline, finger tapping right, finger tapping left, and silent repetition) was a repeated measures

factor. At the multivariate level, there were significant main effects for Age (Wilks' Lamda = .80, $\underline{F}[2,35] = 4.40$, $\underline{p} = .020$) and Interference (Wilks' Lamda = .57, $\underline{F}[6,31] = 3.85$, $p = .006$). The Age by Interference interaction was not significant ($\underline{p} > .05$).

Table 21. Estimated marginal means (standard errors) for the interference task and swallowing measures across groups. Volume is stated in milliliters.

Swallowing Measure	Age Group: Young	Age Group: Old
Volume per Swallow		
Baseline	10.91 (1.40)	13.20 (1.48)
Right Tapping	11.51 (1.46)	13.26 (1.54)
Left Tapping	11.33 (1.51)	12.61 (1.59)
Repetition	9.41 (1.26)	11.46 (1.33)
Number of Swallows		
Baseline	9.86 (.51)	8.19 (.54)
Right Tapping	9.18 (.46)	7.72 (.49)
Left Tapping	9.08 (.49)	7.64 (.51)
Repetition	9.90 (.49)	7.86 (.52)

Univariate tests revealed a significant difference between age groups for Number of Swallows ($\underline{F}[1,36] = 6.90$, $\underline{p} = .013$) but not for Volume per Swallow ($\underline{F}[1,36] = .918$, $\underline{p} = .347$). The younger subjects (9.51 ± .43) averaged 1.5 more swallows than the elderly subjects (7.85 ± .46).

A significant effect of Interference was found for both the Volume per Swallow ($\underline{F}[2.61,93.85] = 4.83$, $\underline{p} = .005$, Huynh-Feldt corrected degrees of freedom) and Number of Swallows ($\underline{F}[2.42,86.94] = 3.04$, $\underline{p} = .044$, Huynh-Feldt corrected degrees of freedom). To determine which interference type affected swallowing, post hoc pairwise comparisons were completed (Table 22). The Volume per Swallow was significantly lower with the silent repetition competing condition as compared to baseline

swallowing (p = .004), right hand finger tapping (p = .004), and left hand finger tapping (p = .024). The Number of Swallows was significantly lower with the competing conditions of finger tapping right hand (p = .034) and finger tapping left hand (p = .027) as compared to baseline.

Table 22. Estimated marginal means (standard errors) for interference task and swallowing parameter (number of swallows and volume per swallow). Volume is stated in milliliters.

	Interference			
Swallow	Baseline	Tap Right	Tap Left	Repetition
Number	9.03 (.37)$_{a}$	8.45 (.33)$_{b,c}$	8.36 (.35)$_{b,c}$	8.88 (.35)$_{a,c}$
Volume	12.05 (1.02)$_{a}$	12.38 (1.06)$_{a}$	11.97 (1.09)$_{a}$	10.43 (.91)$_{b}$

Means with like subscripts do not differ significantly at the .05 level.

Effects of the Higher Order Right Hemisphere Activating Task on Swallowing

Mean rates and volumes for swallowing at baseline and with visuospatial interference for both age groups are shown in Table 23. As only the newly recruited subjects completed this task (young = 6, old = 17), a separate mixed MANOVA was completed to determine the effects of a higher order right hemisphere activating task on swallowing across groups. Swallowing Measure (number of swallows, volume per swallow) was the dependent variable. The independent variables were Age (old, young), which was a between subjects factor, and Interference (baseline, visuospatial task), which was a repeated measures factor. At the multivariate level, there was a significant main effect of Interference (Wilks' Lamda = .65, $F[2,20] = 5.48$, $p = .013$). The main effect of Age and the Age by Interference interaction were not significant ($p > .05$). Univariate tests revealed a significant decrease in the Number of Swallows with

the visuospatial interference task (7.02 ± .54) as compared to baseline (8.57 ± .58; $F[1,21] = 11.49$, $p = .003$). During the 10-second trials, both old and young subjects averaged 1.5 fewer swallows with the visuospatial interference task as compared to baseline swallowing. The Volume per Swallow at baseline (11.59 ± 1.58) and during interference (10.63 ± 1.58) was not significantly different ($F[1,21] = 1.56$, $p = .226$).

Table 23. Estimated marginal means (standard errors) for swallowing measures at baseline and with visuospatial interference across groups.

	Age	
Swallowing Measures	Young	Old
Volume per Swallow		
Baseline	10.04 (2.72)	13.06 (1.62)
Visuospatial	8.66 (2.72)	12.61 (1.61)
Number of Swallows		
Baseline	9.00 (1.00)	8.15 (.59)
Visuospatial	7.50 (.92)	6.53 (.59)

Effects of Swallowing on Manual Performance

Mean tapping rates at baseline and with the interference task of swallowing are shown for both age groups in Table 24. To determine if finger tapping rates varied with swallowing, a three-way mixed ANOVA was completed with Age (old, young) as a between subjects factor, and Hand (left, right) and Interference (baseline, concurrent swallowing) as repeated measures factors. Right hand finger tapping rate (50.13 ± 1.54) was significantly faster than left hand finger tapping rate (44.51 ± 1.18; $F[1,36] = 39.16$, $p = .000$). Young subjects (50.12 ± 1.43) tapped significantly faster than the elderly (44.51 ± 1.56; $F[1,36] = 6.78$, $p = .013$). The effect of Interference approached significance ($F[1,36] = 2.96$, $p = .094$). Finger tapping rates during the swallowing

interference (46.43 ±1.22) were lower than compared to baseline tapping rates (48.00 ± 1.07). No interaction effects were detected ($p > .05$)

Table 24. Estimated marginal means (standard errors) for finger tapping rates at baseline and with swallowing interference across age groups.

	Young (n=20)		Old (n=18)	
Hand	Baseline	Swallowing	Baseline	Swallowing
Right	54.95 (1.76)	52.05 (1.85)	47.36 (1.86)	46.14 (1.95)
Left	47.53 (1.57)	45.95 (1.90)	42.17 (1.65)	42.39 (2.00)

DISCUSSION

The goals of this investigation were two-fold: 1) to examine and elucidate deglutitive biomechanics of sequential straw drinking and study the effects of normal aging on sequential swallowing, and 2) to study the cortical lateralization of swallowing using a dual task paradigm. The rationale of the first experiment stems from the fact that most normative data on swallowing biomechanics has been obtained from studies of single swallows. As healthy adults generally ingest consecutive liquid volumes, knowledge of swallowing biomechanics for sequential swallowing is crucial in order to distinguish between normal and abnormal deglutition. This is particularly critical in the study of the senescent swallow, as the elderly are more apt to present with dysphagia.

The results of the first investigation confirmed the findings of the pilot study concerning patterns of hyolaryngeal movement and bolus placement at swallow onset; that is, variability of a reflexive phenomenon, hyolaryngeal complex movement, exists. As such, the laryngeal vestibule can be either opened or closed between swallows during a continued sequence. Furthermore, unlike single swallows, the bolus is frequently in the hypopharynx at the start initiation of the pharyngeal swallow. This finding was evident for both young and old. Moreover, results were expanded by also focusing on airway invasion. Airway invasion, defined as penetration or aspiration, was evident in the young and old. While uncommon in the younger subjects, airway invasion occurred much more frequently in the older group. Unexpectedly, penetration occurred more often with a closed HLC movement pattern between swallows. These

results expand our knowledge of normal swallowing patterns and the effects on normal deglutition, and suggest greater variability in swallowing behaviors than previously described (Logemann, 1998; Martin et al., 1994; Robbins et al., 1992; Tracy et al., 1988). They also suggest possible risk indicators of penetration in the elderly who demonstrate more frequent airway invasion.

