JSLHR

Research Article

The Swallowing Profile of Healthy Aging Adults: Comparing Noninvasive Swallow Tests to Videofluoroscopic Measures of Safety and Efficiency

Sonja M. Molfenter,[a] Danielle Brates,[a] Erica Herzberg,[a] Mehak Noorani,[a] and Cathy Lazarus[b]

Purpose: It has been widely reported that a proportion of healthy, community-dwelling seniors will develop dysphagia in the absence of a known neurological, neuromuscular, or structural cause. Our objective was to test whether various feasible, noninvasive measures of swallowing could differentiate safe versus unsafe and efficient versus inefficient swallowing on videofluoroscopy (VF) in a sample of healthy seniors.
Method: VFs from 44 (21 male, 23 female) healthy community-dwelling seniors (> 65 years old) were compared with a series of feasible, noninvasive swallowing metrics: maximal tongue strength (anterior and posterior), hand grip strength, pharyngeal volume, age, body mass index, 3-oz water swallow challenge, the 10-item Eating Assessment Tool questionnaire, and the Frailty Index. The VF protocol included 9 liquid barium boluses (3 × 5 ml thin, 3 × 20 ml thin, and 3 × 5 ml nectar). Each swallow was rated (randomized and blind) for safety using the Penetration–Aspiration Scale score and for efficiency using the Normalized Residue Ratio Scale (NRRS). Participants were deemed "unsafe" if they had any single Penetration–Aspiration Scale scores ≥ 3 and "inefficient" if they had any NRRS valleculae score > 0.082 or NRRS pyriform sinus score > 0.067. Univariate analyses of variance were run for each continuous swallowing measure by swallowing safety and swallowing efficiency status. Pearson's chi-square analyses were used to compare binary outcomes by swallow safety and efficiency status. Bonferroni corrections were applied to control for multiple comparisons.
Results: None of the swallowing measures significantly differentiated safe from unsafe swallows. Although several variables trended to distinguishing efficient from inefficient swallows (age, 10-item Eating Assessment Tool, 3-oz water swallow challenge), only one variable, pharyngeal volume, was significantly different between efficient and inefficient swallows ($p = .002$).
Conclusion: Our findings support the notion that larger pharyngeal volumes (measured using acoustic pharyngometry) are associated with worse swallowing efficiency, a finding we attribute to atrophy of the pharyngeal musculature in healthy aging.

A significant proportion of healthy, community-dwelling seniors experience disruption to swallowing function, which places them at risk not only for reduced quality of life (QOL) but also for more dire consequences such as malnutrition, dehydration, aspiration pneumonia, and even death (Altman, Yu, & Schaefer, 2010; Chen, Golub, Hapner, & Johns, 2009; Ekberg, Hamdy, Woisard, Wuttge-Hannig, & Ortega, 2002; Holas, DePippo, & Reding, 1994; Schmidt, Holas, Halvorson, & Reding, 1994; White, O'Rourke, Ong, Cordato, & Chan, 2008). Research indicates that the prevalence of dysphagia in otherwise healthy seniors ranges from 11% to 38% (Bloem et al., 1990; Chen et al., 2009; Holland et al., 2011; Kikawada, Iwamoto, & Takasaki, 2005; Robbins, 2002; Roy, Stemple, Merrill, & Thomas, 2007; Yang, Kim, Lim, & Paik, 2013) depending on the definition of dysphagia and the mechanism used to identify it. The prevalence increases dramatically (40%–72%) in seniors with very advanced age (> 85 years), those with clinical frailty, and those living in long-term care settings (González-Fernández, Humbert, Winegrad, Cappola, & Fried, 2014; Kendall, Leonard, & McKenzie, 2004; Rofes et al., 2010; Steele, Greenwood, Ens, Robertson, & Seidman-Carlson, 1997). When we take into account the fact that our population is rapidly aging, feasible and accurate

[a]Department of Communicative Sciences and Disorders, NYU Steinhardt, New York
[b]Mount Sinai Beth Israel, New York, NY
Correspondence to Sonja M. Molfenter: smm16@nyu.edu

Editor-in-Chief: Julie Liss
Editor: Michelle Ciucci
Received December 20, 2017
Revision received February 5, 2018
Accepted March 12, 2018
https://doi.org/10.1044/2018_JSLHR-S-17-0471

Disclosure: The authors have declared that no competing interests existed at the time of publication.

identification of swallowing disorders in community-dwelling seniors is an important topic of concern. It could allow for proactive management and possibly even preventive therapeutic intervention for dysphagia and its sequelae. This need is further heightened by the knowledge that swallowing disorders in community-dwelling populations are likely underreported. A survey sample of 947 patients visiting their primary care physician confirmed that 22.6% of adults experience swallowing problems, but less than half of these individuals (46.3%) reported their difficulties to their physician (Wilkins, Gillies, Thomas, & Wagner, 2007).

