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ORIGINAL ARTICLE

A Systematic Review of Physiological Changes in Swallowing in the Oldest Old

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Abstract

Age-related swallowing changes are well-researched in deglutology, usually distinguishing those over 60 years as older aged. World-wide, older adults are healthier and forecast to live longer: many over 85 years. It is necessary for clinicians to understand healthy swallowing changes in this 'oldest old' in order to appropriately manage swallowing complaints in older patients. This systematic review collated and critically appraised studies investigating swallowing changes in adults over 85 years using instrumental assessment. Criteria for inclusion were healthy subjects over 85 years. Exclusion criteria included studies focused on anatomy and oral processing. Studies published until December 2018 were retrieved from BIOSIS, CINAHL, Embase, Medline, and Scopus, totaling 2125 articles. During data screening, 64% of studies investigating age-related swallowing changes were excluded, as the oldest old were not recruited. After PRISMA screening, 44 articles met criteria. These were further reviewed for data extraction, bias and quality. Main quantitative age-related changes in swallowing included increases in delay in swallow onset, bolus transit times, duration of UES opening, pressure above the UES and UES relaxation pressure, and reduction in pressure at the UES. Few studies detected increased residue or airway compromise in the form of aspiration. Results were not easily comparable due to differences in age ranges, methods for deeming participants 'healthy', measures used to define swallowing physiology, and swallowing tasks. Age-related swallowing changes are identified that do not compromise safety. The oldest old are underrepresented in normative deglutition research. It is essential future studies plan accordingly to recruit those over 85 years.

Keywords Deglutition · Deglutition disorders · Systematic review · Aged, 80 and over · Healthy volunteers

Introduction

World-wide, populations are aging and include more older adults. A greater number of older adults are forecast to live over 85 years old (the 'oldest old') with mixed health and abilities [1]. Aging alone does not cause swallowing difficulties (dysphagia). However, the prevalence of swallowing impairment increases with age due to age-related diseases, medical events, multimorbidity and polypharmacy [2]. These contribute to rising referrals for swallowing assessment in the oldest old [3]. Physical consequences of dysphagia include aspiration pneumonia [4], malnutrition, and dehydration [5], which may become life-threatening. The perception of an idyllic retirement, centered on social events with eating and drinking, is altered for older adults with swallowing difficulties. Quality of life is negatively impacted, burdening not only the individual, but also their partner, caregiver, family, and friends [6, 7].

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An understanding of swallowing in healthy adults across the lifespan is essential to differentiate pathology from normal variance and optimize dysphagia management [8]. Swallowing changes with aging have been well addressed in the deglutition literature and discussed in a number of age-related swallowing reviews [9–12]. In the late 1980s, studies emerged on swallowing changes in healthy aging [13, 14]. At this time, it was common for participants over 60 years old to be described as 'elderly' and compared with a younger age group. Subsequent studies have been similarly designed. The shift in the aging of our population questions the direction of our future research. For example, are age-related changes best analyzed using dichotomous age groups? Perhaps not for countries with burgeoning aging populations: a global phenomenon with implications for health policy [15]. It is unlikely that current 60–70-year olds from these countries reflect the health status and overall abilities of their counterparts from the 1980s and 1990s. It also does not seem appropriate to compare or equate an adult at the age of retirement with someone in their late 80s or 90s. Without studies that differentiate age groups across the lifespan, it will be difficult to support those living into advanced age presenting with swallowing complaints. We conducted a systematic review to collate and critically appraise studies that have investigated swallowing changes in healthy adults over 85 years old using instrumental assessment. Using the PICO framework [16], our research question was 'what are normal swallowing physiological changes in the oldest old as assessed by instrumental assessment?' We hypothesized that studies report quantifiable swallowing changes in the oldest old which are significantly different from younger adults.

Methods

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and was registered on the International Prospective Register of Systematic Reviews (PROSPERO: CRD42018086084). Studies that identified participants as healthy and without swallowing problems during the recruitment process were included in this review. Studies met criteria for including the oldest old if the age range of a participant group extended beyond 85 years old, or the combined mean age and standard deviation of a participant group exceeded 85 years old. Instrumental assessments included flexible endoscopic evaluation of swallowing (FEES), high-resolution manometry with impedance (HRIM), low-resolution manometry (LRM) and videofluoroscopy (VFS). Studies that used devices to measure oral processing, such as jaw strength, tongue strength, or bite force were not investigated in this review. Quantitative measures of swallowing (oral, pharyngeal and esophageal physiology) were organized into bolus transit, swallow timing, displacement, pressure, and airway compromise (penetration, aspiration, and residue). Inclusion and exclusion criteria are presented in Table 1.

Search Strategy

Studies published until December 2018 were retrieved from BIOSIS, CINAHL, Embase, Medline, and Scopus. A specialist university librarian was consulted for advice on databases and search terms. Our search keywords were broad: 'swallowing' AND 'normal' OR 'healthy' OR 'typical'. Search results were filtered in each database by age (80 years and older), article type (journal article), human studies, and language (English). MeSH terms were searched on Medline: 'deglutition' AND 'healthy volunteers' OR 'aged, 80 and over'.

