Review Article

Respiratory Phase and Lung Volume Patterns During Swallowing in Healthy Adults: A Systematic Review and Meta-Analysis

Theresa Hopkins-Rossabi,^a Philip Curtis,^a Mark Temenak,^a
Corinne Miller,^b and Bonnie Martin-Harris^a

Purpose: The coordination of respiration with swallowing is critical for facilitation of airway protection and the efficiency of movements that propel ingested material through the upper aerodigestive tract. Confirmation of a predominant pattern in healthy adults provides a platform for comparison to aberrant patterns observed in the population with swallowing impairment (dysphagia).

Method: A comprehensive search of published research in MEDLINE via PubMed 1946–2018, Embase 1947–2018, and Proquest Dissertations & Theses Global 1861–2018 was completed.

Results: Thirty-seven articles meeting inclusion criteria were selected for data extraction, and the findings

were reviewed. In addition, a meta-analysis of the data was completed. A significantly higher occurrence ($p < .001$) of expiration prior to and following the swallow was found when compared to 3 other patterns. The predominance of the pattern was influenced by increases in bolus volume when controlling for participant sample size.

Conclusion: Determination of this predominant pattern provides a normative framework for evaluating respiratory–swallow coordination in adults across the age span and highlights the relevance for assessing and incorporating respiratory swallowing coordination during assessment and interventions.

The coordination of respiration with swallowing, and specifically respiratory phase and lung volume surrounding the pharyngeal aspects of swallowing, is critical for facilitation of airway protection and the efficiency of movements that propel ingested material through the upper aerodigestive tract (Martin-Harris, 2006; Martin, Logemann, Shaker, & Dodds, 1994). As such, many studies have attempted to characterize this coordination via describing the phases that bracket the obligate respiratory pause during the pharyngeal swallow (Ayuse et al., 2006; Balasubramaniam & Bhat, 2012; Boden et al., 2009; Dozier, Brodsky, Michel, Walters, & Martin-Harris, 2006; Fontecave-Jallon & Baconnier, 2016; Gürgör et al., 2013; Hårdemark Cedborg et al., 2010, 2009; Hirst, Ford, Gibson, & Wilson,

2002; Hiss, Treole, & Stuart, 2001; Kelly, Huckabee, & Cooke, 2006; Kelly, Huckabee, Jones, & Carroll, 2007; Kelly, Huckabee, Jones, & Frampton, 2007; Klahn & Perlman, 1999; Lederle, Hoit, & Barkmeier-Kraemer, 2012; Leslie, Drinnan, Ford, & Wilson, 2005; Martin et al., 1994; Martin-Harris et al., 2005; Martin-Harris, Brodsky, Price, Michel, & Walters, 2003; Matsuo, Hiiemae, Gonzalez-Fernandez, & Palmer, 2008; Matsuo & Palmer, 2015; McFarland & Lund, 1995; McFarland, Lund, & Gagner, 1994; McFarland et al., 2016; Nilsson, Ekberg, Olsson, Kjellin, & Hindfelt, 1996; Nishino, Yonezawa, & Honda, 1985; Palmer & Hiiemae, 2003; Paydarfar, Gilbert, Poppel, & Nassab, 1995; Perlman, He, Barkmeier, & Van Leer, 2005; Pinto, Balasubramaniam, & Acharya, 2017; Preiksaitis, Mayrand, Robins, & Diamant, 1992; Preiksaitis & Mills, 1996; Smith, Wolkove, Colacone, & Kreisman, 1989; Wang, Li, Lee, Shieh, & Lin, 2016; Wang, Cheng, et al., 2015; K. Wheeler Hegland, Huber, Pitts, Davenport, & Sapienza, 2011; K. M. Wheeler Hegland, Huber, Pitts, & Sapienza, 2009). Further, studies have also measured lung volume relationships at the initiation of swallowing because of the effect of lung volume on the mechanisms of airway closure and bolus propulsion (McFarland et al., 2016; Paydarfar et al., 1995; K. Wheeler Hegland et al., 2011; K. M. Wheeler

^aDepartment of Communication Sciences and Disorders, Northwestern University, Evanston, IL

^bGalter Health Sciences Library, Feinberg School of Medicine, Northwestern University, Chicago, IL

Correspondence to Theresa Hopkins-Rossabi:
trossabi@u.northwestern.edu

Editor-in-Chief: Julie Liss

Editor: Michelle Ciucci

Received August 10, 2018

Revision received October 24, 2018

Accepted November 20, 2018

https://doi.org/10.1044/2018_JSLHR-S-18-0323

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

Hegland et al., 2009). The methods used to study these complex relationships have been varied and may confound the study findings. Despite the variation in measurement methods, there does appear to be general agreement that swallowing occurring during the expiratory limb of respiration at mid–low lung volume offers physiologic and airway protective advantages (Charbonneau, Lund, & McFarland, 2005; Martin et al., 1994; Martin-Harris et al., 2005, 2003; McFarland & Lund, 1995; McFarland et al., 2016; Paydarfar et al., 1995; Perlman et al., 2005).

Precise understanding of respiratory–swallow phase patterns serves as a basis for comparison for how aberrant respiratory–swallow phase patterns may affect swallowing physiology. The primary outcome in studies investigating respiratory–swallow phase patterns has been the determination of when in the respiratory cycle, inspiration or expiration, the swallow occurs. The majority of investigations have recorded and analyzed the respiratory phase preceding and following the swallow. The most frequently reported pattern was expiration preceding and following the swallow; however, the frequency of this pattern ranged depending on several variables including bolus volume, consistency, swallowing task, and cueing (Boden et al., 2009; Wang, Cheng, et al., 2015). The purpose of this investigation was to systematically review the literature for empirical evidence that supports the presence of predominant phase and volume patterns in healthy adult humans.

Method

Literature Search

A protocol was established prior to initiation of the systematic review to define the review question, rationale, and inclusion criteria. In September 2017 and July 2018, a medical librarian searched MEDLINE via PubMed 1946–2017, Embase 1947–2017, and Proquest Dissertations & Theses Global 1861–2017. Keywords and subject headings (when available) were utilized to locate literature on the coordination of breathing and swallowing in healthy adults (see the Appendix for search terms). A filter adapted from the Cochrane Highly Sensitive Search Strategy was used to focus the search to literature on humans. EndNote software was used to identify and remove 3,553 duplicate records. The remaining 12,861 records were uploaded to Rayyan, an online systematic review manager, to expedite the initial screening of abstracts and titles for the systematic review (Ouzzani, Hammady, Fedorowicz, & Elmagarmid, 2016). A repeat literature search was conducted in August 2018, which identified 866 unique records indexed since the original search in September 2017. No new journal articles met inclusion criteria.

Two reviewers independently evaluated the titles and abstracts of articles for inclusion. Blinding was then removed, and the two reviewers agreed by consensus on full article review. In addition, an ancestral bibliography

search was completed, which entails reviewing the complete bibliography of each article identified for inclusion to ensure no relevant article was missed. The inclusion criteria were as follows: Study sample consisted of adult humans with no history of dysphagia (including swallowing impairment related to esophageal dysphagia or medications); objective methods were used to measure respiratory phase (and lung volume in some of the studies); objective methods were utilized to detect swallow; outcome measures identified the respiratory phase at swallow onset (and offset); and the bolus was clearly defined in terms of viscosity, volume, and manner of presentation.

The methodological quality review based on the Joanna Briggs Institute's Critical Appraisal tool, a critical appraisal tool for descriptive studies, was completed by three reviewers (Hannes, Lockwood, & Pearson, 2010). The primary reviewer completed two data extraction spreadsheets at different times for each article, and intra-rater reliability was determined for all data extracted to be over 90%. In addition, 20% of the articles were randomly assigned to an additional reviewer for data extraction. All disagreements of data extraction were resolved by either consensus or returning to the content of the article to confirm accuracy. Data extraction items included demographics of participants (age, sex); bolus type administered (viscosity, volume, presentation method); percentage of occurrence of respiratory phase (inspiration or expiration) at the onset and offset of the swallow; and lung volume at swallow initiation, if available.

Meta-Analysis

Raw percentages of respiratory phase before and after swallow were transformed into logit event rates using Comprehensive Meta-Analysis (CMA) software. Many studies reported multiple swallow trials for each group of participants, creating nonindependent data from the same study (i.e., effect sizes from the same group of participants are correlated with one another). Accordingly, traditional meta-analysis techniques, which require each effect size to come from an independent sample of participants, were not well suited for these types of data. In order to include all effect sizes from each study and to accurately model the dependent data structure arising from these correlated effect sizes, the robust variance estimation (RVE) method was employed (Hedges, Tipton, & Johnson, 2010). This method employs an assumed covariance structure between dependent observations, which is then systematically manipulated to check for sensitivity to different correlation strengths between effect sizes from the same group of participants. All analyses were run using the robumeta package in R (Fisher, Tipton, & Zhipeng, 2017). Two models were created to answer two research questions: One model was run to determine if there was a predominant respiratory–swallow phase pattern across all bolus sizes, and the second model was to determine if this pattern was altered by bolus volume.