The gold standard method for assessment of dysphagia is achieved with videofluoroscopy (VF), a dynamic imaging procedure whereby food and/or liquids impregnated with radiopaque substances (usually barium) are swallowed under fluoroscopy, allowing for real-time observation of both the material being swallowed and the swallowing mechanism's response to that material. Of primary concern is the safe and efficient transport of the bolus to the digestive system. A misdirected bolus to the trachea and respiratory tract reflects an impairment in swallowing safety. It should be noted that swallowing safety in this context refers to the risk of a single bolus entering the lungs, as represented by bolus flow into the laryngeal vestibule and is not representative of overall patient safety. Residual bolus in the pharynx postswallow reflects an impairment in swallowing efficiency. Both safety and efficiency deficits create risk of a bolus being aspirated into the respiratory system and can potentially lead to respiratory compromise. Given that VF necessitates radiation exposure, our understanding of dysphagia in healthy aging using this tool is limited. Several excellent studies have provided a wealth of much-needed normative information regarding the biomechanics and physiology of swallowing in the context of advanced age (Leonard, Kendall, & McKenzie, 2004a, 2004b; Logemann et al., 2000; Logemann, Pauloski, Rademaker, & Kahrilas, 2002; Robbins, Hamilton, Lof, & Kempster, 1992; Rofes et al., 2010). However, our goal for this study is to describe the non-VF swallowing profile of healthy seniors who demonstrate swallowing safety and efficiency deficits on VF, with the end goal of identifying swallowing-related measures that may differentiate functional from impaired swallowing in healthy seniors.

Many research groups have reported on non-VF swallowing parameters in relation to the swallowing status of healthy older adults (see, e.g., Fei et al., 2013; González-Fernández et al., 2014; Maeda & Akagi, 2015; Namasivayam, Steele, & Keller, 2016; Sakai et al., 2017). However, as reported in a recent systematic review (Madhavan, Lagorio, Crary, Dahl, & Carnaby, 2016), these studies lack the direct comparison with instrumental evidence of disruption to swallowing function. One exception is a study by Butler and colleagues (2011), who compared measures of strength (tongue and hand grip) with swallowing function using endoscopic evaluations of swallowing. They found that reductions in tongue strength were significantly related to aspiration (swallowing safety) in healthy seniors. Thus, in this study, we collected various noninvasive, feasible measures such as anthropometrics (age, body mass index [BMI], pharyngeal volume), questionnaires/scales (10-item Eating Assessment Tool [EAT-10], Frailty Index), and behavioral data (tongue strength, grip strength, 3-oz water swallow test) in a sample of 44 healthy community-dwelling seniors and compared them with gold-standard VF measures of swallowing safety (penetration–aspiration) and efficiency (residue). Measures were chosen based on their intended use in screening swallowing (EAT-10, 3-oz water swallow challenge [WSC]) or based on research establishing a link between the measure and age-related changes in swallowing (Butler et al., 2011; González-Fernández et al., 2014). We included pharyngeal volume because it is known to increase with age as a function of pharyngeal muscle atrophy (Molfenter et al., 2015), and we have established that it can be reliably captured using a noninvasive device called acoustic pharyngometry (AP, described below; Molfenter, 2016). BMI was included as a crude measure of nutritional status, given the established relationship between dysphagia and malnutrition in community-dwelling adults (Takeuchi et al., 2014).

Our motivation was to identify feasible, noninvasive methods that can be used to screen for dysphagia in healthy aging. We hypothesized that swallowing safety status would be best differentiated by performance on the 3-oz WSC and the EAT-10 questionnaire (given that they are designed to capture aspiration or directly inquire about signs of aspiration) and that swallowing efficiency status would be differentiated by measures that capture/represent oropharyngeal muscle strength/function (tongue strength, pharyngeal volume). Finally, we hypothesized that more global (nonswallowing) measures of strength/function (BMI, grip strength, or Frailty Index) would not be sensitive to swallowing safety and efficiency status.

Method

Participants

This study was approved by the local institutional review board, and all subjects consented to participation. Healthy seniors were recruited from local senior centers. The inclusion criteria were adults 65 years or older and in general good health. The exclusion criteria included prior history of dysphagia, neurological disease, head and neck cancer, or head and neck surgery (other than routine dental/tonsil/adenoid surgeries). Our sample was nearly balanced for sex (21 male, 23 female), and the participants were, on average, 76.9 years old (SD = 7.1 years old). Anterior tongue strength of all potential subjects was screened using the Iowa Oral Performance Instrument or IOPI (IOPI Medical LLC) during recruitment. The literature converges on approximately 40 kPa as a categorical cutoff for marking tongue weakness in older adults (Nicosia et al., 2000; Stierwalt & Youmans, 2007; Youmans, Youmans, & Stierwalt, 2009). Our goal was to consecutively enroll a convenience sample containing an equal distribution of men and women with tongue strength under 40 kPa or over

40 kPa to provide an adequate distribution of strong and weak seniors in our study. Table 1 summarizes the participant characteristics.