Search results were saved in Endnote (Clarivate Analytics, Philadelphia), where duplicates were removed. Titles of studies retrieved using the search strategy were screened against the exclusion criteria and coded according to Table 1, followed by abstracts of potentially eligible studies. From the articles that met inclusion for review, a hand-search for additional eligible studies was performed using their reference lists, first by screening titles and then abstracts. If a study met criteria, the full texts were critically appraised for inclusion.

Study Analysis

Studies were entered onto a spreadsheet (Microsoft Excel, Version 16.21.1) after title and abstract screening. Data were

Table 1 Criteria for title, abstract and full-text review

Inclusion criteria	Exclusion criteria
Original peer-reviewed quantitative studies	Reviews, meta-analyses, qualitative studies, editorials, commentaries, conference abstracts
Recruitment of participants aged > 85 years old	Participants only aged < 85 years old
Studies investigating oral, pharyngeal, and/or esophageal phases of swallowing	Studies focused on anatomy or oral processing, including mastication, jaw strength, tongue strength, and bite force
Healthy participants without history of dysphagia or diagnosis known to affect swallowing	Participants only with a history of dysphagia or diagnosis known to affect swallowing

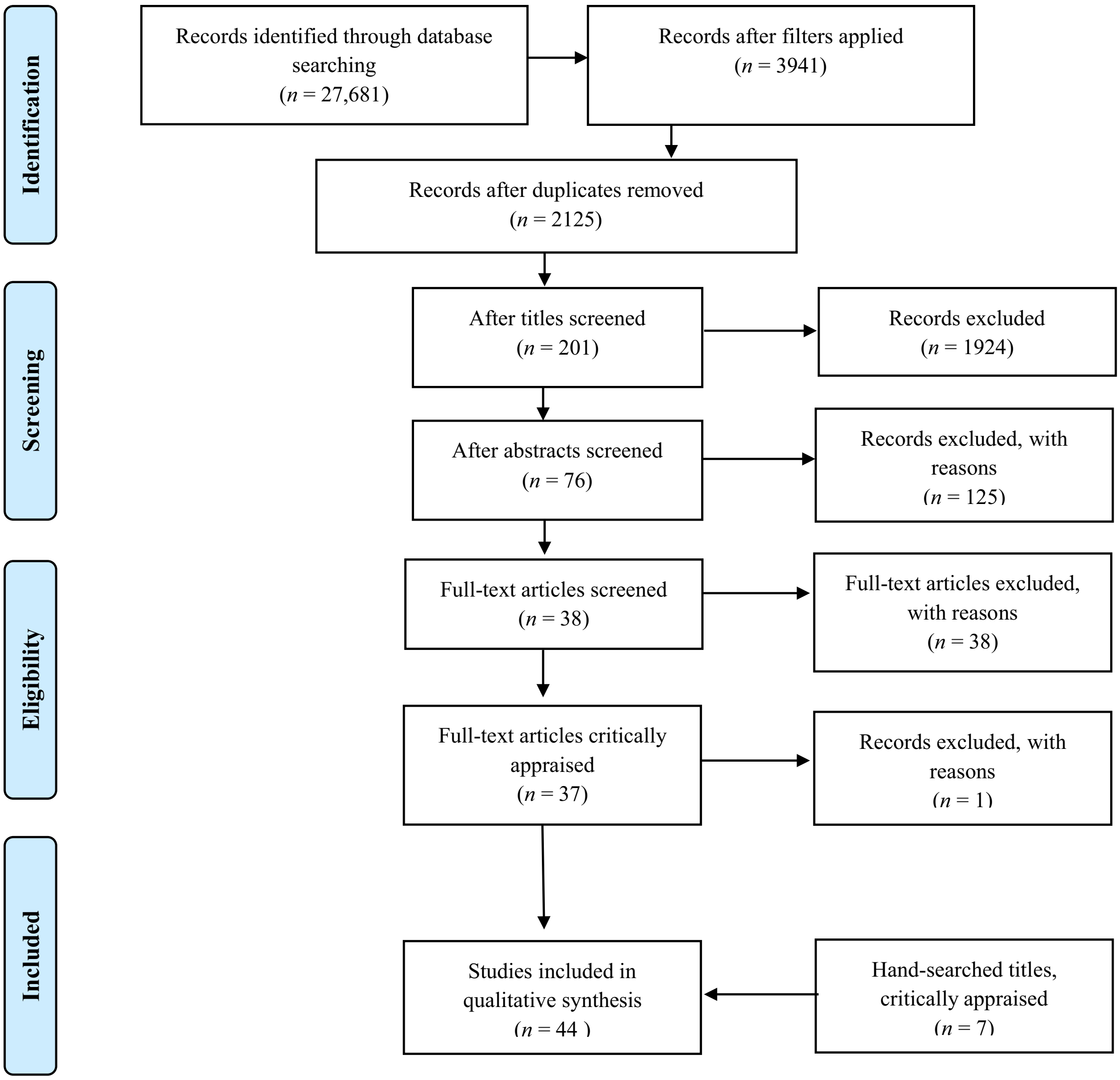

Fig. 1 Adapted PRISMA flow diagram, presenting the different phases of study selection for the systematic review