Results

Two raters independently reviewed all 12,861 articles based on the titles and abstracts. After this independent review, blinding between the reviewers was removed and agreed on by consensus to include 45 studies for full article review. A complete ancestral bibliography search of these 45 articles identified nine additional articles that met inclusion criteria for the current study. Six of the nine had been initially excluded when only the title and abstract were considered because it was not clear from the articles' title or abstract alone that both respiration and swallowing were measured or that the outcomes reported were appropriate. Two of the remaining three articles had similar keywords but were not identified in the original search, and one article was in an open-access journal and not identified. In order to limit publication bias, all articles that included a sample of nondisordered adults were reviewed. When articles compared disordered and nondisordered participants, only data from the nondisordered adults were included. Two articles that described respiratory phase before and after the swallow relative to bolus volume in an experimental control group were also included (Pinto et al., 2017; Wang et al., 2016). Review of the entire content of the 54 articles resulted in 37 studies that met inclusion criterion and were recommended for inclusion (see Figure 1). Data were extracted from 37 articles (Ayuse et al., 2006; Balasubramaniam & Bhat, 2012; Boden et al., 2009; Dozier et al., 2006; Fontecave-Jallon & Baconnier, 2016; Gürgör et al., 2013; Hårdemark Cedborg et al., 2010, 2009; Hirst et al., 2002; Hiss et al., 2001; Kelly et al., 2006; Kelly, Huckabee, Jones, & Carroll, 2007; Kelly, Huckabee, Jones, & Frampton, 2007; Klahn & Perlman, 1999; Lederle et al., 2012; Leslie et al., 2005; Martin et al., 1994; Martin-Harris et al., 2005, 2003; Matsuo et al., 2008; Matsuo & Palmer, 2015; McFarland & Lund, 1995; McFarland et al., 1994, 2016; Nilsson et al., 1996; Nishino et al., 1985; Palmer & Hiimae, 2003; Paydarfar et al., 1995; Perlman et al., 2005; Pinto et al., 2017; Preiksaitis et al., 1992; Preiksaitis & Mills, 1996; Smith et al., 1989; Wang et al., 2016; Wang, Cheng, et al., 2015; K. Wheeler Hegland et al., 2011; K. M. Wheeler Hegland et al., 2009) for the current review.

Interrater reliability on the methodological quality items on the Joanna Briggs Institute exceeded 80% for all items, and interrater reliability was over 90% for decisions to include or exclude studies. Reliability of data extraction on the 20% of randomly assigned double-coded articles exceeded 100% on all extracted variables.

Participants

All studies had participants with no history of dysphagia, respiratory disease, neurological disease, or head and neck surgery (other than minor surgeries such as a tonsillectomy). The number of participants included in each of the studies ranged from 5 to 800. The mean number of participants was 54.5, and the median number of participants was 20. The age of participants ranged from 18 to 83 years:

41% (15/37) of the studies had participants between 18 and 35 years old only, and 38% (14/37) had participants over the age of 60 years (see Table 1 for details from each included study). Mean age and standard deviation for the participants were reported in 11 of the 37 studies included.

Measurement of Respiratory Phase

Respiratory phase patterns surrounding swallowing can be measured using a variety of methods. Expiratory airflow, characterized by higher pressure, temperature, and humidity when compared to inspiratory airflow, can be measured with pressure transducers or thermistors (heat sensors; Al-Khalidi, Saatchi, Burke, Elphick, & Tan, 2011). Multiple methods of recording flow were used in the studies included (detailed in Table 1). Several investigations used a face mask covering the mouth and nose with a thermistor or pressure transducer to detect airflow measurements, but this method limited the ease of administration of food or liquid (Boden et al., 2009; Hårdemark Cedborg et al., 2009; Paydarfar et al., 1995). The majority (68%) of studies, however, used a nasal cannula connected to a pressure transducer or thermistor to measure respiratory airflow at the nares, which allowed for typical presentation of the food or liquid to the mouth (Ayuse et al., 2006; Balasubramaniam & Bhat, 2012; Dozier et al., 2006; Hirst et al., 2002; Hiss et al., 2001; Kelly et al., 2006; Kelly, Huckabee, Jones, & Carroll, 2007; Kelly, Huckabee, Jones, & Frampton, 2007; Klahn & Perlman, 1999; Leslie et al., 2005; Martin-Harris et al., 2005, 2003; Matsuo et al., 2008; McFarland et al., 2016; Nilsson et al., 1996; Nishino et al., 1985; Palmer & Hiimae, 2003; Perlman et al., 2005; Pinto et al., 2017; Preiksaitis et al., 1992; Wang et al., 2016; Wang, Cheng, et al., 2015; Yagi et al., 2017).

Respiratory phase surrounding swallowing was also recorded in 24% of the studies from kinematic measures of combined displacements of the chest wall and abdomen using respiratory inductance plethysmography (Hirst et al., 2002; Martin et al., 1994; McFarland & Lund, 1995; McFarland et al., 1994, 2016; Paydarfar et al., 1995; Preiksaitis & Mills, 1996; Smith et al., 1989; K. Wheeler Hegland et al., 2011; K. M. Wheeler Hegland et al., 2009). This method tracks chest wall and abdominal movements as an indirect measure of respiratory phase and has potential to estimate lung volume when calibrated according to Banzett, Mahan, Garner, Brughera, and Loring's (1995) standard formula (Banzett et al., 1995). The studies that reported lung volume estimates (K. Wheeler Hegland et al., 2011; K. M. Wheeler Hegland et al., 2009; McFarland et al., 2016; Smith et al., 1989) used different calibration tasks (typically quiet resting breaths and/or specific volume maneuvers). The other studies reported only respiratory phase and did not specify calibration tasks. The remaining studies (8%) used alternative measurements (see Table 1).

Measurement of Swallow

The occurrence of swallowing was also recorded using multiple methods including surface electromyography

Figure 1. Systematic review study inclusion.

(Ayuse et al., 2006; Balasubramaniam & Bhat, 2012; Gürgör et al., 2013; Hiss et al., 2001; Kelly et al., 2006; Kelly, Huckabee, Jones, & Carroll, 2007; Kelly, Huckabee, Jones, & Frampton, 2007; Martin et al., 1994; Matsuo & Palmer, 2015; McFarland et al., 2016; Nishino et al., 1985; Palmer & Hiimeae, 2003; Paydarfar et al., 1995; Perlman et al., 2005; Preiksaitis et al., 1992; Preiksaitis & Mills, 1996; Smith et al., 1989; Wang, Cheng, et al., 2015; K. Wheeler Hegland et al., 2011; K. M. Wheeler Hegland et al., 2009), direct visualization of the swallow by videofluoroscopic recordings of barium boluses (Boden et al., 2009; Dozier et al., 2006; Martin-Harris et al., 2005, 2003; Matsuo et al., 2008; Matsuo & Palmer, 2015; Paydarfar et al., 1995; Perlman et al., 2005), visual observations of the swallow with a fiberoptic endoscope (Martin et al., 1994), acoustic recording of the swallow (Balasubramaniam & Bhat, 2012; Kelly et al., 2006; Kelly, Huckabee, Jones, & Carroll, 2007; Kelly, Huckabee, Jones, & Frampton, 2007;

Leslie et al., 2005; Perlman et al., 2005; K. Wheeler Hegland et al., 2011; K. M. Wheeler Hegland et al., 2009), a manual trigger activated by the participant (or investigator) placing a marker on the recorded data or manual annotation of observed laryngeal movements by the investigator (Fontecave-Jallon & Baconnier, 2016; Matsuo & Palmer, 2015; McFarland et al., 2016; Nishino et al., 1985), manometric swallowing pressures (Ayuse et al., 2006; Boden et al., 2009; Hårdemark Cedborg et al., 2010, 2009; Hirst et al., 2002; Paydarfar et al., 1995), elastic strain gauges (McFarland et al., 1994), or pneumatic bellows fastened (Perlman et al., 2005) around the participant's neck (see Table 1).

Respiratory Phases Before and After the Swallow

Four respiratory–swallow phase patterns were introduced as preceding and following the cessation of respiration

Table 1. Demographics and instrumentation.