Data Collection

Each study subject participated in 2 consecutive days of data collection. Data were collected over the course of 2 days to ease time/space constraints at the hospital. All Day 1 data were collected by trained research assistants and supervised by the first author at the NYU Speech-Language-Hearing Clinic. On Day 1, swallowing and health history as well as an oral motor sensory examination were completed to ensure subjects met inclusion/exclusion criteria. Next, each participant completed the EAT-10 (Belafsky et al., 2008), the 3-oz WSC (Suiter, Sloggy, & Leder, 2013), the Frailty Index (Fried et al., 2001), and measures of anterior and posterior tongue strength using the IOPI. Subjects reported that their weight and height were measured using a free-standing stadiometer.

The EAT-10 requires the subject to self-rate level of impairment on a scale of 0 (no problem) to 4 (severe problem) on 10 questions related to swallowing function and QOL. Total EAT-10 scores can range from 0 to 40. Total scores of 3 and higher are considered indicative of a swallowing problem (Belafsky et al., 2008). Thus, for the current analysis, EAT-10 scores were dichotomized as "pass" (total score of 0–2) versus "fail" (total score ≥ 3).

The 3-oz WSC (DePippo, Holas, & Reding, 1992) is used to identify patients who are at risk of aspiration. Each subject was instructed to drink 3 oz of water without interruption and was observed for 1 minute after drinking. The subject was considered to fail the task if he or she demonstrated any of the following: coughing/throat clearing, wet/hoarse vocal quality, or inability to complete the task.

The Frailty Index was administered to assess each participant's frailty level in five domains: shrinking, weakness, exhaustion, activity level, and walking speed. These measures were collected according to a standardized procedure (Fried et al., 2001). Each domain is scored dichotomously, 0 versus 1, with a maximum total Frailty Index score of 5. Total scores of 0 are considered "nonfrail," 1–2 are considered "prefrail," and 3+ are considered "frail." Because of low distribution of "frail" (n = 2) in our healthy sample, we collapsed the scale further to "nonfrail" (n = 18) and "prefrail/frail" (n = 26). Grip strength, measured with a digital hand dynometer (Jamar Plus), is used to capture the "weakness" domain of the Frailty Index. When subjects score in the lowest 20th percentile for their sex and BMI, they were classified as "weak" (normative values were referenced from the Jamar Plus instructions manual). However, because grip strength is a feasible, noninvasive measure of sarcopenia that is often included in other studies (see, e.g., Butler et al., 2011; Sakai et al., 2017), we decided to include the raw data as a continuous variable in our analysis as well (in addition to it representing a component of the Frailty Index).

Table 1. Participant demographics.

Variable	Men (n = 21)		Women (n = 23)	
	M	*SD*	*M*	*SD*
Age (years)	75.3	6.6	78.3	7.5
Height (cm)	171.5	8.0	158.8	7.5
BMI	27.1	3.3	26.0	3.7

Note. BMI = body mass index.

Tongue strength was measured using the IOPI. Each subject was given the opportunity to practice after receiving a demonstration from the research assistant. Maximal anterior tongue was captured as the highest of three isometric maximal tasks in the anterior position. Confirmation of the correct placement of the bulb on the tongue blade was made visually, and the subject was encouraged to achieve maximal force against the alveolar ridge with the tongue blade. Maximal posterior tongue strength was captured as the highest of three isometric maximal tasks in the posterior position. Confirmation of the correct placement of the bulb on the middorsum was made visually, and the subject was encouraged to achieve maximal force against the midpalate with the middorsum.

On Day 2, each subject completed AP and VF at the hospital. AP works much like sonar, whereby sound waves are reflected within the oral and pharyngeal cavities to provide noninvasive three-dimensional measures of space. This method (also known as acoustic reflection technology) is used clinically to test the compliance of the pharynx in obstructive sleep apnea (see Viviano, 2002, for a review article). AP has also been used to quantify vocal tract measures in speech science research (Vorperian et al., 2015; Xue, Cheng, & Ng, 2010; Xue & Hao, 2003). Our previous research using magnetic resonance imaging confirms that the pharyngeal lumen expands in aging alongside reductions in muscle bulk (Molfenter et al., 2015). Thus, we propose that greater pharyngeal volume on AP can be used to represent the degree of atrophy in the pharynx. AP was collected by the first author with an ECCOVISION AP device (Sleep Group Solutions), with participants seated upright in a chair with their head and spine in a neutral position. With the mouthpiece in situ (lips closed, teeth resting in the guard, and tongue underneath the guard), each subject completed two oral breathing tasks, one nasal breathing task, and one modified Valsalva (breathing with vocal folds approximated to allow air escape). These breathing tasks are required for the calculation of pharyngeal volume as per published protocols (Molfenter, 2016; Vorperian et al., 2015). The measurement method is summarized here. First, the most representative oral breathing waveform is identified according to three criteria: the waveform with the smallest error bars, the waveform that best overlaps with the oral cavity of the nasal graph, and the waveform that is higher than the modified Valsalva graph. Next, the nasal breathing task is used to identify the velum location at the base of the first peak of the nasal graph where the difference between consecutive cross-sectional areas is found to be less than 0.15 cm^2. Then, the modified Valsalva task is used to identify the glottis at the lowest point of the third trough in the modified Valsalva graph. The locations of the velum and glottis are transferred onto the representative oral breathing waveform, and the area under the curve is calculated for the velum and glottis. This value represents pharyngeal volume. Note that subjects with upper plate dentures were asked to remove them for AP tasks given that the plate was suspected to change the resonant properties of the oropharyngeal tract. Twenty percent of the data were subjected to interrater and intrarater reliability and yielded "excellent" scores (Fleiss, 1986; intrarater intraclass correlation coefficient [ICC] = 0.92, 95% CI [0.66, 0.98]; interrater ICC = 0.96, 95% CI [0.83, 0.99]).