Lateralization of swallowing is controversial with varying opinions. Thus, the purpose of the second study was to further test this hypothesis using a method novel to swallowing: dual task paradigm. Results indicate both right and left cerebral hemisphere activation with swallowing. This was evident in that both of the higher order interference tasks (silent repetition, silent visuospatial processing) significantly decreased either the volume per swallow or the number per swallows as compared to baseline. Moreover, the motor task of finger tapping right and left hand significantly decreased the number of swallows as compared to baseline. Overall, these findings support the competition of resources model, which suggests that allocation of attentional or processing resources is compromised due to two tasks sharing resources within the same hemisphere. While results revealed aging effects on motor and language tasks as well as the number of swallows, an interference and age interaction never occurred for any of the tasks. Results also revealed three patterns of ingestion: 1) a greater number of swallows relative to the volume per swallow, 2) an equal number of swallows and volume per swallow, and 3) a greater volume per swallow relative to the number of swallows. Findings demonstrated that a subset of older subjects could maintain swallowing efficiency by increasing the volume per swallow. The remaining older

subjects did not demonstrate an increase in volume, suggesting a potential for risk of decreased nutrition or possible increased risk of aspiration. Results of both experiments will be discussed in detail.

Experiment I: Swallowing Physiology of Continuous Straw Drinking

HLC Movement Patterns

Three patterns of HLC movement pattern during sequential swallowing were predicted in healthy young and old adults. This prediction was supported by the data as three patterns of HLC movement were observed. The patterns of HLC movement were: 1) opened laryngeal vestibule between swallows, 2) closed laryngeal vestibule between swallows, and 3) interchangeable opening and closing of the laryngeal vestibule during the swallow sequence. Fifty percent of the subjects presented with an opened HLC pattern, 45% demonstrated a closed pattern, and only 5% demonstrated a mixed pattern with no significant difference among the movement patterns between the two age groups. Fewer consecutive swallows were completed when the laryngeal vestibule was opened between swallows (open HLC pattern). Conversely, 2.5 more swallows were completed when the laryngeal vestibule remained closed between swallows. The younger adults had a faster rate of swallowing (i.e., greater number of consecutive swallows in 10 seconds) compared to older adults, but the volume per swallow did not differ between the groups. The results confirm the findings of the pilot study and expand them by including older adults. This finding is provocative in that it implies a greater degree of variability in deglutitive biomechanics than initially appreciated. This finding of variability in the movement patterns differs from previous research which

found that maintenance of HLC excursion to be a primary biomechanical component of sequential straw drinking (Martin et al., 1994). However, they reported opening of the laryngeal vestibule with respiration in some subjects. In the present study, an equal number of subjects presented with either a closed or opened HLC pattern. Respiration was not measured, so it is difficult to determine if apnea was maintained throughout the 10-second sequence in the subjects with an opened vestibule. No subject demonstrated an interruption in bolus loading and transfer, regardless of HLC movement pattern or age. Thus, one cannot infer that respiration occurred with an opened laryngeal vestibule. Future research elucidating the effects of HLC movement patterns on respiration during sequential swallowing is warranted.

A priori, it was posited that the older adults would present more commonly with an opened or mixed pattern in comparison to the younger adults. It was posited that muscular reserve would be inadequate in the older adults to maintain laryngeal closure during the 10-second swallowing trials. However, there were no age effects on HLC swallowing pattern. The elderly frequently demonstrated a closed pattern (56%), with no older subject demonstrating a predominately mixed pattern. It is unclear how much muscular effort is required to elevate the HLC complex and maintain this partial elevation during a sustained period, versus repeated elevation and lowering. From studies of single swallows, it has been noted that older adults can maintain HLC elevation for equal duration as their young counterparts (Robbins et al., 1992; Shaw et al., 1995) or for even greater duration (Rademaker et al., 1998). For the elderly, maintenance of laryngeal elevation throughout the sequence may accommodate for the

oncoming consecutive swallow and possibly slower pharyngeal bolus transit, which has been identified in the elderly during discrete swallows (Cook et al., 1994; Rademaker et al., 1998; Robbins et al., 1992). Rademaker et al. (1998) also noted increased duration of laryngeal closure (arytenoid to epiglottic base) as volume increased; this was particularly evident for the older adults. This pattern of continued laryngeal vestibule closure, particularly in the elderly, may be related to the continued sensory stimulation evident with sequential swallowing, which may result in extended airway protection. However, this closed movement pattern was not exclusive in older adults, as 44% of the older subjects demonstrated an opened pattern.

Leading Bolus Edge Location at Swallow Onset

When swallowing, the location of leading bolus edge at swallow onset can be divided into three regions: 1) superior to the valleculae, 2) level with the valleculae, and 3) inferior to the valleculae. During consecutive straw drinking, the majority of subjects (66%) demonstrated an overall leading bolus edge location to be inferior to the valleculae at onset of maximum hyolaryngeal excursion. As predicted a priori, there were no age effects on leading bolus edge location. These results confirm the findings of the pilot study and expand them to include healthy elderly adults. Studies that have investigated single swallows have consistently found that the placement of the bolus caudal to the ramus of the mandible to be uncommon in healthy adults (Robbins et al., 1992; Tracy et al., 1989) and may be associated with "delayed" pharyngeal swallow (Logemann, 1998). The results of this study provide strong evidence that the location of the leading bolus edge differs in consecutive swallows, and it is not uncommon to see

the bolus caudal to the ramus of the mandible. Thus, the more distal location of the bolus at swallow onset seems to represent a normal variant. Nevertheless, the older adults did have an increased incidence of airway invasion with distal bolus placement as compared to the younger adults. Studies of adults with dysphagia have shown a correlation between aspiration and longer onsets of the evocation of the pharyngeal swallow (Perlman et al., 1994). Although, the authors did not report bolus location, it is well established that longer delays are associated with hypopharyngeal bolus placement. Further study is warranted to determine whether distal bolus location with sequential swallowing may interact with other variables such as advanced age and chronic medical disorders such as diabetes mellitus to increase the risk of penetration and aspiration. However, findings of the present study strongly suggest that hypopharyngeal bolus location is a normal feature of swallowing, at least in sequential swallowing. Yet, the older adults demonstrated a notably increased incidence of airway invasion as compared to the young with a distal bolus placement. Thus, given other circumstances such as advanced age or diseases that can produce dysphagia, this distal bolus placement at swallow onset may be a risk factor for penetration and aspiration.