First author	Year	N	Age range (years)	Sex, M/F	Respiration detection	Swallow detection
Ayuse	2006	10	22–24	M	Nasal airflow, pneumotachometer	sEMG, manometry
Boden	2009	32	20–35	16 M, 16 F	Face mask, nasal airflow, pressure transducer, thermistor	Manometry, videofluoroscopy
Hårdemark Cedborg	2009	6	21–35	3 M, 3 F	Face mask, nasal airflow, pressure transducer, thermistor electromyography	Manometry, EMG
Hårdemark Cedborg	2010	32	20–35	16, 16 F	Nasal airflow, pressure transducer, thermistor electromyography	Manometry
Dozier	2006	70	23–91	29 M, 41 F	Nasal airflow, pressure transducer, RIP	Videofluoroscopy
Fontecave-Jallon	2016	11	22–64	6 M, 5 F	Nasal airflow, pressure transducer	Manually observed
Gürgör	2013	58	20–83 (two groups)	21 M, 37 F	Nasal airflow, pressure transducer	sEMG
K. M. Wheeler Hegland	2009	20	19–28	9 M, 11 F	RIP	sEMG, acoustics
K. Wheeler Hegland	2011	20	19–28	9 M, 11 F	RIP	sEMG, acoustics
Hiss	2001	60	20–83 (three groups)	30 M, 30 F	Nasal airflow, thermistor	sEMG
Hirst	2002	29	62–84	17 M, 12 F	Chest belt, nasal thermistor, nasal pressure transducer	Manometry
Kelly	2006	16	20–79 (two groups)	8 M, 8 F	Nasal airflow	sEMG, acoustics
Kelly	2007	10	22–34	5 M, 5 F	Nasal airflow	sEMG, acoustics
Kelly	2007	10	22–34	5 M, 5 F	Nasal airflow	sEMG, acoustics
Klahn	1999	12	18–25	6 M, 6 F	Nasal airflow, micromanometer	Electroglottograph
Balasubramaniam	2012	800	18–76+	400 M, 400 F	Nasal airflow, pressure transducer	sEMG, cervical auscultation
Lederle	2012	20	20–29	4 M, 16 W	Respiratory magnetometers	sEMG
Leslie	2005	50	20–78	20 M, 31 F	Nasal airflow, pressure transducer	Acoustic
Martin	1994	13	17–32	10 M, 3 F	RIP	sEMG, FEES (one group)
Martin-Harris	2003	28	21–60 (two groups)	14 M, 14 F	Nasal airflow, pressure transducer	Videofluoroscopy
Martin-Harris	2005	76	18–65+	Not stated	Nasal airflow, pressure transducer	Videofluoroscopy
Matsuuo	2008	10	21–33	5 M, 5 F	RIP, nasal airflow, pressure transducer	sEMG, videofluoroscopy
Matsuuo	2015	10	18–39	5 M, 5 F	RIP	Trigger, videofluoroscopy
McFarland	1994	10	19–33	10 M	Strain gauges at the chest	Strain gauges at the neck
McFarland	1995	14	19–33	14 M	Strain gauges at the chest	Strain gauges at the neck
McFarland	2016	20	26–75	10 M, 10 F	RIP, nasal airflow, pressure transducer	sEMG, event trigger
Nilsson	1996	292	18–64	177 M, 115 F	Nasal thermistor	Doppler probe, piezoelectric
Nishino	1985	8	25–35	8 M	Flowmeter, CO ₂	sEMG, laryngeal movement
Palmer	2003	5	22–27	2 M, 3 F	Nasal airflow, pressure transducer	sEMG, videofluoroscopy
Paydarfar	1995	30	19–45	15 M, 15 F	Face mask, pneumotachograph, pressure transducer	Manometry, videofluoroscopy, sEMG
Perlman	2005	18	17–39	7 M, 11 F	Nasal airflow, pressure transducer	Acoustic, sEMG, videofluoroscopy
Pinto	2017	32	18–65	Not stated	Nasal airflow, pressure transducer	sEMG, cervical auscultation
Preiksaitis	1992	12	20–48	8 M, 6 F	Nasal airflow, pressure	sEMG
Preiksaitis	1996	10	19–25	8 M, 6 F	RIP	sEMG
Smith	1989	7	22–45	7 M	RIP	sEMG
Wang	2014	112	20–70	58 M, 54 F	Nasal airflow, pressure transducer	Piezoelectric sensor, sEMG
Wang	2016	39	37.5 (M)	39 M	Nasal airflow	sEMG

Note. M = male; F = female; sEMG = surface electromyography; RIP = respiratory inductance plethysmography; FEES = fiberoptic endoscopic evaluation of swallowing; CO₂ = carbon dioxide.

accommodating the swallow by Martin-Harris et al. (2005): expiration/expiration (EX/EX), expiration/inspiration, inspiration/expiration, and inspiration/inspiration.

EX/EX Bracketing the Swallow

The occurrence of the EX/EX was consistently reported on the majority (> 50%) of swallows on small-volume liquid boluses (see Table 2). The EX/EX pattern was reported as the predominant pattern in single sips of liquid (ranging from 5 to 25 ml) taken from a cup, spoon, or syringe (Balasubramaniam & Bhat, 2012; Boden et al., 2009; Hårdemark Cedborg et al., 2010, 2009; Hiss et al., 2001; Kelly et al., 2006; Martin-Harris et al., 2005, 2003; Preiksaitis et al., 1992; Preiksaitis & Mills, 1996; Wang, Cheng, et al., 2015). Similarly, Hiss et al. 2001 reported 62% of all swallows (saliva and 5-, 10-, 15-, 20-, and 25-ml water presented by cup) were bracketed by expiration (EX/EX). Preiksaitis et al. (Preiksaitis et al., 1992; Preiksaitis & Mills, 1996) also reported high frequency of expiration (71.5%–78.2%) surrounding 5-, 10-, and 20-ml water volumes presented by cup or syringe. Martin-Harris et al. (2005, 2003) reported similar predominance of expiration (71%–82%) prior to and after the swallows of single sips of 5-ml liquid from a cup. Furthermore, Wang, Cheng, et al. (2015) reported the dominant EX/EX pattern during saliva and 2-, 5-, 10-, and 20-ml liquid swallows presented by cup with frequencies ranging from 62% to 82% (Wang, Cheng, et al., 2015). Kelly et al. (2006) reported the EX/EX pattern in 80% of spontaneous saliva swallows and of 15-ml boluses of water presented by cup. In a study with a much larger sample size (800), Balasubramaniam and Bhat (2012) reported the EX/EX pattern ranged from 93.9% to 97.5% of saliva and 5- and 10-ml boluses presented by spoon in two groups of adults, aged 18–40 and 41–50 years (Balasubramaniam & Bhat, 2012). In two separate studies, Cedborg et al. reported the occurrence of EX/EX pattern ranging from 93% to 98% (Hårdemark Cedborg et al., 2009) with saliva swallows and 99% (Hårdemark Cedborg et al., 2010) during 10-ml bolus volumes presented by syringe. Further, the EX/EX pattern was reported in 99% of 10-ml boluses of water presented by syringe by Boden et al. (2009).

In addition to the studies focusing on respiratory patterns in healthy adults, Pinto et al. and Wang et al. reported respiratory patterns surrounding the swallowing in an experimental control group compared to a diseased population. Consistent with previous reports, EX/EX before and after the swallow was dominant and recorded in over 74% during 1- to 20-ml boluses administered via cup (Pinto et al., 2017; Wang et al., 2016). The remaining 15 studies with control groups reported summary statements indicating that expiration was the predominant pattern either before or after the swallow but failed to report specific percentages (Brodsky et al., 2010; Charbonneau et al., 2005; Costa & Lemme, 2010; Drulia, 2016; Erdem et al., 2016; Gross et al., 2008; Hadjikitidis, Pickersgill, Dawson, & Wiles, 2000; Leslie, Drinnan, Ford, & Wilson, 2002;

Matsuo & Palmer, 2015; Ogha et al., 2017; Shaker et al., 1992; Terzi et al., 2007; Wang, Shieh, Chen, & Wu, 2015).

Expiratory Phase Before or After the Swallow

Several investigations included in this review provided results for the respiratory phase preceding or following a swallow occurrence, but not both. In studies that reported respiratory phase before the swallow, the frequency of expiration ranged from 61% to 100% (Hiss et al., 2001; Klahn & Perlman, 1999; Martin et al., 1994; Nishino et al., 1985; Perlman et al., 2005). In studies that reported the percentage of swallows followed by expiration, frequencies ranged from 82% to 100% (Hiss et al., 2001; Klahn & Perlman, 1999; Leslie et al., 2005; Martin et al., 1994; Nilsson et al., 1996; Nishino et al., 1985; Perlman et al., 2005; Preiksaitis & Mills, 1996; K. M. Wheeler Hegland et al., 2009).