VF was intentionally reserved as the final task in our protocol so that participant safety and efficiency were unknown by study personnel during all data collection tasks. VF was conducted by the final author on a GE Advantix digital fluoroscope (GE Healthcare) at a pulse rate of 30 pulses per second and captured at 30 frames per second on a Kay Pentax Digital Swallowing Workstation. During the VF protocol, each participant self-fed 12 barium boluses (via 30-ml medicine cups) uncued under fluoroscopy. Boluses included 3 × 5 ml "ultrathin" liquid barium, 3 × 20 ml "ultrathin" liquid barium, and 3 × 5 ml nectar-thick barium. Three additional 5-ml nectar swallows were swallowed using the "Effortful Swallow" maneuver and are not included in this analysis. The order of bolus administration was not randomized for the following reasons: Small volumes of thin liquid were administered first to minimize potential risk of large-volume aspiration, and nectar was provided last to prevent potential residue from thicker boluses from contaminating other trials. Each medicine cup contained 1 ml more than the target volume (measured by syringe) to control for residual barium left in the cup (Molfenter & Steele, 2013). "Ultrathin" barium was made by taking Varibar (Bracco Imaging) thin liquid and diluting it 50% with water. This concentration of barium (20% w/v) has been shown to be more sensitive to aspiration than traditional 40% w/v Varibar (40% w/v; Fink & Ross, 2009).

Data Analysis

Individual bolus clips (total N = 372; 5 ml thin = 123, 20 ml thin = 117, 5 ml nectar = 132) were viewed in randomized order by research assistants (doctoral- and master's-level speech pathology students) using ImageJ software (National Institutes of Health). Research assistants were blind to Day 1 results during the VF rating. Twenty percent of all data were selected at random for repeated analysis by the same rater as well as a second rater from the same pool of research assistants to execute reliability analysis using two-way mixed ICCs for consistency. Twenty-one swallows were excluded for piecemeal deglutition (lacked volumetric control), and three swallows were excluded for image quality. Each individual swallow was analyzed on functional swallowing measures: swallowing safety and efficiency. The 8-point Penetration–Aspiration Scale (PAS; Rosenbek, Robbins, Roecker, Coyle, & Wood, 1996) was used to measure swallowing safety. The worst PAS score across each participant's nine boluses was used to represent their PAS score. Scores were then reduced to binary categories of "safe" (PAS of 1–2) and "unsafe" (PAS ≥ 3) based on previous normative samples (Allen, White, Leonard, & Belafsky, 2010; Daggett, Logemann, Rademaker, & Pauloski, 2006). Twenty percent of the data were subjected to interrater and intrarater reliability and yielded "excellent" scores (Fleiss, 1986; intrarater ICC = 0.88, 95% CI [0.83, 0.92]; interrater ICC = 0.96, 95% CI [0.79, 0.90]).

Postswallow residue was measured using the Normalized Residue Ratio Scale (NRRS) for the valleculae (NRRSv) and pyriform sinus (NRRSp; Pearson, Molfenter, Smith, & Steele, 2013). The NRRS expresses the pixels of residue relative to the pixels of the spatial housing (the vallecula or pyriforms) as well as a function of the squared C2–C4 distance (to control for subject size). All NRRS measures were taken after initial swallows on the postswallow rest frames, as originally described in Pearson et al. (2013). Recent research on a large sample of mixed etiology patients has provided functional NRRS cutoffs that correspond to aspiration risk (Steele et al., 2016). Using these cutoffs, participants with any single NRRSv score > 0.082 or NRRSp score > 0.067 were considered "inefficient." If all nine boluses had NRRS scores under these cutoffs, they were considered "efficient." Twenty percent of NRRS ratings were subjected to interrater and intrarater reliability (NRRSv: intrarater ICC = 0.89, 95% CI [0.83, 0.93]; interrater ICC = 0.74, 95% CI [0.61, 0.82]; NRRSp: intrarater ICC = 0.97, 95% CI [0.96, 0.98]; interrater ICC = 0.86, 95% CI [0.79, 0.91]). All values achieved "excellent" ratings with ICC > 0.75 except NRRSv, which narrowly missed this cutoff (0.74) and is described as having "good" reliability (Fleiss, 1986).