Recent studies, particularly of mastication, have identified extended pharyngeal dwell time in healthy adults (Dua et al., 1997; Palmer et al., 1992). Dua et al. (1997) found the epiglottic edge to be particularly sensitive for evocation of the pharyngeal swallow. Chi-Fishman and Sonies (2000) have also noted increased pharyngeal dwell time with sequential cup drinking, with a significant increase in duration of stage transition with sequential swallowing as compared to discrete swallows. While discrete

swallows were evoked within .09 seconds of onset of maximum HLC elevation, sequential swallows from a cup were evoked within .28 seconds. Thus, for discrete and consecutive swallows, all swallows were elicited within substantially less than 1 second of initiation of maximum HLC movement. While duration to onset of the pharyngeal swallow was not measured in the present study, post hoc review of the swallows indicated approximately 1-second difference between onset of maximum HLC movement for each subsequent consecutive swallow. This observation suggests that swallow onset was substantially less than one second for each swallow. Logemann (1998) suggests that a delay greater than 2 seconds in the onset of the pharyngeal swallow should be considered abnormal in discrete swallows. Rather than looking at location of the bolus to judge the normality of swallowing onset, perhaps duration should be the critical factor and if the duration exceeds a certain parameter, then the swallow onset may be judged as "delayed." However, given the known individual variability of normal swallowing, even the use of duration to note abnormality in swallowing onset must be carefully considered, particularly if other parameters are within normal limits.

The results support the importance of the hypopharynx in contributing to evocation of the pharyngeal swallow and indicate similarities between human and animal models. Research in experimental animals has found that fluid receptor sites for evocation of the pharyngeal swallow are located throughout the pharynx and larynx (Miller & Sherrington, 1916, Storey, 1968). In animals, inducement of the pharyngeal swallow occurs with the bolus in the valleculae and hypopharynx, with collection of

multiple boluses until swallow onset (for review, Thexton & Crompton, 1998). When examining all 680 swallows, 64% were caudal to the valleculae at swallow onset. This result suggests that multiple receptor sites within the pharynx must be stimulated to achieve an adequate threshold to induce a swallow (Miller, 1999). Poudreaux et al. (1996) suggested that the hypopharynx is crucial to the evocation of a protective swallow. With slow infusion of liquid directly into the pharynx, the authors noted that a pharyngeal swallow was only triggered when the bolus reached the hypopharynx. The present study suggests that the hypopharynx is critical in the evocation of sequential alimentary swallows in healthy young and old adults.

Can these findings of distal bolus placement at swallow onset be used to expand our interpretation of discrete swallows, particularly since this type of swallowing is generally studied in clinical populations? It is unclear, because comparisons of discrete and sequential swallowing have shown longer duration of stage transition for sequential swallows (Chi-Fishman & Sonies, 2000). However, the results of the current study demonstrate that there is considerable flexibility of the oropharyngeal swallowing system, and hypopharyngeal bolus location at swallow onset may not be pathological as once thought, unless aspiration is associated with this distal bolus placement.

Relationship between Age, HLC Movement Patterns, and Bolus Locations

When analyzing all swallows (n = 680) across all subjects, results revealed strong associations between: 1) HLC movement pattern and age, 2) leading bolus edge location and age, and 3) HLC movement pattern and leading bolus edge location. When comparing the relationship of age to HLC movement pattern, the young adults were

more likely to have opened (n = 226) rather than closed (n = 163) HLC movements. In contrast, the older adults were as likely to have opened (n = 142) as compared to closed (n = 149) movements. It is important to remember that all swallows were compared between the age groups.

It is unclear whether repeated elevation and hyolaryngeal lowering with an opened HLC movement pattern may be more effortful than maintaining laryngeal suspension associated with the closed pattern. Chi-Fishman & Sonies (2000) found that with a closed laryngeal vestibule between swallows there was “activation and partial deactivation” of the HLC complex. The larynx lowered slightly but not completely, as the epiglottis remained inverted. Intuititively, it would appear that energy would be wasted with continued regeneration of a complete movement pattern. Perhaps, during an extended sequence of consecutive swallows, older adults maintain laryngeal vestibule closure more often than young adults in order to conserve muscular reserve and energy. Previous studies have identified reduced muscular reserve in the elderly (Robbins et al., 1995). An opened airway between each swallow may require greater demands on the supra- and infrahyoid musculature with the rapid and repeated occurrences of contraction and relaxation evident during sequential swallowing. Thus, as one ages, there may be a greater tendency for the HLC to remain elevated to maximize economy of movement.

When considering the relationship of leading bolus edge at swallow onset and age across all swallows, results revealed that the young adults were more likely to have the bolus placed caudal to the valleculae at swallow onset as compared to the old adults.

This is contrary to findings in discrete swallows, which indicate that in young adults, the trigger point for the pharyngeal swallow is rostral to the trigger point found in old adults. That is, young adults tend to evoke a pharyngeal swallow when the leading bolus edge is at the level of the anterior faucial arch (Logemann, 1983); whereas old adults tend to evoke a pharyngeal swallow when the bolus is at the level of the ramus of the mandible (Robbins et al., 1992; Tracy et al., 1989). In the present study, 29% of the swallows for the elderly had the leading bolus edge superior to valleculae compared to only 18% for the young adults.

When analyzing age and bolus location, the influence of HLC movement pattern was evident. For the young, more distal bolus placement was evident for the vast majority of swallows, regardless of HLC movement pattern. However, for the older adults, bolus location superior to the valleculae occurred more frequently with an opened HLC movement pattern, whereas the distal pharynx was the location for a closed movement pattern. This finding differs from the a priori hypothesis that suggested that the older adults would demonstrate more distal bolus location regardless of HLC movement pattern. It is a surprising finding in that summation of afferent potentials throughout the entire pharynx was expected for the elderly. That is, for the older adults, it was expected that sensory stimulation of the distal pharynx would be required to evoke a swallow. Previous research using water infusion into the pharynx has indicated that the elderly may have increased sensory thresholds compared to young adults, because the older adults could not discriminate between rapid and slow injection (Shaker et al., 1994). Given this factor, it was posited that the bolus would be in the

distal pharynx for all HLC movement patterns in the elderly. Perhaps with the senescent swallow, the opened laryngeal vestibule is providing sensory information to drive an earlier onset of swallowing, particularly in older adults who may not be as apt to close off the airway in a timely and coordinated manner. These findings suggest that sensory information, particularly proprioception, is crucial, but suggest that the swallowing mechanism may be able to adapt to reduced sensory input.

A strong relationship between HLC movement pattern and location of the leading bolus edge at swallow onset was identified. When the laryngeal vestibule remained closed between swallows with an inverted epiglottis during the sequence, the leading bolus edge was in the distal pharynx in 95% of the swallows. With an opened laryngeal vestibule pattern with the epiglottis returning to upright between swallows, bolus placement was more random, with the bolus generally being superior or inferior to the valleculae. This finding suggests that the configuration of the laryngeal vestibule (opened, closed) prior to swallow onset may determine the magnitude of receptor site stimulation necessary to evoke a swallow. Dua et al. (1997) identified the epiglottic edge to be a crucial trigger zone for swallowing during normal eating. When the epiglottis remains inverted between swallows, the valleculae is no longer an available recess for bolus containment, and the epiglottic edge is in the distal pharynx. Thus, for a closed laryngeal vestibule, the bolus would need to be in the distal pharynx to contact this epiglottic edge. However, the significance of the epiglottic edge is unclear because with an opened HLC pattern, the bolus was randomly placed at swallow onset. That is, the bolus was as likely to be in the oropharynx as the hypopharynx with an opened

laryngeal vestibule. In order to facilitate airway protection, rostral bolus placement would seem critical with an opened laryngeal vestibule; however, this was not the case when analyzing swallowing across age groups. As discussed previously, the older subjects were more likely to have a superior bolus placement at swallow onset with an opened HLC pattern; however, the young tended to have a distal placement. It is unclear how HLC movement and age may interact to drive the afferent summation pattern necessary for the evocation of the pharyngeal swallow. Further study is warranted to investigate these relationships.