Meta-Analysis of Total EX/EX Frequency Results

Quantitative data on the percentage of swallows meeting the EX/EX pattern were available in 19 of the studies (see Table 2) and extracted for each bolus volume reported. Four studies reported this percentage for separate groups within the study (i.e., by age or gender; Balasubramaniam & Bhat, 2012; Gürgör et al., 2013; Kelly et al., 2006; Wang, Cheng, et al., 2015). In these cases, data from all participant groups were included as separate effect sizes.

An intercept-only RVE analysis was run with all bolus volumes to determine the overall proportion of swallows meeting the EX/EX pattern across studies and across bolus sizes. Within this analysis, swallows of different bolus volumes were nested within participant group to control for the dependent data structure. Results revealed the average logit event rate across bolus volumes and studies was 1.23 ($SE = 0.231$), $t(24.5) = 5.34$, 95% CI [0.758, 1.71], $p < .001$, $I^2 = 85.56$, $\tau^2 = 0.97$ (see Table 3). When converted back to percentage, this value was 77.4%. These results reveal that EX/EX was the predominant respiratory pattern when considering all participants and bolus sizes across the investigations.

Sensitivity and Publication Bias

In order to test whether or not the results of the meta-analysis were highly influenced by any one study, a “leave-one-out” analysis was conducted that included a systematic rerun of the meta-analysis excluding one study at a time to determine the influence of each study on the overall results. When the Balasubramaniam and Bhat (2012) study of 800 participants was excluded, the logit event rate of the EX/EX pattern dropped from 1.23 to 0.76 ($p = .002$; corresponding to a percentage of 68.1%).

The sensitivity of the RVE results to changing the covariance structure within each group of participants was

Table 2. Frequency of EX/EX reported.

Author (first)	Year	Percentage of EX/EX (bolus volume [ml]/type; age/sex if reported)		Comments
Nishino	1985	82% (saliva)		
		84% (1 ml/water)		
Preiksaitis	1992	71.4% (all swallows)		
		67.5% (saliva)		
		72.7% (5 ml/ water)		
		78.2% (10 ml/water)		
		72.6 (20 ml/water)		
Preiksaitis	1996	72% (5 ml/water)		Thin, thick, syrup, and semisolid
		77% (all swallows, liquid and solid)		
Martin-Harris	2003	70%–75% (200 ml/water)		
Martin-Harris	2005	79% (5 ml/barium)	82% (5 ml/barium)	Two trials reported
Ayuse	2006	71% (5 ml/barium)	75% (5 ml/barium)	Two trials reported
Dozier	2006	85.1% (5 ml/water)		
Kelly	2006	38.6% (50 ml/water)		
		80.4% (15 ml/water)		
Boden	2009	99% (5 ml/water)		
Hårdemark Cedborg	2009	93% (saliva)		
Hårdemark Cedborg	2010	98% (saliva)		
		99% (10 ml/water)		
K. Wheeler Hegland	2011	33% (100 ml/water by cup)		
		29.2% (100 ml/water by straw)		
Balasubramaniam	2012	96.4% (saliva/18–40 yr M)	85.5% (saliva/60–75 yr M)	64.7% (saliva/75+yr M)
		97.5% (5 ml/18–40 yr M)	81% (5 ml/60–75 yr M)	68.6% (5 ml/75+ yr M)
		95.6% (10 ml/18–40 yr M)	85.6% (10 ml/60–75 yr M)	66.5% (10 ml/75+ yr M)
		95.6% (saliva/18–40 yr W)	83.5% (saliva/60–75 yr W)	67.2% (saliva/75+ yr W)
		96.5% (5 ml/18–40 yr W)	84% (5 ml/60–75 yr W)	63.7% (5 ml/75+ yr W)
		94.6% (10 ml/18–40 yr W)	82.4% (10 ml/60–75 yr W)	59.3% (10 ml/75+ yr M)
Lederle	2012	53% (20 ml/water)		
		42% (87.7 ml/water)		
		46% (177.4 ml/water)		
Gürgör	2013	64.7% (50 ml/20–39 yr)		
		52.95% (100 ml/20–39 yr)		
Wang	2015	75% (saliva/20–30 yr)		
		81% (2 ml/20–30 yr)	52% (saliva/31–50 yr)	
		82% (5 ml/20–30 yr)	50% (2 ml/31–50 yr)	
		73% (10 ml/20–30 yr)	47% (5 ml/31–50 yr)	
		66% (20 ml/20–30 yr)	39% (10 ml/31–50 yr)	
Wang (control group)	2016	70% (1 ml)	44% (20 ml/31–50 yr)	
		74% (3 ml)		
		75% (5 ml)		
		75% (10 ml)		
		86% (20 ml)		
Fontecave-Jallon	2016	86% (saliva)		
Pinto (control group)	2017	81.5% (salvia)		
		78.3% (5 ml)		
		90.6% (10 ml)		

Note. Studies that reported frequency of EX/EX pattern. Saliva swallows are swallows without a bolus given. EX/EX = expiration/expiration; ml = milliliters; yr = years; M = men; W = women.

Table 3. Results of meta-analysis of EX/EX frequency: intercept-only model.

	Estimate (SE)	t (df)	p	95% CI
Intercept	1.23 (0.231)	5.34 (24.05)	< .001	[0.758, 1.71]

Note. Seventy-five effect sizes (min = 1, $M = 2.78$, max = 6). $I^2 = 85.559$, $\tau^2 = 0.970$. EX/EX = expiration/expiration; CI = confidence interval.

tested to account for the differing sample size for each group. A sensitivity analysis was performed (Hedges et al., 2010), varying the assumed within-study correlation value from 0 (no correlation between swallows) to 1 (perfect correlation between swallows). The parameter estimates were virtually unaffected by these changes, strengthening our confidence in the results of the study.

Publication bias is the high likelihood that only published studies are included in a meta-analysis. To assess the potential publication bias effect on the primary outcome, or the selective publication of studies with only significant results (i.e., journals biasing the literature by rejecting studies with nonsignificant results), a publication bias analysis was performed in CMA. The average percentage of EX/EX pattern for all boluses within the same set of participants was used in the CMA. Egger's regression test approached significance at the one-tailed p value (which assumes that any missing studies will have a small or nonsignificant difference from 0; coefficient = 2.11 [1.35]), $t(28) = 1.56$, $p = .06$. However, a fail-safe N test revealed that 3,904 missing studies would be needed to move the logit event rate to a nonsignificant value. Duval and Tweedie's trim-and-fill analysis (Duval & Tweedie, 2000), using the average effect size across bolus volumes within each independent group of participants, suggested a minimal effect of publication bias. Two studies were filled, changing the random effect estimate from 1.26 to 1.19. In summary, while there is some evidence of publication bias, the effects on our interpretation of the data are negligible.

Bolus Volume Effects

It is possible that the size of the bolus may have affected the typical respiratory pattern associated with swallowing. In order to investigate this possibility within the context of the current data, we included log-transformed bolus volume as a covariate predicting the frequency of the EX/EX pattern. Results revealed a significant impact of log-transformed bolus volume (-0.882 [$SE = 0.219$]), $t(15.1) = 4.03$, 95% CI $[-1.35, -0.42]$, $p = .001$, $F^2 = 82.30$, $\tau^2 = 0.77$ (see Table 4). These results reveal that, as the bolus volume of liquids increased, the percentage of swallows following the EX/EX pattern decreased. The stability of the EX/EX pattern decreased as liquid bolus volume increased when the manner of presentation was the same. Lederle et al. (2012) also reported a decrease in EX/EX with larger bolus

volumes (87.7 and 177.7 ml) compared to the 20-ml bolus volume when all boluses were presented by straw. Wang, Cheng, et al. (2015) found that the EX/EX pattern decreased from 82% with 5-ml boluses to 66% with 20 ml when presented by cup. In general, the EX/EX pattern was reported less than 50% of the time when the bolus size was over 50 ml and presented by cup (Dozier et al., 2006; Gürgör et al., 2013; K. Wheeler Hegland et al., 2011) and by straw (Lederle et al., 2012; K. Wheeler Hegland et al., 2011; see Table 5 and Figure 2).

Additional Variables Considered

Multiple variables such as bolus type, manner of presentation, and gender of the participant have been studied for their effect on respiratory phase patterning surrounding the swallow. Swallow during exhalation continued to be the predominant pattern regardless of bolus consistency (semisolids, 79% [K. M. Wheeler Hegland et al., 2009]; solids, 89% [McFarland & Lund, 1995]), manner of presentation ($> 70\%$ [Preiksaitis & Mills, 1996]; see Table 6), body position ($> 70\%$; Ayuse et al., 2006; Boden et al., 2009; Hårdemark Cedborg et al., 2010; Kelly, Huckabee, Jones, & Frampton, 2007; McFarland et al., 1994), or gender ($> 70\%$; Kelly, Huckabee, Jones, & Carroll, 2007; Martin-Harris et al., 2003).