Table 2 Reasons for study exclusions after abstract and full-text reviews

Reasons for study exclusions	Studies excluded after abstract review $n=125$	Studies excluded after full-text review $n=37$
Participants with dysphagia	15	3
Study unrelated to normal swallowing changes in older adults	23	4
Participants < 85 years	42	27
No instrumental assessment performed	16	1
Focus on oral processing	15	1
Not an original article	4	0
Not in English	1	0
Other	9	1

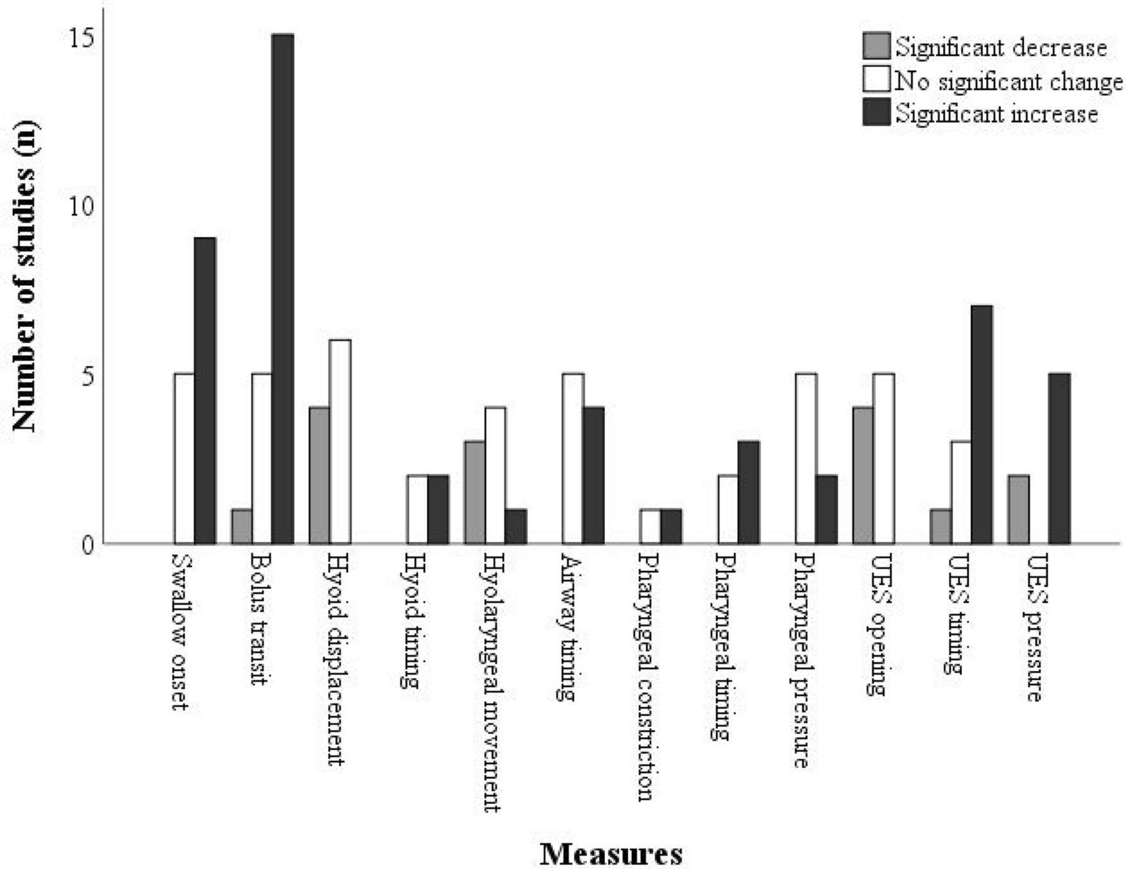

Fig. 2 Most reported significant and non-significant measures across included studies

then extracted from relevant studies, following the PICO framework [16] ("Appendix 1").

1. Participants: age range, mean age of oldest group and standard deviation, names of participant groups, total participants (*n*), how participants were deemed 'healthy'
2. Intervention: instrumental assessment, swallow tasks during the assessment (bolus size and texture)
3. Comparators: names of participant groups and total participants (*n*).
4. Outcomes: bolus transit times (s), swallow times (s), displacement (cm) and pressure (mmHg), as well as events of penetration, aspiration, and residue

The data collection process was presented by the first author to four doctoral candidates from the Department of Speech Science (including three specializing in Dysphagia) during a research meeting, and discussed until consensus was met. Terms and definitions for bolus transit and swallow timing, displacement and pressure were extracted from studies. Significant and non-significant swallowing changes with age were summarized. Measures were tabulated and differences between young and old were presented if there were between-group differences on any bolus type. The proportion of adults over 85 years old was assessed in each study in keeping with the study research question.