Relationship between Age, Bolus Aggregation, and HLC Movement Patterns

Bolus aggregation was identified with sequential straw drinking with the young demonstrating more occurrences of pharyngeal bolus accumulation than the old. These results differ from the a priori hypothesis in which it was predicted that older adults would demonstrate more occurrences of bolus aggregation than the young. As predicted, HLC movement pattern did not influence the occurrence of bolus aggregation.

Pharyngeal accumulation of material prior to swallow onset is an interesting phenomenon and until recently, it was assumed that only animals demonstrated bolus aggregation. Palmer and colleagues (1992) were the first to identify stage II transport during mastication in humans. They noted that a person would move a triturated portion of a solid bolus in the valleculae as mastication continued for the remainder of the bolus. The triturated bolus collected in the valleculae until the pharyngeal swallow was evoked. Palmer et al. (1992) did not identify pharyngeal accumulation with liquids. In

the pilot study for the present investigation, Daniels and Foundas (2001) were the first to identify bolus aggregation for liquids in humans. Unlike vallecular bolus accumulation identified for triturated boluses, Daniels and Foundas (2001) noted hypopharyngeal bolus accumulation for liquids to occur in the hypopharynx. These results are supported by Chi-Fishman and Sonies (2000) who found this same phenomenon with sequential cup drinking.

Results of the present study expand these results to older adults. However, of the 42 occurrences of bolus aggregation across all 680 total swallows, only three episodes of bolus aggregation were generated by the older group. It is unclear why this phenomenon decreases with advancing age. Employment of the mode of transport would require precise coordination of oral and pharyngeal movement and thus may be suppressed by the elderly in order to protect the airway. Most subjects generally transferred only one bolus into the hypopharynx as they reloaded the oral cavity. The additive effect of the second bolus elicited the pharyngeal swallow, and both boluses were simultaneously swallowed. However, in one young adult, up to four occurrences of oral filling and transfer into the pharynx occurred prior to swallow onset. Chi-Fishman and Sonies (2000) reported that bolus aggregation only occurred with a closed HLC movement pattern. In contrast, the present study found that 60% of the episodes of bolus aggregation occurred with an opened laryngeal vestibule. There were only two instances of airway invasion during bolus aggregation, both with an opened vestibule. These instances of airway invasion occurred in an elderly adult who demonstrated aspiration with one episode of aggregation. This finding offers additional support for

the notion that elderly adults may not be able to achieve rapid airway protection with an opened laryngeal vestibule or with distal bolus placement at swallow onset.

Reliability of the Penetration-Aspiration Scale with Sequential Swallowing

Reliability of the Penetration-Aspiration Scale (Table 2) was determined during sequential swallowing. Intrarater reliability was judged to be good, with acceptable interrater reliability as well. Interrater reliability was better than that identified in the original paper (Rosenbek et al., 1996) in which four experts in the field of dysphagia measured reliability. In the original paper, for scores 1-3, the average reliability was $\kappa = .56$, with improved reliabilities reported for scores 7-8 ($\kappa = .85$). In this paper, all the randomly selected subjects for reliability judgement received a score of 1-3 by either the investigator or the interrater judge. Thus, reliability was notably higher in the present study ($\kappa = .69$) as compared to the original paper.

Assignment of the Penetration-Aspiration Scale scores required review of the anatomy prior to and after the swallow, review of the swallow at regular speed, and frame-by-frame and slow motion review. The Penetration-Aspiration Scale was developed for scoring single swallows, not sequential swallowing. To score penetration, particularly scores 2-3, one looks for contrast to break the rim of the laryngeal inlet, which is bounded by the aeryepiglottic folds laterally, the epiglottis rostrally, and the arytenoids caudally. When penetration occurs "during" the swallow, the contrast should cross the apex of the arytenoids and is characterized by a crescent-shaped line between the inverted epiglottis and the arytenoids (Jim Coyle, personal communication). The best way to determine penetration and distinguish between scores

2 and 3 is to focus on this laryngeal inlet rim prior to the swallow and immediately after the swallow when the epiglottis has returned to upright. Thus, one can judge if penetration with contrast clearance (score 2) or penetration with contrast retention (score 3) has occurred.

Use of this scale with sequential swallowing proved challenging for many reasons. First, with many swallows, the epiglottis remained inverted after the swallow, and for many subjects, the epiglottis did not return to upright until after completion of the entire sequence. As a result, it was difficult to continually determine airway invasion. More specifically, it was difficult to determine clearance of contrast for each swallow when the epiglottis remained inverted, because the structures did not return to their resting position after the swallow. This was evident in the reliability scores, as most of discrepancies in scoring occurred between scores 2 and 3.

Second, when the laryngeal vestibule remained inverted, it was difficult to continually determine if the bolus crossed the apex of the arytenoids. For many sequential swallows, contrast was identified between the arytenoids and the laryngeal surface of the inverted epiglottis; however, it did not arch over the arytenoids (i.e., cross the aeryepiglottic apex), thus it was not classified as penetration. Third, when scoring multiple consecutive swallows and trials, particularly with the epiglottis remaining inverted between swallows, it was difficult to distinguish between stasis in the laryngeal inlet from a prior swallow and a new occurrence of penetration. It was also difficult to distinguish between a new occurrence of laryngeal vestibule stasis and prior stasis.

As described above, application of this scale to sequential swallowing proved challenging with expansion of many of the guidelines used to classify single swallows. However, given the good reliability, particularly in relation to the original paper, it was felt that this scoring system could be reliably used with sequential swallowing and that the scale could provide useful information concerning characteristics of airway invasion during consecutive straw drinking.

Relationship between Age, Swallowing Parameters, and Airway Invasion

Airway invasion was significantly correlated with advancing age. Young adults rarely had airway invasion or airway invasion with clearing (score 2). Only one young adult had airway invasion with supraglottic stasis (score 3). Conversely for the older adults, 12 individuals demonstrated laryngeal penetration frequently with supraglottic stasis. Two of these older adults had TVC contact of the bolus and one older adult aspirated. Until now, studies have not identified increased occurrences of airway invasion with advancing age. Studies of the effects of normal aging on swallowing have all been conducted with discrete swallows. These studies have not found airway invasion associated with increasing age (Robbins et al., 1992, Robbins et al., 1999, Tracy et al., 1989). Robbins et al. (1999) noted similar scores on the Penetration-Aspiration Scale for young and old adults. For the older group (age range 63-84 years), only 3% of the swallows received a score of 3. There were no scores of 4 or 5 (penetration to the TVC) for any of their subjects, and one older adult received a score of 6 (aspiration with clearing out of the trachea). Results from the present study suggest that penetration may be part of normal swallowing behavior, and frequency of

occurrence and supraglottic retention may increase with normal aging. Furthermore, depth of penetration and aspiration may increase slightly with aging. It would be difficult to determine whether these occurrences are abnormal, particularly if there are no associated medical complications.