Age

There was conflicting evidence regarding the frequency of the respiratory-swallow pattern in older versus younger participants. Four studies reported no difference in respiratory-swallow patterning in older versus younger participants with the EX/EX pattern predominant (Gürgör et al., 2013; Hirst et al., 2002; Kelly et al., 2006; Kelly, Huckabee, Jones, & Carroll, 2007; Kelly, Huckabee, Jones, & Frampton, 2007). Three additional studies, however, reported a less frequent EX/EX pattern in older adults (> 60 years old) when compared to a younger cohort (Balasubramaniam & Bhat, 2012; Martin-Harris et al., 2005; Wang, Cheng, et al., 2015; see Table 7).

Sex

Significant differences in respiratory-swallow pattern in men compared to women were not found (Kelly et al., 2006; Kelly, Huckabee, Jones, & Carroll, 2007; Kelly, Huckabee, Jones, & Frampton, 2007; Klahn & Perlman, 1999; Martin-Harris et al., 2003).

Lung Volume at Swallow Initiation

Lung volume at the initiation of the swallow was reported in only three studies meeting criteria for inclusion in this review. McFarland et al. (2016) reported mid-to-low lung volume (relative to resting expiratory level) as the typical lung volume range found at the initiation of the swallow. Wheeler Hegland et al. (K. Wheeler Hegland et al., 2011, K. M. Wheeler Hegland et al., 2009) reported

Table 4. Meta-regression of EX/EX frequency by bolus volume: intercept and log-transformed bolus volume.

	Estimate (SE)	t (df)	p	95% CI
Intercept	2.020 (0.303)	6.66 (19.4)	< .001	[1.39, 2.654]
Log-transformed bolus volume	−0.882 (0.219)	−4.03 (15.1)	.001	[−1.35, −0.416]

Note. Seventy-five effect sizes (min = 1, $M = 2.78$, max = 6). $I^2 = 82.300$, $\tau^2 = 0.773$. EX/EX = expiration/expiration; CI = confidence interval.

that larger volume liquid swallows (20 ml) when compared to thin and thick paste (pudding) boluses and sequential swallows of liquid from a straw when compared to single sips were initiated at higher lung volumes (percentage of vital capacity). McFarland et al. (2016) also found water and uncued swallows (participant initiated the swallow without a directed prompt) to be initiated at a slightly higher lung volume when compared to pudding and cued swallows (participant cued to swallow typically after two or three respiratory cycles), but still within the range of tidal volume. Differences in reported lung volume may be attributed to differences in measures used (i.e., percentage of vital capacity vs. percentage of resting expiratory level), as well as different calibration methods according to McFarland et al. (2016). However, both Hegland et al. and McFarland et al. reported higher lung volume percentage at the initiation of the swallow for larger bolus sizes but approximately 50% of respective lung volume measures for single sips (McFarland et al., 2016; K. Wheeler Hegland et al., 2011). In contrast to these results, Lederle et al. (2012) reported no difference in lung volume (relative to resting expiratory level) at the initiation of the swallow with three different bolus volumes: 20, 87.7, and 177.7 ml.

Discussion

A systematic review of the literature resulted in 37 articles meeting the criteria for inclusion. The expiratory phase of respiration was the predominant phase surrounding swallowing in the majority of studies. A meta-analysis confirmed an average of 77.4% of thin liquid swallows were initiated during and followed by the expiratory phase of respiration. The frequency of this EX/EX pattern, although remaining the most predominant pattern, was reported to decrease as bolus volume increased. However, the meta-regression analysis, which confirmed the decrease in the EX/EX pattern with increased bolus volume, did not control for manner of presentation that may have influenced the respiratory phase bracketing the swallow.

Variations in the Predominant EX/EX Pattern

The EX/EX pattern varied with bolus volume, the manner of presentation, and the age of the participant. The EX/EX pattern was less frequent with liquid bolus volumes greater than 50 ml (Dozier et al., 2006; Gürgör

Table 5. Frequency of EX/EX pattern by bolus volume of thin liquids.

Author (first)	Year	EX/EX (bolus volume [ml] and age/sex)				
Volumes: 1–20 ml						
Nishino	1985	84% (1 ml)				
Preiksaitis	1992	72.7% (5 ml)		78.2% (10 ml)	72.6% (20 ml)	
Preiksaitis	1996	72% (5 ml)				
Martin-Harris	2003	79% (5 ml, Trial 1)		82% (5 ml, Trial 2)		
Martin-Harris	2005	71% (5 ml, Trial 1)		75% (5 ml, Trial 2)		
Ayuse	2006	85.1% (5 ml, upright with chin tuck)				
Kelly	2006	80.4% (15 ml)				
Boden	2009	99% (10 ml)				
Hårdemark Cedborg	2010	99% (10 ml)				
Balasubramaniam	2012	97.5% (5 ml/18–40 yrs M)		96.5% (5 ml/18–40 yrs W)		
		95.6% (10 ml/18–40 yrs M)		94.6% (10 ml/18–40 yrs W)		
Lederle	2012	53% (20 ml)				
Wang	2015	81% (2 ml)	82% (5 ml)	73% (10 ml)	66% (20 ml)	
Wang (control group)	2016	70% (1 ml)	74% (3 ml)	75% (5 ml)	75% (10 ml)	86% (20 ml)
Pinto (control group)	2017	78.3% (5 ml)	90.6% (10 ml)			
Volumes: 50–200 ml						
Preiksaitis	1996	70%–75% (200 ml)				
Dozier	2006	38.6% (50 ml)				
K. Wheeler Hegland	2011	33% (100 ml, cup)		29.2% (100 ml, straw)		
Gürgör	2013	64.7% (50 ml/18–40 yrs)		52.9% (100 ml/18–40 yrs)		

Note. EX/EX = expiration/expiration; ml = milliliters; yrs = years; M = men; W = women.

Figure 2. Scatter plot of reported expiration/expiration (EX/EX) percentage by bolus volume.

et al., 2013; Lederle et al., 2012; K. Wheeler Hegland et al., 2011). Decreased frequency of exhalation prior to the swallow during larger volume swallows may occur to accommodate the increased length and respiratory demands of the sequential drinking task when compared to a single sip (Dozier et al., 2006; K. Wheeler Hegland et al., 2011).

Despite the manner of presentation of the bolus, the EX/EX pattern remained predominant. Three studies reported the respiratory phase pattern with different presentations of the same bolus volume. Preiksaitis et al. reported that there was a significant decrease in the EX/EX pattern with cup swallows when compared to syringe swallows containing 20-ml bolus volumes (Preiksaitis & Mills, 1996). Two studies (Hirst et al., 2002; K. Wheeler Hegland et al., 2011) compared cup and straw drinking with the same bolus volume and reported decreased EX/EX with straw drinking, but neither of these studies indicated if the

difference was significant. Increased frequency of inspiration surrounding straw swallows may be facilitated following the negative pressure required to siphon the liquid through the straw (Lederle et al., 2012). Others have conjectured that the larger volumes associated with sequential straw swallowing may result in perceived air hunger following a longer period of sustained airway closure and facilitating an inspiratory gesture at the conclusion of the task (Dozier et al., 2006; Lederle et al., 2012).

The consistency of the EX/EX pattern in healthy individuals over the age of 60 years had conflicting results in the studies reviewed. Although EX/EX remained the most frequent pattern observed in this age group in all studies, three reported significant differences with aging and four others did not. Given the known physiologic advantages of swallows initiated in the expiratory phase of respiration, particularly at mid-to-low lung volume, a reduction in stability of this pattern may place older people at a physiologic disadvantage in the presence of a disease or condition known to be associated with dysphagia. In addition, age has been reported as a factor for decreased frequency of expiration surrounding swallow.

It has been reported that many of the studies could not be directly compared because of the wide variation in methods used to elicit swallows and record respiration. One such example are the studies that recorded only spontaneous saliva swallows (no bolus given). These swallows characteristically showed a lower percentage of the EX/EX pattern during wakefulness (Kelly, Huckabee, Jones, & Frampton, 2007; Preiksaitis et al., 1992; Preiksaitis & Mills, 1996) and sleep (Kelly et al., 2006).

Lung Volume at Swallow Initiation

Three studies documented specific lung volume at the onset of swallowing. All three studies showed the obligate onset of respiratory cessation at swallowing initiation occurred at mid-to-low lung volume (McFarland et al., 2016; K. Wheeler Hegland et al., 2011; K. M. Wheeler Hegland et al., 2009). These studies further detailed factors that influence lung volume at swallow initiation including

Table 6. Frequency of EX/EX with liquid swallows by presentation method.