Risk of Bias and Quality

The full texts of included studies were critically appraised using an adapted checklist from the Critical Appraisal Skills Programme ("Appendix 2"). The Cochrane Collaboration's tool for assessing risk of bias was adapted to assess performance, detection, attrition, reporting, and other sources of bias [17]. The GRADE approach was used to assess quality of evidence, including imprecision, inconsistency, indirectness, and publication bias, as well as risk of bias [18]. All data were reviewed by the second author at both study

Table 3 Delay in swallow onset

Study	Assessment	Measure	Authors' definition	Old age
Rademaker et al. [19]	VFS	Pharyngeal delay time	From bolus head passing ramus of mandible until onset of laryngeal elevation	↑
Logemann et al. [20]	VFS	Pharyngeal delay	From bolus head reaching point where lower edge of mandible crosses tongue base until first laryngeal elevation in swallow is seen	↑
Logemann et al. [21]	VFS	Pharyngeal delay	From bolus head reaching point where lower edge of mandible crosses tongue base until first laryngeal elevation in swallow is seen	⇡
Kim et al. [22]	VFS	Pharyngeal delay time	From bolus head passing posterior edge of ramus of mandible until initial observation of laryngeal elevation	↑
		Stage transition duration	From bolus passing posterior edge of ramus of mandible until maximal excursion of hyoid is initiated	↑
		Delayed pharyngeal swallow	From head of bolus reaching valleculae to initiation of laryngeal movement	⇡
Yoshikawa et al. [23]	VFS	Pharyngeal delay time	Begins when bolus head reaches point where lower edge of mandible crosses tongue base, and ends when laryngeal elevation begins in context of rest of swallow	↑
Martin-Harris et al. [24]	VFS	Delayed pharyngeal swallow	Difference between bolus head arrival at the posterior angle of mandible and onset of hyoid motion	⇡
McCullough et al. [25]	VFS	Stage transition duration	Arrival of first material at ramus of mandible to initiation of maximal hyoid excursion	⇡
		Stage transition duration 2	From bolus head at ramus of mandible to initiation of maximal hyoid excursion	↑
Ayala and Logemann [26]	VFS	Pharyngeal delay time	Difference between onset of laryngeal elevation and point when bolus head passes cross-point between the inferior edge of mandible and tongue base	⇡*
Butler et al. [27]	FEES	Bolus dwell time	Bolus hesitation in pharynx before onset of pharyngeal swallow	↑
Omari et al. [28]	HRIM	Flow interval	Bolus dwell time, not further defined	↑
Cock et al. [29]	HRIM	Flow interval	Reference to Omari et al. [30] (duration of impedance drop in distal pharynx)	↑

↑Statistically significant increase observed in older adults; – no significant age-related change; ⇡ increase reported for older adults that was not statistically significant; *effects of use: a steady increase was observed for old and very old towards end of swallow sets

selection and quality appraisal stages. Discrepancies were resolved through consensus.

Results

The study selection process is presented in Fig. 1. Forty-four studies met inclusion criteria.

Reasons for study exclusions after abstract and full-text screening are detailed in Table 2. Out of 107 studies investigating normal swallowing in older adults, 64% of studies (69/107) did not recruit the oldest old. Instrumental assessments included VFS (59%), FEES (11%), VFS with LRM (9%), HRIM (9%), LRM (7%), and FEES with LRM (5%). Figure 2 provides a graphic representation of the most reported significant and non-significant findings across measures.

Timing of Bolus Entry into Pharynx Compared to Swallow Onset

Eleven studies analyzed the timing of bolus entry into the pharynx compared to swallow onset [VFS (8/11), HRIM (2/11), and FEES (1/11)] using 14 different measures (Table 3). More than half of measures (9/14) demonstrated a significant increase in delay of swallow onset compared to bolus movement.