A notable decline in airway protection was observed in adults over the age of 70. For adults under the age of 70 years, the average Penetration-Aspiration Scale score across all swallows clustered around a score of 1, whereas a higher range of average scores was noted for adults 70 years of age or older. Although adults over the age of 70 years had more occurrences of penetration, it is important to note that aspiration did not increase, and the only person who aspirated was younger than 70 years of age. For the most part, the airway invasion was generally high in the laryngeal vestibule; however, occurrences of vestibule stasis increased with advancing age in this subgroup. These results suggest that advancing age, particularly 70 years and older, may notably alter the ability to maintain airway protection and to achieve supraglottic clearance.

As these results demonstrated increased airway invasion with advancing age, it is important to consider several factors that may impact the results, including the possibility that the study protocol inflated the risk of airway invasion. Was the study protocol artificial? The fact that subjects were swallowing during an imposed duration of 10-seconds, raises the question that self-pacing may yield different swallowing patterns. The effects of the use of a straw versus cup drinking should also be considered. While continuous straw drinking for a 10-second duration may not be representative of any one individual's drinking pattern, they are not atypical swallowing

conditions. Most humans swallow sequentially, and when thirsty, the duration of the sequence may approach or extend beyond 10-seconds. While straw drinking may not be part of the daily intake pattern of liquid ingestion, the opportunity to drink from a straw is present, particularly in restaurants or when hospitalized. Thus, the environment was not artificial, although it may not be typical for all subjects. Furthermore, speed was not an imposed factor. Subjects were instructed to swallow continuously for 10 seconds, and not to drink as rapidly as possible. This allowed for each subject to pace himself in a more normal manner. However, given the nature of other tasks in which speed was a critical issue, it cannot be assumed that subjects drank at their normal rate.

In employing a specified duration of drinking time, the study was, in a sense, testing muscle reserve and the ability to maintain airway protection during a sustained time. For the young adults, scores on the Penetration Aspiration Scale were similar to those of the younger adults drinking a single bolus (Robbins et al., 1999). However, as previously stated, older adults demonstrated greater occurrences of airway invasion and laryngeal vestibule retention during sequential swallowing as compared to previous discrete swallow results. This suggests that muscle reserve may be compromised over the course of continuous swallowing, thus allowing for airway invasion. This fact may account for the finding of increased occurrences of airway invasion with advancing age that was not identified in previous studies (Robbins et al., 1992; Robbins et al., 1999; Tracy et al., 1989). These results suggest that airway invasion may occur more frequently during the course of a meal, possibly as a result of a decrease in muscular reserve over time and with repetitive action. However, it is possible that in a natural

environment, the old unconsciously modify swallowing patterns to facilitate airway protection. That is, older adults may not swallow sequentially, or if they do, they may complete fewer consecutive swallows. Results of this study indicate that old adults complete significantly fewer swallows than the young. It is unclear if this is due to decreased muscular strength and reserve, or an intuitive drive to protect the airway by decreasing the frequency of sequential swallows. Given that other motor tasks were shown to decrease with advancing age (as will be discussed), it is likely, that in the course of this study, the number of swallows was reduced due to a reduction in coordinated sequential movements, not to facilitate airway protection. However, older adults should be studied in a more natural eating environment to determine normal ingestive behavior.

Results revealed several associations between age and swallowing features. There were associations between 1) age, HLC movement pattern, and airway invasion, and 2) age, leading bolus edge location, and airway invasion. Both young and old adults were more likely to demonstrate airway invasion during sequential straw swallowing when the bolus was in the hypopharynx at swallow onset. Penetration was likely to occur 5.8 more times in the elderly as compared to the young adults. This pattern of distal bolus placement, particularly with increased age was associated with greater occurrences of airway invasion. This result suggests that while hypopharyngeal bolus location prior to swallow onset may be a normal variant in sequential swallowing, the ability to maintain airway protection with this distal bolus placement may be reduced, particularly with increased age. The ability to obtain rapid and coordinated airway

protection may be compromised with increasing age and with distal pharyngeal bolus placement.

Airway invasion was generally associated with a closed laryngeal vestibule as compared to an opened vestibule, with older adults demonstrating this occurrence 3.8 more times than younger adults. This result is provocative because laryngeal vestibule closure with an inverted epiglottis has long been associated with airway protection. When evaluating the implications of this unexpected result, the components of airway protection should be examined. These components: include HLC elevation, TVC adduction, false vocal cord adduction, tilting of the arytenoids and contact with the base of the epiglottis, contraction of the aeryepiglottic folds, and retroflexion of the epiglottis over the airway. With a closed laryngeal vestibule between swallows, a tight seal is assumed. But as previously reported, there is partial laryngeal lowering between swallows with a closed HLC pattern (Chi-Fishman & Sonies, 2000). This partial lowering in an apparent closed and protected system may result in a reduced superior supraglottic seal that enables liquid to enter the laryngeal vestibule. With a closed HLC movement pattern, there was an extraordinary preponderance of hypopharyngeal bolus location at swallow onset. Increased bolus pressure prior to opening of the UES may decrease resistance of epiglottic and arytenoid to epiglottic base seals, thereby allowing for airway invasion. Employment of manometry in the study of sequential swallowing may help explain this occurrence of airway invasion with a closed laryngeal vestibule.

Chi-Fishman and Sonies (2000) reported that three of their 10 subjects demonstrated supraglottic penetration with clearing (score 2) during sequential cup

drinking. While they did not describe the vestibule position, it appeared that these subjects demonstrated a slight opening of the vestibule while the epiglottis remained inverted. This alight laryngeal vestibule opening with the epiglottis inverted was not found in the majority of occurrences of penetration in the present study. A closed laryngeal vestibule, without visible evidence of opening was found with the occurrences of penetration. Air space between the arytenoid and epiglottis base was generally not observed; there was only movement of contrast into the vestibule. It is important to note that the older adults (25%) also demonstrated increased frequency of penetration with an opened laryngeal vestibule as compared to the younger adults (10%). Again, this finding suggests that the elderly may not be able to obtain the necessary speed and coordination necessary to protect the airway in a timely manner.

Finally, in this discussion of airway invasion, particularly for healthy, nondysphagic adults, a normal response to supraglottic penetration should be considered. The SLN_{ib} supplies sensation to the supraglottic region. Surfaces innervated by this nerve are tested to determine integrity of sensation and safety of swallow intake. Using air puff stimulation, Aviv et al. (1994) reported that sensory detection, characterized by the subject raising his/her hand following stimulation, decreased with normal aging. The authors concluded that increased sensory discrimination thresholds might lead to an increased risk of aspiration in the elderly. Recent research has focused on the laryngeal adductor response (LAR) or the laryngeal cough reflex (LCR) to determine the integrity of laryngeal sensation. With the LAR, brief adduction of the TVC is expected with airpuff stimulation of the aeryepiglottic

folds (Aviv et al., 1999). For the LCR, a cough is expected upon inhalation of a mild chemical irritant (Addington, Stephens, & Goulding, 1999). Both of these tests are assessing the integrity of the SLN_{ib}. In the present study, a cough was not evoked with any occurrence of laryngeal penetration in these healthy adults. Even laryngeal vestibule stasis did not evoke a cough in the single young adults or in the numerous older adults with this feature. The only occurrence of a cough was noted with aspiration. While the LCR and the LAR may provide important information concerning the SLN_{ib}, they may not fully correspond to a normal response of mechanostimulation by liquid or food in the supraglottic region. Another possibility may be that recurrent laryngeal nerve stimulation, as opposed to SLN_{ib} stimulation, is required to evoke a cough during actual ingestion. It is interesting to note that a cough was evoked in the only person who aspirated. Further research concerning normal response to airway invasion and the role of the SLN_{ib} in protection from aspiration is warranted.