Author (first)	Year	Injection		Syringe		Cup		Straw	
		ml	% EX/EX	ml	% EX/EX	ml	% EX/EX	ml	% EX/EX
Nishino	1985	1	84						
Preiksaitis	1992			5	82.5	5	80		
				10	80	10	72.5		
				20	62.5	20	51.7		
Hirst ^a	2002					100	78.5	100	63.5
Martin-Harris	2003					5	79, 82		
Martin-Harris	2005					5	71, 75		
Dozier	2006					50	38.6		
K. Wheeler Hegland	2011					100	33	100	29.2

Note. Data included that specified presentation method, volume, and EX/EX %. EX/EX = expiration/expiration; ml = milliliters.

^aParticipants were all older, aged 62–84 years.

Table 7. Frequency of respiratory–swallow phase by age with thin liquid.

Author (first)	Year	Respiratory–swallow		Age	
Hirst	2002	91% EX after the swallow		62–84 yrs	
Martin-Harris	2005	Increased inspiration before and after swallow		65+ yrs	
Kelly	2006	76.2% EX/EX	67% EX/EX		
Balasubramaniam	2012	97.5	95.5	Sleep and 15 ml (20–29 yrs)	Sleep and 15 ml (60–79 yrs)
		95.6	96.9	5 ml, 18–40 yrs, M	5 ml, 60–75 yrs, M
		96.5	94.5	10 ml, 18–40 yrs, M	10 ml, 60–75 yrs, M
		94.6	93.9	5 ml, 18–40 yrs, W	5 ml, 60–75 yrs, W
		64.7%	82.4	10 ml, 18–40 yrs, W	10 ml, 60–75 yrs, W
Gürgör	2013	52.9%	71.43%	50 ml (20–30 yrs)	50 ml (60–83 yrs)
		81%	78.57%	100 ml (20–30 yrs)	100 ml (60–83 yrs)
Wang	2015	82%	50%	2 ml (31–50 yrs)	2 ml (51–70 yrs)
		73%	47%	5 ml (31–50 yrs)	5 ml (51–70 yrs)
		66%	50%	10 ml (31–50 yrs)	10 ml (51–70 yrs)
			39%	20 ml (31–50 yrs)	20 ml (51–70 yrs)

Note. EX/(EX) = expiration/(expiration); yrs = years; ml = milliliters; M = men; W = women.

liquid bolus volume, bolus type, manner of presentation, and instructions given (cueing to swallow) to the participants. These findings appear to show small changes in lung volume and effects on normal swallowing mechanics can occur without any apparent risk to healthy adults. On the other hand, even slight increases in lung volume at swallowing initiation may have significant clinical implications for patients with dysphagia who already have reductions in laryngeal elevation, laryngeal closure, and pharyngoesophageal segment opening.

Advantages of Predominant Phase Pattern

Swallow during a pause in the expiratory cycle of respiration at mid-to-low lung volume results in physiological advantage for anterior–superior movement of the hyolaryngeal complex, airway closure, and pharyngoesophageal segment opening (Martin-Harris, 2008; Matsuo & Palmer, 2008; Shaker et al., 1992). An expiratory flow of respiration before and after the swallow also has an airway protective advantage, in that the risk of inhalation of food or liquid particles before or after the swallow is decreased (Martin-Harris, 2008). The higher frequency of the expiratory–swallow–expiratory pattern and the physiological advantages support the conclusion of this pattern as the predominant and potentially optimal coordination of these two systems.

Limitations

Limitations to a systematic review include drawing conclusions from empirical evidence acquired with different methodologies. The variability in the percentage of the EX/EX pattern reported across all studies may be due to several factors highlighted throughout the text including different methods used to detect the onset of the swallow and different measures used to determine and analyze respiratory–swallow patterns as well as the variety of conditions studied (bolus type, bolus size, manner of presentation, and age of participants). Additional limitations include the possibility that, despite attempting to complete an extensive and systematic literature search, a relevant study could have been overlooked.

Conclusions

Expiration before or expiration before and after the swallow in single sips of thin liquids and single sips of thickened liquids and solids was consistently reported as the most consistent and common respiratory phase pattern across the age span in healthy, nondysphagic adults. Despite the predominance of the pattern, it frequently appears to be related to bolus volume, manner of presentation, and age of the adult. Determination of this predominant pattern provides a predictable pattern of respiratory swallowing behavior observed during clinical assessments of swallowing. Wide deviations from these predictable

patterns may signal airway protection vulnerability in patients with coexisting swallowing impairments.

Acknowledgments

Northwestern University supported this work. B. M. H., as the principal investigator, received the following: Veterans Administration Rehabilitation Research and Development Grant 1101RX002352-01A1, “Respiratory Phase Training in Dysphagic Veterans with Oropharyngeal Cancer,” 2018–2022; National Institute on Deafness and Other Communication Disorders Grant 1K24DC12801, “Research and Mentoring on Swallowing Impairment and Respiratory–Swallow Coordination,” 2013–2018; National Institute on Deafness and Other Communication Disorders Grant 1R01DC011290, “Standardization of Videofluoroscopic Swallow Studies for Bottle-Fed Children,” 2010–2018; and funding from Bracco Diagnostics, “Refining and Expanding a Dysphagia Database: Standardized Practice, Estimates of Severity and Outcomes,” 2015–2018. B. M. H. and C. M. received salary from Northwestern University. Copyright royalties are from Northern Speech Services through agreement with Medical University of South Carolina. The authors would like to thank Munirah Alkhuwaiter for her contribution to this review article.

References

- Al-Khalidi, F. Q., Saatchi, R., Burke, D., Elphick, H., & Tan, S. (2011). Respiration rate monitoring methods: A review. *Pediatric Pulmonology*, 46(6), 523–529. <https://doi.org/10.1002/ppul.21416>
- Ayuse, T., Ayuse, T., Ishitobi, S., Kurata, S., Sakamoto, E., Okayasu, I., & Oi, K. (2006). Effect of reclining and chin-tuck position on the coordination between respiration and swallowing. *Journal of Oral Rehabilitation*, 33(6), 402–408. <https://doi.org/10.1111/j.1365-2842.2005.01586.x>
- Balasubramaniam, R. K., & Bhat, J. S. (2012). Respiratory swallow coordination in healthy individuals. *International Journal of Advanced Speech and Hearing Research*, 1(1), 1–9.
- Banzett, R. B., Mahan, S. T., Garner, D. M., Brughera, A., & Loring, S. H. (1995). A simple and reliable method to calibrate respiratory magnetometers and RespiTrace. *Journal of Applied Physiology*, 79(6), 2169–2176.
- Boden, K., Hardemark, C. A. I., Eriksson, L. I., Hedström, H. W., Kuylenstierna, R., Sundman, E., & Ekberg, O. (2009). Swallowing and respiratory pattern in young healthy individuals recorded with high temporal resolution. *Neurogastroenterology and Motility*, 21(11), 1163–e101.
- Brodsky, M. B., McFarland, D. H., Dozier, T. S., Blair, J., Ayers, C., Michel, Y., . . . Martin-Harris, B. (2010). Respiratory–swallow phase patterns and their relationship to swallowing impairment in patients treated for oropharyngeal cancer. *Journal of the Sciences and Specialties of the Head and Neck*, 32(4), 481–489. <https://doi.org/10.1002/hed.21209>
- Charbonneau, I., Lund, J. P., & McFarland, D. H. (2005). Persistence of respiratory–swallowing coordination after laryngectomy. *Journal of Speech, Language, and Hearing Research*, 48(1), 34–44.
- Costa, M. M., & Lemme, E. M. (2010). Coordination of respiration and swallowing: Functional pattern and relevance of vocal folds closure. *Arquivos de Gastroenterologia*, 47(1), 42–48.
- Dozier, T. S., Brodsky, M. B., Michel, Y., Walters Jr., B. C., & Martin-Harris, B. (2006). Coordination of swallowing and respiration in normal sequential cup swallows. *Laryngoscope*,