Statistical Analysis

All statistical analyses were conducted in SPSS Version 22. Distributions and descriptive statistics of all independent variables were calculated separately by safety and efficiency conditions. For continuous variables, univariate analyses of variance were calculated for both safety and efficiency categories for age and BMI. Where appropriate (based on significant correlational findings), age and/or height was included as a covariate to control for the known influence of participant age/size on several of our variables such as grip strength (Mathiowetz et al., 1985), maximal tongue strength (Nicosia et al., 2000), and pharyngeal volume (Inamoto et al., 2015). Effect size was quantified using Cohen's d, with values of .20–.49 considered small effects, .50–.79 considered medium effects, and .80+ considered large effects (Kotrlik & Williams, 2003). Pearson's chi-square analyses were conducted for each categorical independent variable by safety and efficiency conditions. Sensitivity and specificity were calculated for significant categorical independent variables. A Bonferroni adjustment was used to correct for the 10 comparisons; therefore, two-tailed *p* values of < .005 were considered statistically significant.

Results

Pearson correlations revealed that participant height was significantly related to pharyngeal volume (r = .47, p = .001), anterior tongue strength (r = .39, p = .008), posterior tongue strength (r = .40, p = .008), and hand grip strength (r = .76, p < .001) and age was negatively correlated to anterior tongue strength (r = −.40, p = .008), posterior tongue strength (r = −.61, p < .001), and hand grip strength (r = −.48, p = .001); thus, corresponding univariate analyses of covariance were conducted to control for height/age in these variables.

Swallowing Safety

Of the 372 boluses administered, the overall distribution of the PAS score was as follows: 261 scores of 1, 103 scores of 2, eight scores of 3, and one score of 5. The nine aberrant scores (PAS ≥ 3) represented eight of 44 participants, which results in classifying only 18% of the participants as unsafe. Unsafe swallowing status is equally distributed between men and women. Inferential statistics (Table 2) reveal that none of the variables included in this study differs significantly between those participants with safe versus unsafe swallowing.

Swallowing Efficiency

The NRRSv and NRRSp were measured on the original sample of 372 boluses (NRRSv: M = 0.017, minimum = 0.00, and maximum = 0.54; NRRSp: M = 0.028, minimum = 0.00, and maximum = 2.72). Of note, 64 boluses demonstrated NRRSv and/or NRRSp scores above cutoffs. These 64 boluses with significant amounts of residue represented 16 of 44 (36%) of the participants. Inefficient swallowing status was relatively equally distributed between men (n = 9) and women (n = 7). Several independent variables appeared to differentiate efficient and inefficient swallowers (Table 3). Under a conservative corrected *p* value (to control for multiple comparisons), however, only pharyngeal volume is significantly different. Participants with inefficient swallows had greater pharyngeal volume than those who had efficient swallows, with a strong effect (p = .002, d = 0.81). Despite the fact that other values failed to reach statistical significance at p < .005, it is worth calculating their effect size to explore their potential clinical significance. Participants with poor efficiency appear to be older (d = 0.65, medium effect) and have weaker posterior tongue strength (d = 0.70, medium effect).

In their systematic review regarding the prevalence and risk factors for dysphagia in healthy older adults, Madhavan and colleagues point out that identifying variables that are associated with evidence of impaired swallowing using univariate analyses limits our ability to predict the value of these variables to detect dysphagia in community-dwelling seniors (Madhavan et al., 2016). Thus, despite a relatively low sample size, we decided to conduct an exploratory post hoc logistic regression to ascertain the effects of the significant and marginally significant independent variables (age, pharyngeal volume, 3-oz WSC, EAT-10) on the likelihood that participants have inefficient swallowing. Linearity of the continuous variables with respect to the logit of the dependent variable was confirmed using the Box–Tidwell procedure. The logistic regression model was statistically significant, $\chi^2(5) = 17.093$, p = .002, and

Table 2. Distribution of continuous and categorical independent variables by swallow safety status as well as inferential statistics for each variable.

	Safe				Unsafe				ANOVA	
Continuous variables	***M***	***N***	**Lower CI**	**Upper CI**	***M***	***N***	**Lower CI**	**Upper CI**	***F***	***p***
Age (years)	76.3	36	73.9	78.7	79.4	8	72.7	86.0	1.17	.280
Body mass index	26.4	36	25.4	27.4	26.9	8	22.5	31.4	0.15	.702
Anterior tongue (kPa)[a]	36.7	36	32.5	40.8	39.6	8	31.6	47.6	1.61	.212
Posterior tongue (kPa)[a]	39.5	36	34.1	44.8	41.4	8	34.8	47.9	1.77	.192
Hand grip strength (kg)[a]	26.3	36	23.0	29.7	26.0	8	17.3	34.8	0.77	.385
Pharyngeal volume (cc)[b]	34.1	36	31.1	37.2	36.2	8	27.0	45.4	0.31	.580
	Safe				**Unsafe**				**Chi-square**	
Categorical variables		***N***		***N***		***N***		***N***	χ^2	***p***
Sex	Male	17	Female	19	Male	4	Female	4	0.02	.887
3-oz WSC	Pass	29	Fail	7	Pass	6	Fail	2	0.12	.725
EAT-10	Pass	32	Fail	4	Pass	7	Fail	1	0.01	.911
Frailty Index	Not frail	15	Prefrail/frail	21	Not frail	3	Prefrail/frail	5	0.05	.828

Note. ANCOVA = analysis of covariance; ANOVA = analysis of variance; CI = confidence interval; EAT-10 = 10-item Eating Assessment Tool; kPA = kilopascals; WSC = water swallow challenge; cc = cubic centimeters.