These results have important clinical implications because they expand our definition of normal swallowing and redefine parameters of pathological swallowing. It appears that airway invasion may be a normal variant of ingestive behavior during consecutive swallowing. Furthermore, healthy elderly adults may have a reduced ability to clear penetrated material from the laryngeal vestibule. It is critical that swallowing therapists understand this variability in normal swallowing as they evaluate clinical populations. Expansion of our concepts of normal swallowing will allow a more accurate diagnosis of pathological swallowing in older adults who are more likely to present with chronic and acute disease processes that can further impact deglutition. In

healthy young adults, penetration was not found to be a risk factor for aspiration. However, as we learn more about inherent swallowing patterns and normal variability of swallowing behaviors associated with advancing age, it will be critical to determine under what circumstances and conditions these inherent patterns and age-related differences become risk factors that may lead to pathological swallowing.

Experiment II: Swallowing Lateralization Using a Dual Task Paradigm

Age Effects on Baseline Tasks

The effects of normal aging were examined for finger tapping with both the right and left hands, repetition, the number of swallows, and the volume per swallow. As predicted a priori, finger tapping, repetition, and number of swallow rates significantly declined with increased aging; however, volume per swallow did not.

These age-related changes may be explained by physiological and neurological changes associated with normal aging. Brain weight and volume decrease with advancing age (Davis & Wright, 1977; Dekaban & Sadowski, 1978). The width of cerebral sulci and fissures increases with advancing age as does ventricular size (for review, Freedman, Knoefel, Naeser, & Levine, 1984). Intracranial white matter significantly decreases with age; whereas age-related decreases in gray matter are not significantly different (Guttman et al., 1998). Muscle atrophy, characterized by a decrease in the number of muscle fibers, is typical in people over the age of 60 (Campbell, McComas, Petito, 1973). Muscle strength also decreases with age (Larsson, 1978). EMG recordings of muscles of the lips and face have indicated that responses are most variable for the oldest group, with investigators positing that facial muscle

atrophy resulted in the variable recordings for the elderly (Rastatter, McGuire, Bushong, & Loposky, 1987). Using ultrasound, Sonies, Baum, and Shawker (1984) revealed significantly reduced tongue thickness in older subjects. Baum and Bodner (1983) evaluated a variety of oral musculature parameters including muscle tone, symmetry, and movement. A decrease in muscle tone and strength and changes in neurological functioning have been associated with advancing age. Results of the present study demonstrated a decline in fine motor speed, repetition, and swallow rate, and these results are consistent with the findings in the literature.

Given the research on oral and facial muscle changes with advancing age, the result of a decreased swallowing rate with increasing age was expected. However, unexpectedly, the volume per swallow did not significantly decline with advancing age. In fact, as a group, the older adults tended to ingest a larger volume per swallow. Previous research has indicated that the average volume swallowed with cup drinking is 21 ml (Anderhill et al., 1989) and that the average volume with straw drinking is 24 ml for healthy elderly adults and 26 ml for healthy young adults (Nilsson, Ekberg et al., 1996). However, these measures were obtained for single swallows, and not consecutive straw drinking as was used in the current study. Normal parameters for the average volume per swallow with consecutive straw drinking have not been reported. With consecutive straw drinking, a reduced volume per swallow was evident as compared to the volume per discrete swallow that has been reported (Anderhill et al., 1989; Nilsson, Ekberg et al., 1996). In addition, the younger adults averaged 11 ml and the older adults averaged 13 ml with sequential straw swallowing. This slight

difference in volume per swallow between age groups differs from results found with single swallows. Nilsson , Ekberg et al. (1996) identified a slight increase in the bolus volume for young as compared to older adults. With consecutive straw drinking, this increase in volume per swallow resulted in equal amounts of liquid ingestion by both groups, as was reflected in the total volume swallowed for each 10-second trial, which was about equal between groups. Thus, while aging may induce a decline in the number of swallows, some healthy older adults appear to compensate for this decreased swallowing rate by increasing the volume swallowed. However, not all of the older adults increased the volume per swallow, nor did all of these older adults demonstrate an increase in the number of swallows. When analyzing patterns of intake during sequential swallowing, three patterns were identified 1) increased number of swallows relative to volume per swallow, 2) equal number of swallows relative to volume per swallow, and 3) increased volume per swallow relative to the number of swallows. Results indicated that as one ages, the number of swallows decreases. An older adult may compensate for this change by increasing the amount of liquid ingested with each swallow. Advancing age, however, appears to be incompatible with the ability to increase the number of swallows to compensate for low volume of intake. This factor is supported by the findings that none of the older adults demonstrated a greater number of swallows to volume ratio. This finding indicates decreased efficiency in swallowing for a subset of the older population, and has important clinical implications for nutrition in the elderly. Whereas the number of swallows decreases as one ages, some older adults may compensate for this change by increasing the volume of each swallow, thereby

maximizing efficiency and probably maintaining adequate caloric intake. However, some older adults may not be able to increase the volume swallowed as their number of swallows declines. Thus, in order to achieve adequate nutrition, they would have to extend the length of a meal. Increased duration of a meal may lead to fatigue and decreased muscular reserve over the course of the meal. This may put an older person at risk of reduced nutrition, or even possibly increased airway invasion as increased duration of a meal may yield reduced muscular reserve.

Verbal-Manual Interference

The effect of language competition on finger tapping rates was tested. The effect of motor competition on repetition rate was also tested. Baseline tapping rates significantly decreased with verbal interference, similarly across the two age groups. A significant difference in interference effect for right and left hands was expected; however, this interaction was not observed. Repetition did no differ significantly from baseline with the addition of motor interference. Previous research has demonstrated verbal-manual interference with a decremental response in right hand tapping rate in right handers. The subjects for this study consisted of self-professed right handed adults, all of whom demonstrated right hand dominance on a handedness questionnaire and had no history of left handedness in immediate family members. Declines in tapping rates for both hands were found with verbal interference. When examining the means, the effect of verbal interference was in the expected direction. That is, the decline in right hand finger tapping rate with the language competition was greater than the decline in left hand finger tapping rate. Although a significant interaction was not

found, the different effects of verbal interference observed for both the right and left hands was consistent with the expected pattern of results.

Greater tapping asymmetry was evident for the young adults at baseline. That is, there was a significantly greater difference between right and left hand tapping rates in the young as compared to the old. Extensive studies have been conducted on age-related effects on motor tasks, but the results are not consistent. Some studies have found a reduced asymmetry in tapping rate between dominant and nondominant hand with increasing age (Goldstein & Braun, 1974). Conversely, other studies have not found these age-related effects (Borstein & Suga, 1988).

Effects of Interference on Swallowing

The main finding of the study was that concurrent cognitive and motor tasks associated with left (silent repetition, right hand finger tapping) and right (visuospatial processing, left hand finger tapping) hemisphere functioning produced significant decrements in swallowing behavior. These results support the notion that both the right and left hemispheres contribute to swallowing. Silent repetition during swallowing produced a decrease in the volume per swallow. Finger tapping with right and left hands during swallowing induced a decrease in the number of swallows. In addition, the higher order right hemisphere task of visuospatial processing decreased the number of swallows. These results partially support the a priori hypothesis, in which the higher order left hemisphere task of silent repetition was expected to have an effect.

