Research Article

Physiological Compensation for Advanced Bolus Location at Swallow Onset: A Retrospective Analysis in Healthy Seniors

Erica G. Herzberg,^{a,b} Danielle Brates,^a and Sonja M. Molfenter^a

Purpose: Previous work has established that advanced bolus location at swallow onset (BLSO) alone is not correlated with an increased swallowing safety risk in healthy seniors. The primary goal of this retrospective study was to examine whether healthy seniors systematically alter their laryngeal vestibule closure reaction time (LVCrt) to maintain a safe swallow in the context of advanced BLSO. The secondary goal was to determine if longer LVCrt distinguished Penetration–Aspiration Scale (PAS; Rosenbek, Robbins, Roecker, Coyle, & Wood, 1996) scores of 1 versus 2.

Method: Videofluoroscopy studies from 43 healthy seniors (21 men, 22 women; $M_{\text{age}} = 76.7$ years, $SD = 7.2$) were analyzed. LVCrt was calculated for 3 × 5 ml and 3 × 20 ml thin liquid barium boluses per participant. PAS and BLSO (Modified Barium Swallow Impairment Profile Component 6) were scored for all swallows. Reliability (intraclass correlation coefficient > .75) was established on

all measures. A linear mixed-effects regression was run to examine the effect of PAS and BLSO on LVCrt while controlling for bolus volume and repeated swallow trial.

Results: There was a main effect of BLSO ($F = 4.6$, $p = .004$) and PAS ($F = 29.3$, $p < .001$) on LVCrt. Post hoc pairwise comparisons revealed that LVCrt was significantly faster in BLSO scores of 3 (pyriforms) compared to scores of both 0 (posterior angle of the ramus) and 1 (valleculae). Significantly prolonged LVCrt was observed in PAS scores of 2 in comparison to 1. No significant main effects of bolus volume or trial, or interactions, were observed.

Conclusions: Our findings suggest that healthy seniors compensate for advanced BLSO by increasing their LVCrt. Furthermore, faster LVCrt was shown to distinguish PAS scores of 1 versus 2. Additional work should explore the relationship between LVCrt, BLSO, and PAS scores in dysphagic populations, specifically those with known sensory impairments.

Initiation of the pharyngeal swallow is typically characterized by the onset of brisk, superior–anterior hyoid movement. Traditionally, swallow initiation occurring after the bolus head passes the ramus of the mandible was defined as “delayed” (Logemann, 1997; Robbins, Hamilton, Lof, & Kempster, 1992). Such “delays” have been repeatedly observed and reported in aging populations (Ekberg & Feinberg, 1991; Kendall & Leonard, 2001; Kendall, Leonard, & McKenzie, 2004; Kendall, McKenzie,

Leonard, Gonçalves, & Walker, 2000; Mendell & Logemann, 2007; Molfenter & Steele, 2012; Robbins et al., 1992; Tracy et al., 1989). Delayed swallow initiation often raises concern for airway invasion, given the possibility of the bolus being adjacent to an open, unprotected airway. In clinical practice, advanced bolus location at swallow onset (BLSO) is often cited as a cause of aspiration.

Subsequent research has shown, however, that advanced BLSO alone is not correlated with increased safety risk. In a study of 10 older adults ($M_{\text{age}} = 71.6 \pm 7.5$ years), Stephen, Taves, Smith, and Martin (2005) found that, while 52% of swallows were initiated with the bolus head below the intersection of the base of the tongue and the ramus of the mandible, penetration/aspiration did not occur in any of the swallows analyzed (Stephen et al., 2005). In a study of 76 healthy adults (aged 21–97 years, $M = 58.7 \pm 23$), Martin-Harris, Brodsky, Michel, Lee, and Walters (2007) found that, while 94 of the 152 swallows analyzed were

^aDepartment Communicative Sciences and Disorders, NYU Steinhardt, New York

^bDepartment of Speech-Language Pathology, NYU Langone Health–Rusk Rehabilitation, New York

Correspondence to Erica G. Herzberg: eh1695@nyu.edu

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triggered with the bolus head below the ramus of the mandible, a Penetration–Aspiration Scale (PAS) score (Rosenbek, Robbins, Roecker, Coyle, & Wood, 1996) of 3 or greater was observed on only three trials (Martin-Harris et al., 2007). Both studies utilized two repeated trials of 5-ml thin liquid boluses. The authors of both studies concluded that advanced BLSO alone does not represent a disorder. They argue that this “delay” only poses a threat of airway invasion in the context of physiological impairment of the airway protective mechanisms.