[a]ANCOVA model control for influence of subject age and height. [b]ANCOVA model control for influence of subject height.

Table 3. Distribution of continuous and categorical independent variables by swallow efficiency status as well as inferential statistics for each variable.

	Efficient				Inefficient				ANOVA	
Continuous variables	*M*	*N*	Lower CI	Upper CI	*M*	*N*	Lower CI	Upper CI	*F*	*p*
Age (years)	75.1	28	72.4	77.8	79.8	16	76.4	83.5	5.02	.030
Body mass index	26.2	28	24.9	27.5	27.0	16	25.0	28.9	0.50	.482
Anterior tongue (kPa)[a]	38.2	28	33.5	42.9	35.4	16	29.4	41.5	1.19	.920
Posterior tongue (kPa)[a]	43.6	28	37.9	49.3	33.2	16	26.6	39.8	1.99	.166
Hand grip strength (kg)[a]	27.1	28	23.2	30.9	24.9	16	19.6	30.2	0.05	.824
Pharyngeal volume (cc)[b]	31.8	28	28.6	35.9	39.3	16	34.3	44.4	11.53	.002
	Efficient				**Inefficient**				**Chi-square**	
Categorical variables		*N*		*N*		*N*		*N*	χ^2	*p*
Sex	Male	12	Female	16	Male	9	Female	7	0.73	.392
3-oz WSC	Pass	25	Fail	3	Pass	10	Fail	6	4.49	.034
EAT-10	Pass	27	Fail	1	Pass	12	Fail	4	4.64	.031
Frailty Index	Not frail	14	Prefrail/frail	14	Not frail	4	Prefrail/frail	12	2.63	.105

Note. ANCOVA = analysis of covariance; ANOVA = analysis of variance; CI = confidence interval; EAT-10 = 10-item Eating Assessment Tool; kPA = kilopascals; WSC = water swallow challenge; cc = cubic centimeters.

[a]ANCOVA model control for influence of subject age and height. [b]ANCOVA model control for influence of subject height.

explained 44.1% (Nagelkerke R^2) of the variance for the identification of inefficient swallowing. When controlling for the other independent variables, age (p = .045) and pharyngeal volume (p = .043) significantly predicted inefficient swallowing. With every increased cubic centimeter of pharyngeal volume, there was a 1.11 increase in the odds of having inefficient swallowing. With every increased year of age, there was a 1.13 increase in the odds of having inefficient swallowing.

Discussion

This study describes noninvasive and feasible measures of swallowing (anthropometric, questionnaire/scale, and behavioral measures) in a series of 44 healthy seniors (aged 65 years and older). These measures were compared in individuals with videofluoroscopic evidence of functional swallowing versus evidence of deficits in swallowing safety (penetration–aspiration) and/or swallowing efficiency (residue). Our goal was to determine whether any of these noninvasive, non-VF tools/measures could adequately distinguish seniors with functional swallowing versus deficits in swallowing safety and/or efficiency. Accurate identification of seniors with dysphagia has the potential to improve QOL and positively impact nutrition, hydration, and/or respiratory health. Ideally, healthy seniors may have the capacity to reverse their age-related deficits in swallowing to prevent the aforementioned negative sequalae of dysphagia through the identification of appropriate, physiologically targeted interventions.

The natural loss of muscle strength and coordination, known as sarcopenia, has often been cited as a potential cause for the decline in swallowing function present in the context of healthy aging. For example, reductions in maximal isometric strength have been confirmed in the tongue in healthy aging populations (Butler et al., 2011; Fei et al., 2013; Robbins et al., 2005; Vanderwegen, Guns, Van Nuffelen, Elen, & De Bodt, 2013). The cross-sectional area of the geniohyoid has been shown to reduce in aging, and reductions are associated with aspiration status (Feng et al., 2013). Our hypothesis was that swallowing efficiency status would be differentiated by measures that capture/represent oropharyngeal strength (tongue strength, pharyngeal volume). In our study, one single variable, pharyngeal volume, emerged as significantly differentiating swallowing function at our adjusted p value. Specifically, participants with inefficient swallowing (significant residue) had larger pharyngeal volumes after controlling for participant height. Our interpretation is that larger pharyngeal volumes represent worse pharyngeal atrophy, which in turn manifests in poorer pharyngeal muscle function. Loss of pharyngeal musculature in aging has been confirmed by several studies (Aminpour, Leonard, Fuller, & Belafsky, 2011; Eikermann et al., 2007; Molfenter et al., 2015). The primary function of the longitudinal pharyngeal muscles is to shorten/elevate the pharynx/larynx to reduce the distance the bolus must travel and open the upper esophageal sphincter, while the pharyngeal constrictors squeeze around the bolus to propel it efficiently through the upper esophageal sphincter (Kahrilas, Logemann, Lin, & Ergun, 1992; Leonard et al., 2004b). Deficits in either of these actions will theoretically result in postswallow residue. Our findings lend support to this interpretation. Significant vallecular and/or pyriform sinus residue was defined in this study according to the risk of this residue leading to aspiration based on recently reported cutoffs (Steele et al., 2016). Thirty-six percent (16/44) of our sample had significant residue in one or more locations. At the swallow level, 43 of 372 swallows (8.6%) displayed significant vallecular residue (M = 0.017, minimum = 0.00, and maximum = 0.54), and