Bilateral activation of the sensorimotor cortex during swallowing has been identified in animal studies (Sumi, 1969) and using functional imaging methodologies

of PET and fMRI (Hamdy, Mikulis et al., 1999; Zald & Pardo, 1999). Studies of focal lesions in stroke patients have found that dysphagia occurs with equal frequency following unilateral left and right hemisphere stroke (Alberts et al., 1992; Chen et al., 1990; Daniels & Foundas, 1999; Daniels et al., 1999; Johnson et al., 1992). In the majority of healthy right handed adults, the left hemisphere predominately mediates right hand finger tapping and language, whereas the right hemisphere mediates left hand finger tapping and visuospatial processing. Each of these tasks significantly reduced some behavior of swallowing. A significant decrement in the number of swallows as compared to baseline was evident for the motor task and for the visuospatial task. Silent repetition produced a significant decrement in the volume per swallow as compared to baseline. The effect of finger tapping on the number of swallows appears fairly straightforward as an effect of co-activation of motor systems. There are several explanations for the finding that concurrent cognitive tasks of silent repetition and visuospatial processing affected swallowing in different ways. Further research is required to clarify the potential mechanisms.

Assuming a bilateral representation for swallowing, the decline in the number of swallows with right and left finger tapping supports the cerebral space model. This model suggests that inhibitory interference results from the competition of two activities that require access to brain regions that are anatomically close with high neural interconnectivity (Kinsbourne & Hicks, 1978). At the cortical level, swallowing and finger tapping are driven by the primary motor cortex. The motor hand representation is anatomically close to the representation of the face, larynx, and pharynx along the

length of the primary motor cortex (precentral gyrus, Brodmann's area 4). Thus, co-activation of these anatomically close neural substrates during the concurrent finger tapping-swallowing task may have contributed to the decline in the number of swallows with right and left finger tapping. Distal unilateral hand movements, like those incorporated in the finger tapping task, are mediated by the contralateral motor hand representation located along the primary motor cortex. Oromotor functions are also mediated by the contralateral motor cortex, in that the right side of the face and oral cavity is controlled by the left primary cortex and vice versa. However, bilateral activation of the oromotor cortex is required to initiate swallowing. Moreover, phonation and the pharyngeal stage of swallowing require integrated interaction of bilateral motor cortices. Thus, the requisite motor programs that initiate and complete swallowing are mediated by bilateral motor systems. These findings support the cerebral space model of interference.

The volume per swallow was significantly reduced during the silent repetition language task. Moreover, the number of swallows significantly decreased with the competing task of visuospatial processing. These results again suggest that both the left and the right hemisphere contribute to swallowing; however, different models may need to be considered when explaining these results. The neural regions activated in swallowing and silent repetition are anatomically close and functionally overlapping, thus offering support for the cerebral space model. Speech and swallowing share the same musculature with close proximity of the mouth, pharynx, and larynx along the primary motor cortex. Functional imaging studies have identified activation of the left

dorsolateral prefrontal cortex and the left supplementary motor cortex in "silent" verb generation (Wise et al., 1992) and activation of the left primary motor cortex in "silent" repetition (Warburton et al., 1995). These same areas are activated during swallowing (Hamdy, Mikulis et al., 1999; Hamdy, Rothwell et al., 1999; Zald & Pardo, 1999). This is not true for the neural regions activated in swallowing and visuospatial processing, as the deglutitive and the visuospatial regions are not anatomically close nor are they functionally overlapping. Thus, another model such as the allocation of resource model must be considered.

The allocation of resource model can be used to explain the effects of all of the interference tasks on swallowing. The allocation of resource model suggests that when two competing tasks share the same hemisphere, allocation of attentional or processing resources is compromised (Kee et al., 1984). Thus, finger tapping with either hand, silent repetition, or visuospatial processing may compromise swallowing because attention is divided between the two tasks. There are two important features to consider when applying this model. First, significant age-related dual task decrements were not observed. Age-related differences in performance have been identified (Salthouse, 1988), with declines in divided attention being one of the most predictable changes associated with increased age (Craik, 1977). Thus, if reduced attentional resources were evident, one would posit that an age-related change in swallowing measures should have been apparent when implementing this dual task paradigm. However, the older adults did not demonstrate a significant decline in swallowing measures as compared to the young adults when a competing task was imposed. Swallowing, however, is an

automatic, over-practiced response, and research indicates that well-practiced skills have equivalent performance across the younger and older age groups (McDowd & Craik, 1988). For this reason, age-related declines would not have been expected.

The allocation of resource explanation cannot be fully confirmed by the current study as the level of complexity of the competing tasks could not be determined and rank-ordered. This step is essential to determine whether performance declines as cognitive-motor resources are overloaded. In the current study, varying levels of task difficulty were not quantified. In addition, as each individual may demonstrate varying strengths and weaknesses across the given tasks, the levels of complexity across tasks cannot be assumed. To ensure that allocation of attentional resources was compromised when using a dual task paradigm, a test with objective, multiple levels of complexity should be included. Only in this manner can allocation of resources be adequately assessed as a potential explanation for the observed effects. Without the competing tasks having objective levels of complexity, one cannot determine whether other factors are contributing to the results.

Effect of Swallowing on Motor Performance

The effect of concurrent swallowing on finger tapping rates was tested. It was predicted that finger tapping rates would significantly decline with swallowing interference. This prediction was not supported by the data. While the swallowing interference did produce a decrement in tapping rate for both the right and left hand as compared to baseline, the magnitude of decline was small. As discussed earlier, right and left finger tapping produced a significant decline in swallowing measures. Norman

and Bobrow (1975) indicated that the degree to which performing one task affects the performance of the second task is an index of the capacity demanded by the first task. This may indicate that finger tapping demanded more attention than swallowing, thus swallowing rather than tapping was impacted by the competition.

CONCLUSION

This research study was designed with two major goals: 1) to determine the effects of sequential swallowing on basic deglutitive biomechanics and to identify any age-related effects, and 2) to identify swallowing laterality using a dual task paradigm. Both goals were met and yielded important results that contribute to an improved understanding of swallowing physiology in healthy adults and have clinical applications.

Experiment I: Swallowing Physiology of Sequential Straw Drinking

Varying patterns of hyolaryngeal complex movement were identified during sequential straw drinking: 1) opening of the laryngeal vestibule between swallows with the epiglottis returning to upright, 2) continued closure of the laryngeal vestibule between swallows with the epiglottis remaining inverted, and 3) a mixed movement pattern characterized by interchangeable opened and closed patterns. Hypopharyngeal bolus location, which is a more distal location than typically seen with discrete swallows, was found to be a consistent location for bolus placement prior to swallow onset during consecutive swallows. Significant age-related differences in HLC movement patterns and leading bolus edge location at swallow onset were not evident. A relationship between HLC movement pattern and leading bolus location was identified with a closed laryngeal vestibule strongly associated with the more distal hypopharyngeal bolus location. These findings are crucial when considering normal and pathological features of swallowing and should help to extend the understanding of

swallowing physiology and biomechanics. These results provide empiric evidence that may broaden the definition of normal swallowing.