Table 4 Bolus transit times

Study	Assessment	Measure	Authors' definition	Old age
Dejaeger et al. [31]	LRM VFS	Oropharyngeal transit time	Time to pass distance between first and second sensor	–
		Hypopharyngeal transit time	Time to pass distance between second and fourth sensor	–
		Pharyngeal transit time	Time between arrival of bolus head at first sensor and passage of bolus tail at fourth sensor. Duration of bolus passage in pharynx	–
Rademaker et al. [19]	VFS	Oral transit time	From onset of tongue movement propelling bolus posteriorly until bolus head passes ramus of the mandible	–
		Pharyngeal transit time	From bolus head passing ramus of mandible until bolus tail passes through cricopharyngeal sphincter	↑
Yokoyama et al. [32]	LRM VFS	Oropharyngeal transit	Segmental transit time	↑
		Hypopharyngeal transit	Duration from moment bolus head touches respective sensor to moment bolus tail leaves same sensor	↑
		Upper esophageal sphincter (UES) transit		↑
		Pharyngeal transit time	Duration from moment bolus head touches oropharyngeal sensor to moment bolus tail leaves UES sensor	↑
Leonard et al. [33]	VFS	Hypopharyngeal transit time	Time between bolus head exiting or passing valleculae and bolus tail clearing UES	↑
Martin-Harris et al. [34]	VFS	Total swallow duration	Not further defined	⇡
Martin-Harris et al. [35]	VFS	Total swallow duration	Not further defined	⇡
Yoshikawa et al. [23]	VFS	Oral transit time	Time from beginning of tongue movement to beginning of voluntary oral stage until tail of bolus reaches point where lower edge of mandible crosses tongue base	↑
		Pharyngeal transit time	Time from trigger of pharyngeal swallow to when tail of bolus passes through cricopharyngeal region	↑
McCullough et al. [25]	VFS	Oral transit duration	Beginning of posterior movement of bolus to bolus head at ramus of mandible	↓
		Pharyngeal transit duration	From bolus head at ramus of mandible to bolus tail entering cricopharyngeus	↑*
		Total swallow duration	From beginning of posterior bolus movement to hyoid return to rest	↑
Im et al. [36]	VFS	Pharyngeal transit duration	Duration of bolus flow from ramus of mandible to UES	↑
Veiga et al. [37]	FEES	Time of intake	Stopwatch was started when water touched participant's lips and was stopped when utensil was handed to researcher	↑
Miles et al. [38]	VFS	Esophageal transit time	Not further defined	↑
Jardine et al. [39]	VFS	Total pharyngeal transit time	Onset of swallow (first movement past posterior nasal spine) to clearance of bolus tail through pharyngoesophageal segment (PES)	↑
		Esophageal transit time	Entrance of bolus through PES to clearance through lower esophageal sphincter	↑

↑ statistically significant increase observed in older adults; ↓ statistically significant decrease observed in older adults; – no significant age-related change; ⇡ increase reported for older adults that was not statistically significant; *significant systematic increase in pharyngeal transit duration across age groups until ≥ 80 years

Bolus Transit Time

The majority of bolus transit measures (15/22) demonstrated a significant age-related increase (Table 4). All but one study (10/11) measured bolus transit using VFS; two included concurrent manometry.

Hyoid Measures

Studies that measured hyoid displacement and timing all used VFS and showed varying results on the effect of age (Table 5).

Table 5 Hyoid displacement and timing measures

Study	Assessment	Measure	Authors' definition	Old age
Displacement				
Kern et al. [40]	LRM VFS	Anterior excursion of hyoid	Maximum anterior excursion of the hyoid bone from resting position	↓
		Superior excursion of hyoid	Maximum superior excursion of the hyoid bone from resting position	–
Logemann et al. [20]	VFS	Anterior hyoid movement	From rest position to maximal elevation	↓
		Hyoid elevation	From rest position to maximal elevation	↓
Logemann et al. [21]	VFS	Anterior hyoid movement	Maximal extent of structural movement, not further defined	–
		Vertical hyoid movement	Maximal extent of structural movement, not further defined	–
Leonard et al. [33]	VFS	Hyoid displacement (Hmax)	Hyoid position was determined at baseline and again at point of its greatest excursion from baseline during swallow	–
Kim and McCullough [41]	VFS	Anterior displacement	Distance between resting position of hyoid and maximum displacement of hyoid bone during swallow	↓
		Vertical displacement	Distance between resting position of hyoid and maximum displacement of hyoid bone during swallow	⇣
Jardine et al. [39]	VFS	Hmax	Change in hyoid position from rest to maximum anterior–posterior displacement	–
Timing				
Rademaker et al. [19]	VFS	Duration of hyoid movement	Time between start of movement and return to rest of hyoid bone	–*
McCullough et al. [25]	VFS	Duration of hyoid maximum elevation (DOHME)	From hyoid first maximum elevation to hyoid last maximum elevation	⇡
		Duration of hyoid maximum anterior excursion (DOHMAE)	From first frame showing maximum anterior hyoid movement to last frame showing maximum anterior hyoid movement	↑
Jardine et al. [39]	VFS	Hdur	Duration of maximum hyoid displacement	–

↑ statistically significant increase observed in older adults; ↓ statistically significant decrease observed in older adults; – no significant age-related change; ⇡ increase reported for older adults that was not statistically significant; ⇣ decrease reported for older adults that was not statistically significant; *60–79 years demonstrated longer duration of hyoid movement, while 80–89 years demonstrated shorter duration of hyoid movement

Airway Closure

Hyolaryngeal movement and airway closure timing using VFS featured in eight studies (Table 6).