21 of 372 (4.2%) displayed significant pyriform sinus residue (M = 0.028, minimum = 0.00, and maximum = 2.72).

None of the measures included in this study dissociated safe from unsafe swallowing. For this analysis, we chose to classify swallowing safety status at the participant level. That is, any individual with a single swallow with a PAS score ≥ 3 resulted in that participant being classified as "unsafe." This resulted in eight of 44 (18%) individuals being "unsafe." Our low distribution of unsafe individuals in this sample may have underpowered our analyses. This is an inherent limitation of conducting this research in healthy individuals. Our findings for participant-level penetration rates are very closely matched by Daggett et al. (2006), who found that 16.8% of healthy older adults (over 50 years old) penetrated. Yet, when we go back to the data, we can see that, of the entire data set of 372 swallows, there were only nine swallows that had PAS scores ≥ 3. These swallows (eight scores of 3, one score of 5) came from nine individuals. Therefore, the swallow level of safety impairment in this data set is 9 of 372 (2.4%). The swallow level results mimic the work of Allen and colleagues (2010), who found that 2.9% of swallows had penetration. Yet, their participant level prevalence of penetration was slightly lower than ours (8/86 = 9.4%). Importantly, this comparison of our data with the literature gives us confidence in the "health" of our participants. This is especially robust given that we used "ultrathin" barium (~20% w/v concentration), which has been shown to be more sensitive to penetration–aspiration compared with standard 40% w/v concentrations (Fink & Ross, 2009).

In our study, we did not find any statistically significant relationships between swallow status (safe vs. unsafe, efficient vs. inefficient) and any measures of strength (anterior tongue, posterior tongue, and hand grip strength). Butler and colleagues (2011) investigated tongue and grip strength in healthy seniors who did aspirate compared with those who did not aspirate. They found that aspirators had significantly lower tongue strength in both the anterior and posterior positions. They did not find an association between aspiration and grip strength but reported a significant moderate correlation between posterior tongue strength and grip strength (r = .34). Our data reveal a similar relationship (anterior: r = .33; posterior: r = .42). Notable differences between these studies are the instrumentation method (endoscopy), the higher cutoff for the unsafe group (PAS score of 6–8), and the lack of residue measures. Finally, our analysis controlled for subject height given that all measures of strength were significantly correlated with it.

One might argue that clinical frailty is the manifestation of sarcopenia. Fried and colleagues (2001) developed a five-item scale to categorize seniors as nonfrail, prefrail, and frail. This scale is meant to capture frailty at a global level and is not swallow specific. Rofes and colleagues (2010) used the Frailty Index to describe the swallowing of 45 hospitalized patients and documented disruptions to swallowing safety and swallowing efficiency. Consistent with our hypothesis, we did not find any association between our frailty categorization and swallowing safety/efficiency status in this sample of healthy community-dwelling seniors. Indeed, none of the more global measures of strength/frailty (Frailty Index, grip strength, and BMI) differentiated safety or efficiency status. Our findings for the Frailty Index are in contrast with Gonzáles-Fernández and colleagues (2014), who found that prefrail status was associated with signs of aspiration on a water-drinking task but acknowledged the need for confirmation with an instrumental assessment. We did a post hoc analysis to explore whether any of the five binary components of the Frailty Index (shrinking, weakness, exhaustion, low activity, and slow walking speed) were different by swallowing safety or efficiency status. This resulted in 10 (5 components × 2 conditions) exploratory chi-square analyses. Interestingly, 100% of seniors with "low activity" also had inefficient swallowing (4/4), whereas 30% of seniors with normal activity levels had inefficient swallowing (12/40; p = .013). Despite the low distribution of individuals who scored with "low activity" (likely the result of a sampling bias), the Frailty Index and its components warrant further prospective investigation.