Work in the field of motor learning has suggested that variability is inherent in any complex motor system and that such variability allows the system to effectively adapt to a variety of constraints. It has also been argued that such dynamic systems are continuously evolving throughout the life span. As a result, in the field of sports medicine, it has been argued that rehabilitation should be aimed not at attaining an “ideal” motor pattern but rather at ensuring that individuals have the functional capacity to adapt to any constraints faced (Davids, Glazier, Araújo, & Bartlett, 2003). This led us to consider the specific adaptations healthy older adults make in order to achieve a safe swallow when faced with delayed swallow initiation. An understanding of these mechanisms might ultimately allow clinicians to develop more appropriately tailored treatment plans and may provide a theoretical basis for the development of novel treatment methods.

The primary goal of the current study is to examine laryngeal vestibule closure reaction time (LVCrt) as a potential airway protective mechanism, which allows healthy older adults with normal airway protection to compensate for advanced BLSO. Our hypothesis was that healthy seniors systematically alter their LVCrt in order to maintain a safe swallow in the context of advanced BLSO. LVCrt captures the speed at which complete laryngeal vestibule closure (LVC) is achieved. The secondary aim of this study was to determine whether longer LVCrt distinguished PAS scores of 1 (contrast does not enter the airway) versus 2 (contrast enters the airway above the vocal folds and is ejected). Our hypothesis was that PAS scores of 2 would exhibit longer LVCrt than PAS scores of 1. Both aims have the potential to contribute to understanding physiological variation in normal swallowing in healthy older adults. Furthermore, these analyses will serve as a foundation for the exploration of these relationships in swallows with impaired airway protection.

Materials and Method

Participants

This study represents a secondary analysis of data collected from 44 healthy seniors who were recruited from local community centers and was approved by the New York University Institutional Review Board. All participants signed informed consent. Exclusionary criteria for the original study included a history of dysphagia, neurological insult/injury, and/or head and neck cancer or surgery. In

order to be included in this study, image quality and collimation had to be adequate for our planned analysis and PAS scores had to be within the normal range (scores of 1 or 2). This ultimately yielded data from 43 healthy seniors (21 men) ages 65–95 years ($M = 76.7$, $SD = 7.2$).

Videofluoroscopy Procedure

Videofluoroscopic data were collected on a GE Advantix digital fluoroscope (GE Healthcare) at 30 pulses per second and captured on a KayPENTAX digital swallowing workstation at 30 frames per second. In this retrospective analysis, 3×5 ml thin liquid barium and 3×20 ml thin liquid barium boluses were analyzed. All boluses were self-administered via medicine cup, and swallows were uncued. Barium stimuli were standard Varibar (Bracco Imaging) thin liquid barium, diluted with 50% water, to create a 20% weight/volume concentration of “ultra-thin” liquid. This preparation has been shown to improve detection of penetration–aspiration (Fink & Ross, 2009). The order of stimuli was intentionally fixed to minimize risk of potential aspiration of large volumes (5 ml prior to 20 ml) and to minimize contamination of postswallow residue to later occurring swallows.

Data Analysis

Individual swallows were spliced out of the full-length study for randomized analysis. Swallows with a PAS score of 3 or greater were excluded from analysis ($n = 6$). Eight swallows were excluded due to inability to identify one or more event of interest. One swallow was excluded due to incomplete LVC. This yielded 223 swallows for analysis. All data measures were completed using frame-by-frame viewing of each swallow in ImageJ software (National Institutes of Health). In the event that multiple swallows were executed for a single bolus ($n = 8$), BLSO, LVCrt, and PAS scores associated with the initial swallow were recorded. Twenty percent of the data were selected at random and rerated by both the original and a second trained rater to establish intra- and interrater reliability, respectively.

BLSO. The first frame depicting the sudden onset of brisk anterior–superior hyoid movement was identified to indicate onset of the swallow. Next, the BLSO was identified at this moment of swallow onset, according to Component 6 of the MBSImP protocol (Martin-Harris et al., 2008).

- 0: Bolus head at posterior angle of ramus
- 1: Bolus head in valleculae
- 2: Bolus head at posterior surface of the epiglottis
- 3: Bolus head in pyriforms
- 4: No visible initiation at any location

LVCrt. The frame of the BLSO measurement (onset of brisk anterior–superior hyoid movement) was subtracted from the first frame depicting complete LVC and

converted to milliseconds, in order to determine LVCrt (Guedes et al., 2017).