Pharyngeal Constriction

Six studies reported age-related changes in pharyngeal constriction ratio—a validated fluoroscopic surrogate for manometric pharyngeal pressure [43] and manometric pharyngeal timing and pressure measures (Table 7).

Upper Esophageal Sphincter (UES) Measures

Seven studies reported UES opening using VFS (including one study with concurrent LRM) and HRIM. Eleven studies measured duration of UES opening using VFS (including two studies with concurrent LRM) and LRM. UES pressure measures were calculated from HRIM and LRM in five studies (Table 8).

Esophageal Measures

Four studies investigating age-related changes in the esophagus were included in this systematic review using a range of esophageal measures, protocols, and analysis approaches (Table 9).

Observations

Most studies using FEES and VFS documented whether or not penetration (19/36) and aspiration (25/36) were observed. Six studies did not detect any penetration and 14 did not observe aspiration. Just under half of studies

Table 6 Airway measures

Study	Assessment	Measure	Authors' definition	Old age
Hyolaryngeal movement				
Kern et al. [40]	LRM VFS	Laryngeal anterior excursion	Maximum anterior excursion of larynx from resting position	↓
		Laryngeal superior excursion	Maximum superior excursion of larynx from resting position	–
Logemann et al. [20]	VFS	Anterior laryngeal movement	Laryngeal position was measured at rest in relation to anterior-inferior corner of second cervical vertebra	–
		Laryngeal elevation	Maximal extent of structural movement, not further defined	↓
Logemann et al. [21]	VFS	Anterior laryngeal movement	Laryngeal position was measured at rest in relation to anterior-inferior corner of fourth cervical vertebra.	⇡
		Vertical laryngeal movement	Maximal extent of structural movement, not further defined	↑
Leonard et al. [33]	VFS	HLmax	Point of maximum approximation of hyoid and larynx during swallow	–*
Jardine et al. [39]	VFS	HLmax	Difference in distance between hyoid and larynx at rest and when maximally approximated during swallow	↓
Timing				
Rademaker et al. [19]	VFS	Duration of laryngeal closure	Length of time that laryngeal entrance between arytenoid and base of epiglottis was closed in lateral plane during swallow	↑
		Duration of laryngeal elevation	Time between the beginning of laryngeal elevation and laryngeal return to rest	↑
Logemann et al. [20]	VFS	Laryngeal closure	Not further defined	–
Logemann et al. [21]	VFS	Laryngeal closure	Not further defined	⇡
Ayala and Logemann [26]	VFS	Duration of laryngeal closure	Time laryngeal entrance (between arytenoid and base of epiglottis) is closed during swallow	↑
		Duration of laryngeal elevation	Not further defined	⇡
Kurosu and Logemann [42]	VFS	Duration of laryngeal closure	Time laryngeal entrance between the arytenoids and base of epiglottis is closed	–
Jardine et al. [39]	VFS	Airwaycl	Onset and completion of supraglottic closure	–
		Airwaydur	Duration of airway closure	–

↑ statistically significant increase observed in older adults; ↓ statistically significant decrease observed in older adults; – no significant age-related change; ⇡ increase reported for older adults that was not statistically significant; *significant increase only for older females with cricopharyngeal bars

commented on pharyngeal residue (17/36), with no findings of residue reported in four. Few studies documented age-related effects: penetration (3/19), aspiration (4/25), and pharyngeal residue (5/17) (Tables 10, 11).

Risk of Bias and Quality Assessment Across Studies

Sample sizes varied greatly across studies, from 16 [20, 21] to 203 [55]. No studies demonstrated high risk of bias and risk of reporting bias was rated low across all studies (Table 12). Using the GRADE approach, observational studies are first rated low quality. No studies were downgraded, as ratings of unclear risk of bias were unlikely to seriously alter studies' results. Methods for instrumental assessments and definitions for swallowing measures were detailed in all studies. Most studies (38/44) provided references for study protocols and/or data analyses. There was limited scope for meta-analysis due to the variety of swallowing measures and definitions across studies.

Calculation of proportion of over 85-year olds studied was precluded in 73% (32/44) of studies: unknown mean age in the oldest group (17/44), mean age in the 70s (13/44),