We had hypothesized that swallowing safety status would be best differentiated by performance on the 3-oz WSC and EAT-10. However, our study did not yield any significant differences in the proportions of unsafe swallowing for either of these measures. Interestingly, there was a trending relationship between failing either the EAT-10 or the 3-oz water swallow task and swallow efficiency. There were more participants who had abnormal EAT-10 scores and had an inefficient swallow (4/16) than those who had abnormal EAT-10 scores and did not have an inefficient swallow (1/28; p = .031, sensitivity = 0.96, specificity = 0.25). Post hoc item analysis of EAT-10 questions revealed that most responses that our participants rated as abnormal (scores of 1 or higher) were Q4, "swallowing solids takes extra effort" (n = 6); Q5, "swallowing pills takes extra effort" (n = 11); Q8, "food sticks in my throat" (n = 6); and Q9, "I cough when I eat" (n = 5). The remaining questions had fewer than five respondents rate answers > 0. We chose to categorize the EAT-10 data as per the original article (Belafsky et al., 2008): < 3 (pass) and ≥ 3 (fail). It is acknowledged that alternative values may have yielded different results (Cheney, Siddiqui, Litts, Kuhn, & Belafsky, 2015). With respect to the 3-oz WSC, the proportion who failed and had an inefficient swallow (6/16) trended toward being significantly greater than those who failed and had an efficient swallow (3/28; p = .034, sensitivity = 0.89, specificity = 0.38). Findings for Q9 of the EAT-10 and the 3-oz WSC were surprising, given that these tests/questions exploit signs of aspiration, not residue. One speculation is that these healthy seniors may be more inclined to experiencing coughing as the result of postswallow aspiration of residue rather than aspiration before or during the swallow.

This research adds to the growing body of literature that documents functional disruptions to swallowing in healthy aging and emphasizes the importance of routinely screening healthy seniors for swallowing difficulties to prevent aspiration pneumonia and maximize future nutrition and hydration outcomes in this population. Age, in and of itself, appears to be a potential risk factor for having inefficient swallowing (a trending finding). Unfortunately, in this study, none of the widely available tests, patient-reported outcomes, or strength measuring devices was a significant predictor of functional impairment to swallowing. The sole significant predictor of swallowing impairment was pharyngeal atrophy as measured by AP. AP is relatively inexpensive, easy to administer, and noninvasive, yet it is a novel tool in dysphagia assessment/management. This work establishes the feasibility of the use of AP in dysphagia research. We feel that this tool shows promise for inexpensively and noninvasively capturing pharyngeal lumen volume. Yet, we also recognize that alternative surrogate measures to represent (or predict) pharyngeal volume will be desirable for clinical uptake and should be a goal for future research. Post hoc analyses in this data set revealed that two-dimensional pharyngeal area at rest is moderately correlated with pharyngeal volume ($r = .554$, $p < .001$) but it did not detect significant differences between efficient and inefficient swallows in a univariate analysis of variance ($F = 0.743$, $p = .394$). Future research should examine the relationship between pharyngeal lumen volume and biomechanics of swallowing to identify potential relationships between lumen size and physiological impairment and to identify potential therapeutic targets to combat and/or reverse pharyngeal atrophy.

We recognize that this study is not without limitations. First, our relatively small sample was skewed to low distributions of unsafe and inefficient swallows. This is expected in a healthy sample but limits the statistical power of our analyses. Furthermore, it is plausible that we have a sampling bias, whereby individuals who attend day programs at local senior centers and volunteer for research studies are in fact "healthier" than the average healthy senior. We tried to limit this by recruiting an equal distribution of individuals with both weak and normal tongue strengths. Second, we recognize that our method for dichotomizing individuals based on their worst PAS and NRRS performance across a series of nine swallows could be considered conservative and that other methods may warrant exploration (Steele & Grace-Martin, 2017). Related to this, our VF stimuli were restricted, and replication with larger volumes and a wider array of textures/viscosities is warranted. Third, we did not test an exhaustive list of potential screening tools and tests to predict swallowing outcomes on VF. For example, measures of respiratory function, cough reflex testing, sensory evaluation of taste/smell/stereognosis, and swallow functional reserve may be worthwhile variables to include in future research. Finally, our methods did not capture the nutritional status of these individuals beyond the very basic (and notably flawed) measure of BMI. We advocate that future work expand on the variables that we tested.

Conclusion

In conclusion, we collected swallowing profiles of 44 healthy seniors that included feasible, noninvasive swallowing tests and measures including anthropometrics, questionnaires/scales, and behavioral data and compared them with gold-standard videofluoroscopic measures of swallowing safety (penetration–aspiration) and efficiency (postswallow residue). Our analysis revealed that none of the measures collected significantly differentiated unsafe from safe swallowing. Several variables approached significance for differentiating efficient from inefficient swallowing: increasing age, failing the EAT-10 questionnaire, and failing the 3-oz WSC. An exploratory logistic regression revealed that pharyngeal volume and age appear to significantly differentiate inefficient from efficient swallowing. Increasing age and larger pharyngeal volumes (which we interpret to represent pharyngeal muscle atrophy) were associated with inefficient swallowing.

Acknowledgments

This study was funded by NIH National Institute on Deafness and Other Communication Disorders 1R21DC015067. The authors would like to thank Charles Lenell, Emily Ottinger, Shelby Norman, Il Young Jung, Julie Bancroft, Wendy Liang, Chelsea Sandler, Marina Casale, and Katrin Gabriel for their assistance during data collection and data analysis. Portions of this work were presented at the 2017 ASHA Convention in Los Angeles, CA.

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