PAS. The 8-point PAS score was rated for each swallow (Rosenbek et al., 1996).

Statistical Analysis

All data were analyzed using SPSS Version 24. Reliability was established using two-way mixed intraclass correlation coefficients. Descriptive statistics were used to determine the distribution of BLSO and PAS scores for each bolus condition. A linear mixed-effects regression was run to examine the effect of PAS and BLSO on LVCrt while controlling for bolus volume and repeat swallow trial. Post hoc pairwise comparisons were completed where appropriate. Main effects were considered statistically significant at $p < .05$. Post hoc pairwise comparisons were completed, and Bonferroni correction was applied where appropriate. When pairwise comparisons were found to be statistically significant, effect size was calculated with Cohen's d .

Results

Reliability results for all variables measured can be found in Table 1. All variables were found to have "excellent" reliability, as indicated by an intraclass correlation coefficient of $> .75$ (Fleiss, 2011). The overall distribution of BLSO scores was 0 = 35%, 1 = 26%, 2 = 14.3%, and 3 = 24.7%. The distribution of PAS scores was 1 = 64.6% and 2 = 35.4%. This is further broken down by bolus volume in Table 2.

The linear mixed-effects regression model revealed a main effect of both BLSO ($F = 4.6$, $p = .004$) and PAS ($F = 29.3$, $p < .001$) on LVCrt. No significant main effects of bolus volume or trial, or interactions, were observed. As can be visualized in Figure 1, post hoc pairwise comparisons revealed that LVCrt was significantly faster in BLSO scores of 3 ($M = 174$ ms, $SD = 27$) compared to scores of both 0 ($M = 268$ ms, $SD = 22$; $p = .006$, $d = 0.95$) and 1 ($M = 266$ ms, $SD = 24$; $p = .009$, $d = 0.92$). Scores of 2 ($M = 206$ ms, $SD = 26$) did not differ significantly from other scores. Furthermore, post hoc pairwise comparisons reveal that significantly prolonged LVCrt was observed in PAS scores of 2 ($M = 284$ ms, $SD = 22$) in comparison to 1 ($M = 172$ ms, $SD = 20$; $p < .001$, $d = 1.13$; see Figure 2).

Discussion

In this study, we explored the relationship between the speed of laryngeal vestibule closure (LVCrt) and both BLSO and PAS scores. PAS scores of both 1 (contrast does not enter the airway) and 2 (contrast enters the airway above the vocal folds and is ejected) have been established to be normal in healthy populations (Allen, White, Leonard, & Belafsky, 2010; Daggett, Logemann, Rademaker, & Pauloski, 2006). Our findings confirmed the hypothesis that, in healthy seniors with safe swallows ($PAS < 3$), quicker speeds of LVCrt would be seen in the setting of advanced BLSO. A faster LVCrt was also seen in PAS scores of 1 versus 2.

These data suggest that healthy seniors systematically compensate for advanced BLSO by increasing the speed of LVC, resulting in a shorter LVCrt. This finding is consistent with the known ability of the oropharyngeal swallow to adapt in response to various sensory stimuli (Steele & Miller, 2010). Afferent fibers are present throughout the pharynx (Mu & Sanders, 2000), and the application of anesthetics to the muscles of the pharynx and larynx has been found to result in an increased occurrence of premature spillage and penetration and aspiration events (Sulica, Hembree, & Blitzer, 2002). While sensory testing was not conducted in the current sample, it is plausible that healthy seniors, receiving sensory feedback indicating a lower BLSO, are able to physiologically compensate by altering their motor response and increasing the rate of LVC.

The dynamical systems theory of motor movement provides a strong theoretical basis for our findings. Swallowing is a highly complex motor skill and involves the coordinated function of many muscle groups, responding to changing sensory input, in order to achieve a safe and efficient outcome. According to dynamical systems theory of motor movement, the individual components of any complex motor system do not act in isolation but rather form "functional synergies," which not only constrain the system's many available degrees of freedom but also promote coordination and flexibility in a dynamic, moving system (Davids et al., 2003; Glazier, Wheat, Pease, & Bartlett, 2006; Thelen, Kelso, & Fogel, 1987). In this way, the swallowing system of a healthy individual, responding to afferent information about bolus location in the pharynx, is able to program and execute a motor pattern that adequately manages this environmental "constraint." The system is self-organizing, such that voluntary control is not required,

Table 1. Reliability results.