Table 7 Pharyngeal constriction, timing, and pressure measures

Study	Assessment	Measure	Authors' definition	Old age
Constriction				
Leonard et al. [33]	VFS	Unobliterated pharyngeal space	Portion of pharynx remaining unobliterated at point of maximum pharyngeal clearing during swallow	↑
Jardine et al. [39]	VFS	Pharyngeal constriction ratio	Pharyngeal area of maximum constriction/open pharyngeal area	–
Timing				
Yokoyama et al. [32]	LRM VFS	Oropharyngeal pressure duration	Duration of oropharyngeal positive pressure	↑
		Hypopharyngeal pressure duration	Duration of hypopharyngeal positive pressure	↑
Van Herwaarden et al. [44]	LRM	Duration of pharyngeal contraction	Time between onset and end of pharyngeal contraction	↑
Omari et al. [28]	HRIM	TZn to Peak P	Latency from tongue base bolus propulsion to pharyngeal stripping wave peak: interval from nadir impedance to peak pressure	–
Cock et al. [29]	HRIM	TNIPP	Distension-contraction latency, defined in Cock [45]: time of nadir impedance to peak pressure	–
Pressure				
Dejaeger et al. [31]	LRM VFS	Amplitude of Pharyngeal Contraction	Height of pharyngeal contraction peak, not further defined	–
Dejaeger et al. [46]	LRM VFS	Amplitude of Pharyngeal Contraction	Peak amplitude of pharyngeal contraction, not further defined	↑
Yokoyama et al. [32]	LRM VFS	Oropharyngeal Pmax	Maximum value of oropharyngeal pressure	⇡
		Hypopharyngeal Pmax	Maximum value of hypopharyngeal pressure	⇡
Van Herwaarden et al. [44]	LRM	Amplitude of pharyngeal contraction	Highest pressure of contraction with the pharyngeal baseline as reference	↑
Omari et al. [28]	HRIM	PeakP	Peak pressure of pharyngeal stripping wave: pharyngeal contractile vigor	–
Cock et al. [29]	HRIM	PeakP	Pharyngeal peak pressure	⇡

↑Statistically significant increase observed in older adults; – no significant age-related change; ⇡ increase reported for older adults that was not statistically significant

and unknown age range (4/44) (two of these limitations were in two studies). For studies published prior to 2010, 24/26 demonstrated limitations regarding the representation of the oldest old compared to 8/18 of studies published from 2010 to 2018. Figure 3 presents the trend towards increased age of participants in more recent years. Most studies (19/44) divided their cohort into younger and older age groups. Number of age groups across studies included three (8/44), four (8/44), five (1/44), 7 (1/44), and eight (1/44); while 6 studies investigated swallowing changes with age as a continuum ("Appendix 1").

Methods to confirm participants were healthy were reported in just over half of studies (23/44): questionnaires (21/44), interviews (10/44), head and neck or cranial nerve examinations (7/44), and a swallowing test (1/44). The other studies (21/44) reported statements such as no relevant medical history, self-reported as healthy, or without any swallowing difficulties ("Appendix 1").

Discussion

This systematic review was conducted to acknowledge the globally aging population and subsequent need to understand healthy swallowing changes in the oldest old (> 85 years old). Even with the exclusion of 64% of accessed studies because the oldest old were not recruited, there was still a large body of literature using a variety of instrumental assessments that investigated age-related swallowing changes into the 8th decade and beyond. Three quarters of

Table 8 UES opening, timing, and pressure measures

Study	Assessment	Measure	Authors' definition	Old age
UES opening				
Kern et al. [40]	LRM VFS	Anteroposterior UES diameter	Maximum anteroposterior diameter of the narrowest area of UES opening	↓
		Lateral UES diameter	Maximum lateral diameter of the narrowest area of UES opening	–
Logemann et al. [20]	VFS	Width of cricopharyngeal opening	Maximal extent of structural movement	↓
Logemann et al. [21]	VFS	Anterior–posterior cricopharyngeal opening	Maximal extent of structural movement: anterior–posterior diameter of cricopharyngeal opening	–
Leonard et al. [33]	VFS	Maximum UES opening: UESmax-lat	Narrowest point between cervical vertebrae 3 and 6, measured at its point of maximum distension during swallow	–*
		UESmax-a/p	Above measure is repeated in anterior–posterior view	–**
Omari et al. [28]	HRIM	UES Zn	UES nadir impedance: center of swallowed bolus (UES opening diameter during bolus flow)	↑***
Cock et al. [29]	HRIM	UES Max Adm	UES maximum admittance at maximal UES diameter	↓
Jardine et al. [39]	VFS	PESmax	Maximum distension of PES	–
Timing				
Rademaker et al. [19]	VFS	Duration of cricopharyngeal opening	Length of time that cricopharyngeal region was open during each swallow	↑
Kern et al. [40]	LRM VFS	Total duration of UES opening	From entry of bolus to return to resting closed state following passage of bolus tail	↑
Logemann et al. [20]	VFS	Cricopharyngeal opening	Maximal extent of structural movement, not further defined	–
Yokoyama et al. [32]	LRM VFS	UES relaxation duration	Duration from Pmin (pressure becomes minimal) to moment at which UES pressure begins to rise with recontraction of UES	–
Logemann et al. [21]	VFS	Cricopharyngeal opening	Not further defined	↑
Van Herwaarden et al. [44]	LRM	Duration of UES relaxation	Time difference between onset and end of UES relaxation	↓
Leonard et al. [33]	VFS	UESopen	Total duration of UES opening during swallow	↑
McCullough et al. [25]	VFS	Duration of opening of UES (DOOUES)	From UES opening to its closing	↑
Ayala and Logemann [26]	VFS	Duration of cricopharyngeal opening	Time cricopharyngeal region is open during the swallow, from onset of opening to when tail of bolus leaves cricopharyngeal region	↑#
Kurosu and Logemann [42]	VFS	Duration of cricopharyngeal opening	Time the cricopharyngeal region is open during swallow	↑
Jardine et al. [39]	VFS	PESop	PES opening duration	–
Pressure above UES				
Kern et al. [40]	LRM VFS	Hypopharyngeal intrabolus pressure	Maximum UES opening at site immediately proximal to the UES, seen in anteroposterior projection	↑
Omari et al. [28]	HRIM	Pharyngeal PZn	Hypopharyngeal intrabolus pressure: pressure at the time of nadir impedance	–
Cock et al. [29]	HRIM	PNadImp	Hypopharyngeal intrabolus pressure	↑
Pressure at UES				
Van Herwaarden et al. [44]	LRM	Resting UES pressure	Measured by using the esophageal baseline pressure as reference	↓
Omari et al. [28]	HRIM	UES PZn	UES intrabolus pressure	–