Airway invasion was identified in healthy young and old adults. This finding was unexpected, as airway invasion is usually associated with pathological swallowing. This feature was uncommon in the sample of healthy young adults, and it occurred more frequently in the healthy older adults studied. Penetration appeared to be a normal variant in sequential straw swallowing. Whereas younger adults may generally clear this material from the laryngeal vestibule, older adults may demonstrate greater supraglottic retention of the material. A closed laryngeal vestibule between swallows and a distal hypopharyngeal bolus location were strongly associated with increased incidence of airway invasion in both the young and old adults. It is unclear whether these inherent patterns may increase the risk of aspiration in healthy adults. Although speculative, it may be that these patterns may put adults with medical conditions associated with dysphagia at even greater risk of aspiration. In addition, it is unknown if healthy older adults unconsciously decrease airway invasion by decreasing the duration of consecutive swallowing.

Experiment II: Swallowing Lateralization Using a Dual Task Paradigm

Results of the second experiment revealed declines in baseline rates of finger tapping, repetition, and number of swallows for older adults as compared to the younger adults. Volume of swallow was not effected by age, and in fact a subset of older adults increased the volume of swallowing. This increase in volume may be associated with increased efficiency. The remaining older adults did not increase the volume per

swallow, nor did they increase the overall number of swallows. This finding may be associated with reduced swallowing efficiency. No older adult in the sample demonstrated a greater number of swallows relative to volume per swallow. These results therefore, suggest that the number of swallows may decrease with normal aging in some adults, and increasing the number of swallows does not appear to be a viable strategy for an older person to employ to increase oral intake. Some older adults may be able to compensate for this decrease in the number of swallows by increasing the volume per swallow thus, maintaining an efficient swallow. Other older adults may not be able to adjust the volume swallowed and may be at risk for reduced nutritional intake. That is, an extended duration of a meal may be required to meet caloric and nutritional needs; however, fatigue may occur causing the older adult to stop eating. Muscular reserve may decrease during an extended meal thereby, increasing the risk of aspiration.

Findings indicated that both the right and left hemisphere contribute to swallowing. Both right and left finger tapping, which selectively activate the left and right hemisphere respectively, interfered with swallowing. Moreover, silent repetition, which primarily activates the left hemisphere, and visuospatial processing, which primarily activates the right hemisphere, also interfered with swallowing behavior when performed concurrently. These results indicate that both hemispheres contribute to the mediation of swallowing. It is unclear, however, whether the left or right hemisphere plays a more dominant role.

These results provided partial support for both the cerebral space and attentional models in dual tasks. It is unclear if normal activities such as reading or participating in conversation can adversely impact swallowing behaviors, such as the number of swallows or the volume per swallow. Moreover, it is unclear if these attentional demands affect overall nutritional intake or increase the risk of aspiration, especially with increasing age and associated medical diseases. Further research concerning swallowing intake mechanisms and safety in the healthy elderly is warranted.

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APPENDIX A

Letters of Permission

Hightower, Chaun

From: Daniels, Stephanie [Stephanie.Daniels@med.va.gov]
Sent: Tuesday, October 30, 2001 4:33 PM
To: 'chightow@lww.com'
Subject: permission

I am completing my dissertation at Louisiana State University in Baton Rouge, LA. I would like to include a figure from a journal published by your company in the dissertation. I am the primary author for the article.
Below is the requested information:
Journal: Journal of Neuroimaging
Volume: 9 (2)
Year: 1999
Article: Lesion localization in acute stroke patients with risk of aspiration
Authors: Stephanie K Daniels and Anne L. Foundas
Pages: the figure is on page 97. It is figure 6.

The dissertation will be provided to UMI (Bell & Howell Information and Lerning Company), which will supply copies of the dissertation per request

I will also fax a copy of this request. Thank you for your prompt attention to this matter.

Stephanie Daniels

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[signature] date: 10-31-01

October 30, 2001

Loretta Scott
Pro-Ed
8700 Shoal Creek Blvd
Austin, TX 78757-6897

Stephanie K. Daniels
5961 Tchoupitoulas
New Orleans, LA 70115

RE: Copyright Agreement

Dear Ms. Scott

I am completing my dissertation at Louisiana State University in Baton Rouge, LA. I would like to include a figure from the book, Evaluation and Treatment of Swallowing Disorders (Volume 2) by Jeri Logemann. The figure is on page 14 "mid-sagittal section of the head and neck." The dissertation will be provided to UMI (Bell & Howell Information and Learning Company, which will supply copies of the dissertation per request.

If you are in agreement to this, please sign below.

Reference the author + publisher.
Loretta Scott 10-31-01

Thank you for your prompt attention to this matter.

Sincerely,

Stephanie K. Daniels

APPENDIX B

Abbreviations

ANOVA—analysis of variance

BOLD—blood oxygen level dependent

CT—computed tomography

EMG—electromyography

fMRI—functional magnetic resonance imaging

HLC—hyolaryngeal complex

IOPI—Iowa Oral Performance Index

LAR—laryngeal adductor reflex

LCR—laryngeal cough reflex

LHD—left hemispheric damage

MANOVA—multivariate analysis of variance

MMSE—Mini-Mental State Examination

MRI—magnetic resonance imaging

NTS—nucleus tractus solitarius

OPSE—oropharyngeal swallowing efficiency

PET—positron emission tomography

PVWM—periventricular white matter

RHD—right hemispheric damage

SLN—superior laryngeal nerve

SLN_{ib}—internal branch of the superior laryngeal nerve

TMS—transcranial magnetic stimulation

TOLA—Test of Oral and Limb Apraxia

TVC—true vocal cords

UES—upper esophageal sphincter

VAMC—Veterans Affairs Medical Center

APPENDIX C

Experiment I: Swallowing Physiology of Continuous Straw Drinking

1. The question examined the HLC movement patterns during sequential straw swallowing across individuals and across age groups.
2. The question examined patterns of leading bolus edge location at swallow onset across individuals and across age groups.
3. The question examined the relationship between age, HLC movement patterns, and bolus locations.
4. The question examined the relationship between age, bolus aggregation, and HLC movement patterns.
5. The question examined the relationship between age, swallowing parameters, and airway invasion.

Experiment II: Swallowing Lateralization Using a Dual Task Paradigm

1. The question examined the effects of normal aging on baseline motor, language and swallowing tasks.
2. The question examined the effects of language interference on motor performance.
3. The question examined the effects of motor and language interference on swallowing performance.
4. The question examined the effects of visuospatial interference on swallowing performance.

5. The question examined the effects of swallowing interference on motor performance.

VITA

Stephanie Kay Daniels received her bachelor of science degree in speech and hearing therapy at East Texas State University in Commerce, Texas. She received her master of science degree in communication disorders at the University of Texas at Dallas in Dallas, Texas. She has worked 16 years as a hospital-based clinician, first at Ochsner Clinic in New Orleans. She continues to work at the Veterans Affairs Medical Center in New Orleans. She completed her doctoral studies at Louisiana State University, while continuing to work full time. She has published numerous articles on dysphagia.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Stephanie Kay Daniels

Major Field: Communication Disorders

Title of Dissertation: Physiology and Lateralization of Swallowing: A Comparison Between Young and Old Adults

Approved:

Hugh W. Buckingham
Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

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Paul R. Hoffman

J. B. Kitty

D.G. Homberger

Date of Examination:

October 26, 2001