Variable	Intrarater			Interrater		
	ICC	95% CI		ICC	95% CI	
Penetration–Aspiration Scale	.88	.83	.92	.86	.79	.90
Bolus location at swallow onset	.97	.95	.98	.85	.77	.90
Laryngeal vestibule closure reaction time	.94	.88	.97	.79	.60	.89

Note. ICC = intraclass correlation coefficient; CI = confidence interval.

Table 2. Distribution of bolus location and swallow onset (BLSO) and Penetration–Aspiration Scale (PAS) scores by bolus volume.

Bolus	Variable	Value	Frequency	Percentage
5 ml thin (<i>N</i> = 116)	BLSO	0	52	44.8
		1	29	25
		2	15	12.9
		3	20	17.2
		4	0	0.0
	PAS	1	87	75
20 ml thin (<i>N</i> = 107)	BLSO	2	29	25
		0	26	24.2
		1	29	27.1
		2	17	15.9
		3	35	32.7
	PAS	4	0	0.0
		1	57	56.5
		2	50	43.5

and changes in one aspect of the system (in this case, initiation of a swallow trigger) will be reflected through compensations in another component (closure of the laryngeal vestibule).

Clinically, it is important to understand that if, as we believe, the swallowing mechanism is a dynamical system, then a potentially problematic event that occurs early in the swallow can still be effectively and safely mediated downstream. This may explain why advanced BLSO alone has not been found to be associated with an increased risk of airway invasion (Martin-Harris et al., 2007; Stephen et al., 2005). Our findings highlight the importance of assessing all aspects of swallow function in relation to each other and the system as a whole, rather than considering individual physiological components in isolation. Furthermore, understanding an individual system's capacity for adaptation and compensation has implications for the prognosis and development of treatment protocols in dysphagic populations.

The distribution of BLSO in this sample of 223 safe swallows adds to the body of evidence showing that, in healthy seniors, advanced BLSO alone should not be considered pathological (Martin-Harris et al., 2007; Stephen et al., 2005). We concur that researchers and clinicians should use caution when associating the location of the bolus at swallow onset with a risk for impaired swallowing safety. This study adds novel data for BLSO in the 20-ml bolus condition. Our results did not indicate differences in LVCrt between bolus volumes in this sample of healthy older adults.

The finding that LVCrt is longer in PAS scores of 2 compared to 1 is not surprising. Presumably, it is the slower speed of LVC that allows time for the bolus to enter the airway, with subsequent ejection as closure is achieved. This work may provide preliminary support for the use of interventions targeting LVCrt in individuals with compromised swallow safety, secondary in part to advanced BLSO.

This study is not without limitations. First, the range of stimuli analyzed was narrow. Future research should expand the analysis to various volumes and viscosities, including habitual sip sizes. This study is further limited by the fact that the data include only swallows with normal airway protection (PAS scores of 1 or 2). Future research should include PAS scores of 3 and greater in order to confirm differences in LVCrt, between safe and unsafe swallows, at each BLSO. This may require exploring alternative methods of quantifying LVC, for swallows where complete LVC is not achieved. Populations with known sensory impairments would be of particular interest. Findings of slower LVCrt in populations with sensory deficits would be of interest, given the potential of exercise to increase the speed of LVCrt (Guedes et al., 2017). Future research should also focus on the kinematic mechanisms that modulate LVCrt in healthy populations.

Figure 1. Pairwise comparison between bolus locations at swallow onset scores by laryngeal vestibule closure reaction time (LVCrt) measured in milliseconds. Error bars represent the standard error. **p* < .0125.

Figure 2. Pairwise comparison between Penetration–Aspiration Scale (PAS) scores of 1 and 2 by laryngeal vestibule closure reaction time (LVCrt) measured in milliseconds. Error bars represent the standard error. * $p < .05$.

Finally, we acknowledge that there are likely to be other physiological adaptations beyond LVCrt that facilitate functional swallowing in the context of advanced BLSO and that future research should explore additional parameters. For example, the velocity of structural displacement of the hyolaryngeal complex may be of interest. Furthermore, the dynamic relationship between various physiological parameters (such structural displacements and velocity and/or event durations and sequences) is of particular interest for future exploration.

Conclusion

Our data suggest that healthy seniors compensate for advanced BLSO by adjusting their LVCrt. Our data also suggest that LVCrt distinguishes normal variation in PAS scores of 1 and 2. Additional work should explore the relationship between LVCrt, BLSO, and PAS scores in dysphagic populations, specifically those with known sensory deficits.

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