- 116(8), 1489–1493. <https://doi.org/10.1097/01.mlg.0000227724.61801.b4>
- Drulia, T. C.** (2016). *The effects of lung volume on swallowing in chronic obstructive pulmonary disease* (Doctoral dissertation). Retrieved from JMU Scholarly Commons. (130)
- Duval, S., & Tweedie, R.** (2000). Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*, 56(2), 455–463.
- Erdem, N. S., Karaali, K., Ünal, A., Kızılay, F., Ögüş, C., & Uysal, H.** (2016). The interaction between breathing and swallowing in amyotrophic lateral sclerosis. *Acta Neurologica Belgica*, 116(4), 549–556. <https://doi.org/10.1007/s13760-016-0643-0>
- Fisher, Z., Tipton, E., & Zhipeng, H.** (2017). *robumeta: Robust variance meta-regression*. Retrieved from <https://CRAN.R-project.org/package=robumeta>
- Fontecave-Jallon, J., & Baconnier, P.** (2016). A simple mathematical model of spontaneous swallow effects on breathing based on new experimental data. *Conference Proceedings of the IEEE Engineering in Medicine and Biology*, 2016, 4260–4263. <https://doi.org/10.1109/embc.2016.7591668>
- Gross, R. D., Atwood, C. W., Ross, S. B., Eichhorn, K. A., Olszewski, J. W., & Doyle, P. J.** (2008). The coordination of breathing and swallowing in Parkinson's disease. *Dysphagia*, 23(2), 136–145. <https://doi.org/10.1007/s00455-007-9113-4>
- Gürgör, N., Arıcı, Ş., Kurt Incesu, T., Seçil, Y., Tokuçoğlu, F., & Ertekin, C.** (2013). An electrophysiological study of the sequential water swallowing. *Journal of Electromyography and Kinesiology*, 23(3), 619–626. <https://doi.org/10.1016/j.jelekin.2012.12.003>
- Hadjikitis, S., Pickersgill, T. P., Dawson, K., & Wiles, C. M.** (2000). Abnormal patterns of breathing during swallowing in neurological disorders. *Brain*, 123(9), 1863–1873. <https://doi.org/10.1093/brain/123.9.1863>
- Hannes, K., Lockwood, C., & Pearson, A.** (2010). A comparative analysis of three online appraisal instruments' ability to assess validity in qualitative research. *Qualitative Health Research*, 20(12), 1736–1743.
- Hårdemark Cedborg, A. I., Boden, K., Witt Hedstrom, H., Kuylensstierna, R., Ekberg, O., Eriksson, L. I., & Sundman, E.** (2010). Breathing and swallowing in normal man—effects of changes in body position, bolus types, and respiratory drive. *Neurogastroenterology and Motility*, 22(11), 1201–e316. <https://doi.org/10.1111/j.1365-2982.2010.01551.x>
- Hårdemark Cedborg, A. I., Sundman, E., Bodén, K., Hedström, H. W., Kuylensstierna, R., Ekberg, O., & Eriksson, L. I.** (2009). Co-ordination of spontaneous swallowing with respiratory airflow and diaphragmatic and abdominal muscle activity in healthy adult humans. *Experimental Physiology*, 94(4), 459–468. <https://doi.org/10.1113/expphysiol.2008.045724>
- Hedges, L. V., Tipton, E., & Johnson, M. C.** (2010). Robust variance estimation in meta-regression with dependent effect size estimates. *Research Synthesis Methods*, 1(1), 39–65.
- Hirst, L. J., Ford, G. A., Gibson, G. J., & Wilson, J. A.** (2002). Swallow-induced alterations in breathing in normal older people. *Dysphagia*, 17(2), 152–161.
- Hiss, S. G., Treole, K., & Stuart, A.** (2001). Effects of age, gender, bolus volume, and trial on swallowing apnea duration and swallow/respiratory phase relationships of normal adults. *Dysphagia*, 16(2), 128–135. <https://doi.org/10.1007/s004550011001>
- Kelly, B. N., Huckabee, M. L., & Cooke, N.** (2006). The coordination of respiration and swallowing for volitional and reflexive swallows: A pilot study. *Journal of Medical Speech-Language Pathology*, 14(2), 67.
- Kelly, B. N., Huckabee, M. L., Jones, R. D., & Carroll, G. J.** (2007). The influence of volition on breathing–swallowing coordination in healthy adults. *Behavioral Neuroscience*, 121(6), 1174–1179.
- Kelly, B. N., Huckabee, M. L., Jones, R. D., & Frampton, C. M.** (2007). Integrating swallowing and respiration: Preliminary results of the effect of body position. *Journal of Medical Speech-Language Pathology*, 15(4), 347.
- Klahn, M. S., & Perlman, A. L.** (1999). Temporal and durational patterns associating respiration and swallowing. *Dysphagia*, 14(3), 131–138.
- Lederle, A., Hoit, J. D., & Barkmeier-Kraemer, J.** (2012). Effects of sequential swallowing on drive to breathe in young, healthy adults. *Dysphagia*, 27(2), 221–227. <https://doi.org/10.1007/s00455-011-9357-x>
- Leslie, P., Drinnan, M. J., Ford, G. A., & Wilson, J. A.** (2002). Swallow respiration patterns in dysphagic patients following acute stroke. *Dysphagia*, 17(3), 202–207.
- Leslie, P., Drinnan, M. J., Ford, G. A., & Wilson, J. A.** (2005). Swallow respiratory patterns and aging: Presbyphagia or dysphagia. *Journals of Gerontology: Series A: Biological Sciences and Medical Sciences*, 60(3), 391–395.
- Martin, B. J., Logemann, J. A., Shaker, R., & Dodds, W. J.** (1994). Coordination between respiration and swallowing: Respiratory phase relationships and temporal integration. *Journal of Applied Physiology*, 76(2), 714–723.
- Martin-Harris, B.** (2006). Coordination of respiration and swallowing. *GI Motility Online*. Retrieved from <https://www.nature.com/gimo/contents/pt1/full/gimo10.html>
- Martin-Harris, B.** (2008). Clinical implications of respiratory–swallowing interactions. *Current Opinion in Otolaryngology & Head and Neck Surgery*, 16(3), 194–199.
- Martin-Harris, B., Brodsky, M. B., Michel, Y., Ford, C. L., Walters, B., & Heffner, J.** (2005). Breathing and swallowing dynamics across the adult lifespan. *Archives of Otolaryngology—Head & Neck Surgery*, 131(9), 762–770. <https://doi.org/10.1001/archotol.131.9.762>
- Martin-Harris, B., Brodsky, M. B., Price, C. C., Michel, Y., & Walters, B.** (2003). Temporal coordination of pharyngeal and laryngeal dynamics with breathing during swallowing: Single liquid swallows. *Journal of Applied Physiology*, 94(5), 1735–1743. <https://doi.org/10.1152/jappphysiol.00806.2002>
- Matsuo, K., Hiemae, K. M., Gonzalez-Fernandez, M., & Palmer, J. B.** (2008). Respiration during feeding on solid food: Alterations in breathing during mastication, pharyngeal bolus aggregation, and swallowing. *Journal of Applied Physiology*, 104(3), 674–681. <https://doi.org/10.1152/jappphysiol.00527.2007>
- Matsuo, K., & Palmer, J. B.** (2008). Anatomy and physiology of feeding and swallowing: Normal and abnormal. *Physical Medicine and Rehabilitation Clinics of North America*, 19(4), 691–707.
- Matsuo, K., & Palmer, J. B.** (2015). Coordination of oropharyngeal food transport during chewing and respiratory phase. *Physiology and Behavior*, 142, 52–56. <https://doi.org/10.1016/j.physbeh.2015.01.035>
- McFarland, D. H., & Lund, J. P.** (1995). Modification of mastication and respiration during swallowing in the adult human. *Journal of Neurophysiology*, 74(4), 1509–1517.
- McFarland, D. H., Lund, J. P., & Gagner, M.** (1994). Effects of posture on the coordination of respiration and swallowing. *Journal of Neurophysiology*, 72(5), 2431–2437.
- McFarland, D. H., Martin-Harris, B., Fortin, A. J., Humphries, K., Hill, E., & Armeson, K.** (2016). Respiratory–swallowing

- coordination in normal subjects: Lung volume at swallowing initiation. *Respiratory Physiology and Neurobiology*, 234, 89–96. <https://doi.org/10.1016/j.resp.2016.09.004>
- Nilsson, H., Ekberg, O., Olsson, R., Kjellin, O., & Hindfelt, B. (1996). Quantitative assessment of swallowing in healthy adults. *Dysphagia*, 11(2), 110–116. <https://doi.org/10.1007/bf00417900>
- Nishino, T., Yonezawa, T., & Honda, Y. (1985). Effects of swallowing on the pattern of continuous respiration in human adults. *American Review of Respiratory Disease*, 132(6), 1219–1222. <https://doi.org/10.1164/arrd.1985.132.6.1219>
- Ogna, A., Prigent, H., Lejaille, M., Samb, P., Sharshar, T., Annane, D., ... Orlikowski, D. (2017). Swallowing and swallowing-breathing interaction as predictors of intubation in Guillain-Barré syndrome. *Brain and Behavior*, 7(2), e00611.
- Ouzzani, M., Hammady, H., Fedorowicz, Z., & Elmagarmid, A. (2016). Rayyan—A web and mobile app for systematic reviews. *Systematic Reviews*, 5, 210. <https://doi.org/10.1186/s13643-016-0384-4>
- Palmer, J. B., & Hiimae, K. M. (2003). Eating and breathing: Interactions between respiration and feeding on solid food. *Dysphagia*, 18(3), 169–178.
- Paydarfar, D., Gilbert, R. J., Poppel, C. S., & Nassab, P. F. (1995). Respiratory phase resetting and airflow changes induced by swallowing in humans. *The Journal of Physiology*, 483(1), 273–288.
- Perlman, A. L., He, X., Barkmeier, J., & Van Leer, E. (2005). Bolus location associated with videofluoroscopic and respiro-deglutometric events. *Journal of Speech, Language, and Hearing Research*, 48(1), 21–33.
- Pinto, C. F., Balasubramaniam, R. K., & Acharya, V. (2017). Nasal airflow monitoring during swallowing: Evidences for respiratory-swallowing incoordination in individuals with chronic obstructive pulmonary disease. *Lung India*, 34(3), 247–250. https://doi.org/10.4103/lungindia.lungindia_117_16
- Preiksaitis, H. G., Mayrand, S., Robins, K., & Diamant, N. E. (1992). Coordination of respiration and swallowing: Effect of bolus volume in normal adults. *American Journal of Physiology—Regulatory, Integrative and Comparative Physiology*, 263(3), R624–R630.
- Preiksaitis, H. G., & Mills, C. A. (1996). Coordination of breathing and swallowing: Effects of bolus consistency and presentation in normal adults. *Journal of Applied Physiology*, 81(4), 1707–1714.
- Shaker, R., Li, Q., Ren, J., Townsend, W. F., Dodds, W. J., Martin, B. J., ... Rynders, A. (1992). Coordination of deglutition and phases of respiration: Effect of aging, tachypnea, bolus volume, and chronic obstructive pulmonary disease. *American Journal of Physiology*, 263(5), G750–G755.
- Smith, J., Wolkove, N., Colacone, A., & Kreisman, H. (1989). Coordination of eating, drinking and breathing in adults. *Chest*, 96(3), 578–582.
- Terzi, N., Orlikowski, D., Aegerter, P., Lejaille, M., Ruquet, M., Zalcman, G., ... Lofaso, F. (2007). Breathing-swallowing interaction in neuromuscular patients: A physiological evaluation. *American Journal of Respiratory and Critical Care Medicine*, 175(3), 269–276.
- Wang, C.-M., Chen, J.-Y., Chuang, C.-C., Tseng, W.-C., Wong, A. M., & Pei, Y.-C. (2015). Aging-related changes in swallowing, and in the coordination of swallowing and respiration determined by novel non-invasive measurement techniques. *Geriatrics & Gerontology International*, 15(6), 736–744. <https://doi.org/10.1111/ggi.12343>
- Wang, C.-M., Li, H.-Y., Lee, L.-A., Shieh, W.-Y., & Lin, S.-W. (2016). Non-invasive assessment of swallowing and respiration coordination for the OSA patient. *Dysphagia*, 31(6), 771–780. <https://doi.org/10.1007/s00455-016-9740-8>
- Wang, C.-M., Shieh, W.-Y., Chen, J.-Y., & Wu, Y.-R. (2015). Integrated non-invasive measurements reveal swallowing and respiration coordination recovery after unilateral stroke. *Neurogastroenterology and Motility*, 27(10), 1398–1408.
- Wang, C.-M., Shieh, W.-Y., Weng, Y.-H., Hsu, Y.-H., & Wu, Y.-R. (2017). Non-invasive assessment determine the swallowing and respiration dysfunction in early Parkinson's disease. *Parkinsonism & Related Disorders*, 44, 22–27. <https://doi.org/10.1016/j.parkreldis.2017.05.024>
- Wheeler Hegland, K., Huber, J. E., Pitts, T., Davenport, P. W., & Sapienza, C. M. (2011). Lung volume measured during sequential swallowing in healthy young adults. *Journal of Speech, Language, and Hearing Research*, 54(3), 777–786. [https://doi.org/10.1044/1092-4388\(2010/09-0237\)](https://doi.org/10.1044/1092-4388(2010/09-0237))
- Wheeler Hegland, K. M., Huber, J. E., Pitts, T., & Sapienza, C. M. (2009). Lung volume during swallowing: Single bolus swallows in healthy young adults. *Journal of Speech, Language, and Hearing Research*, 52(1), 178–187.
- Yagi, N., Nagami, S., Lin, M.-K., Yabe, T., Itoda, M., Imai, T., & Oku, Y. (2017). A noninvasive swallowing measurement system using a combination of respiratory flow, swallowing sound, and laryngeal motion. *Medical & Biological Engineering & Computing*, 55(6), 1001–1017. <https://doi.org/10.1007/s11517-016-1561-2>

Appendix

Database Search Strategies

Database: Pubmed

Date: 09/12/2017 (updated 07/31/18)

Query: (((("Deglutition"[mh] OR Deglutition*[tiab] OR Swallow[tiab] OR Swallows[tiab] OR Swallowing[tiab] OR "Deglutition disorders"[mh:noexp] OR "Eating"[mh:noexp] OR Eating[tiab] OR ingesting[tiab] OR ingestion[tiab] OR ("Drinking"[mh] NOT alcohol*[tiab]) OR (drinking[tiab] NOT alcohol*[tiab])) AND ("Respiration"[mh:noexp] OR Respiration[tiab] OR Breath[tiab] OR breaths[tiab] OR breathes[tiab] OR breathing[tiab] OR "Exhalation"[mh] OR Exhale[tiab] OR exhales[tiab] OR exhaling[tiab] OR exhalation*[tiab] OR "Inhalation"[mh] OR Inhale[tiab] OR inhales[tiab] OR inhaling[tiab] OR inhalation*[tiab] OR "Respiratory phase"[tiab] OR "respiratory phases"[tiab] OR "Lung volume measurements"[mh:noexp] OR "Lung volume"[tiab] OR "lung volumes"[tiab] OR "expiratory reserve volume"[mh] OR "expiratory reserve volume"[tiab] OR "expiratory reserve volumes"[tiab] OR "tidal volume"[mh] OR "tidal volume"[tiab] OR "tidal volumes"[tiab] OR "Plethysmography"[mh] OR Plethysmograph*[tiab] OR "Respiratory physiological phenomena"[mh:noexp])) NOT ("animals"[mh] NOT "humans"[mh])) NOT ("child"[mh] NOT "adult"[mh]))

Database: Embase

Date: 09/12/2017 (updated 07/31/18)

Query: ('swallowing'/exp OR deglutition*:ti,ab OR swallow:ti,ab OR swallows:ti,ab OR swallowing:ti,ab OR 'dysphagia'/de OR 'eating'/exp OR eating:ti,ab OR ('drinking'/exp NOT alcohol*) OR (drinking:ti,ab NOT alcohol*) OR 'food intake'/de OR 'ingestion'/exp OR ingesting:ti,ab OR ingestion:ti,ab) AND ('breathing'/de OR respiration:ti,ab OR breath:ti,ab OR breaths:ti,ab OR breathes:ti,ab OR breathing:ti,ab OR 'exhalation'/de OR exhale:ti,ab OR exhales:ti,ab OR exhaling:ti,ab OR exhalation*:ti,ab OR 'expiratory flow'/exp OR 'expiratory flow rate'/exp OR 'inhalation'/exp OR inhale:ti,ab OR inhales:ti,ab OR inhaled:ti,ab OR inhaling:ti,ab OR inhalation*:ti,ab OR 'respiratory phase':ti,ab OR 'lung volume'/de OR 'lung volume':ti,ab OR 'expiratory reserve volume'/exp OR 'expiratory reserve volume':ti,ab OR 'tidal volume'/exp OR 'tidal volume':ti,ab OR 'plethysmography'/exp OR 'plethysmograph':ti,ab) NOT ('animal'/exp NOT 'human'/exp) NOT ('child'/exp NOT 'adult'/exp)

Database: Proquest Dissertations & Theses Global

Date: 09/12/2017 (updated 07/31/18)

Query: TI((Deglutition* OR Swallow OR swallows OR swallowing OR eating OR (Drinking NOT alcohol*) OR ingesting OR ingestion) AND (respiration OR breath OR breaths OR breathes OR breathing OR exhale OR exhales OR exhaling OR exhalation* OR inhale OR inhales OR inhaled OR inhaling OR inhalation* OR 'respiratory phase*' OR 'lung volume*' OR 'expiratory reserve volume*' OR 'tidal volume*' OR 'plethysmograph*')) OR AB((Deglutition* OR Swallow OR swallows OR swallowing OR eating OR (Drinking NOT alcohol*) OR ingesting OR ingestion) AND (respiration OR breath OR breaths OR breathes OR breathing OR exhale OR exhales OR exhaling OR exhalation* OR inhale OR inhales OR inhaled OR inhaling OR inhalation* OR 'respiratory phase*' OR 'lung volume*' OR 'expiratory reserve volume*' OR 'tidal volume*' OR 'plethysmograph*'))