Table 8 (continued)

Study	Assessment	Measure	Authors' definition	Old age
Relaxation pressure				
Yokoyama et al. [32]	LRM VFS	UES Pmin	Minimum value of UES pressure	↑
Cock et al. [29]	HRIM	IRP0.2	UES-integrated relaxation pressure: median of the lowest pressures recorded over 0.2 cumulative seconds	↑

↑Statistically significant increase observed in older adults; ↓ statistically significant decrease observed in older adults; – no significant age-related change; *significant decrease for older adults with cricopharyngeal bars; **significant decrease for older males with cricopharyngeal bars; ***higher UES Zn indicates narrower UES opening; #effects of use: CP duration was longer for old vs very old in final swallow set

the 44 included studies focused primarily on pharyngeal measures, while five studies solely focused on esophageal, and six on observations of penetration, aspiration, or pharyngeal residue. While age-related swallowing changes were reported across all measures, more consistent changes with older age were increased delay of swallow onset, bolus transit times, duration of UES opening, pressure above the UES, and UES relaxation pressure, as well as reduced pressure at the UES. Hyoid and laryngeal timing and displacement measures were inconclusive. Few studies detected airway compromise in the form of increased aspiration or residue in healthy older adults.

Effects of Age on Swallowing

The impact of neurological, anatomical, and physiological age-related changes on swallowing function in older adults has been described. Studies using fMRI during swallowing tasks have observed the activation of more cortical [65] and subcortical regions [66] in older adults, as well as limited activation of sensory processing and sensorimotor integration with age [67]. Age-related loss of muscle mass and function, termed sarcopenia, is prevalent in adults 85 years and older [68], and has been positively associated with swallowing difficulties [69]. In healthy older adults, decreased pharyngeal wall thickness and increased pharyngeal lumen volume were measured on MRI [70]. Even though participants from all included studies were considered healthy, it is unknown how many presented with risk factors for sarcopenia. This is a developing research area and important consideration for future studies that include the oldest old. Other anatomical changes observed with age include spinal changes, such as osteophytes and non-obstructive cricopharyngeal bars [71]. There has been no reported effect of cricopharyngeal bars on hypopharyngeal transit times, UES opening duration [33], maximum admittance, or 0.2 s integrated relaxation pressure [29].

Quality

Sample sizes across studies were variable and often lacked power calculations to reassure against Type II errors. Each study presented with at least one source of unclear risk of bias. When analyzing age effects, it is essential that raters are blinded to participant age, yet only 20% of studies detailed blinding methods in reports. Instrumental assessments risk human error, such as poor image quality or missed recording. Yet, it is surprising that only 39% of studies detailed missing data. Less than half (45%) of studies provided details of reliability testing. While standard protocols were often used and reported, cross-study comparisons were not easy due to differences in age ranges, methods for deeming participants 'healthy', measures and definitions of swallowing physiology, swallowing tasks, and sample sizes. A meta-analysis was therefore not advisable.

Methods for deeming participants 'healthy' differed greatly across studies. Using standardized questionnaires or specifying the methods in which medical history is reviewed are essential to increase the reliability and applicability of results and to avoid bias. Medicine use increases with older age [72] and medicines are known to impact swallowing function [73]. Therefore, when screening for healthy older adults, it is also important to consider all prescription medications, and this was not consistently reported across studies.

Oldest Old

The definition of old age differs world-wide and is dependent on economic, social, and political factors [15]. Studies included in this systematic review were all conducted in developed countries experiencing rapid growth in the oldest old: Australia, Belgium, Brazil, Canada, England, Japan, Korea, New Zealand, The Netherlands, and the USA. Our findings may be limited to countries with similar life expectancy rates. Although all studies recruited participants over

Table 9 Esophageal pressure measures

Study	Assessment	Measure	Authors' definition	Old age
Pressure-flow analysis				
Cock et al. [45]	HRIM	PeakP	Peak pressure, not further defined	–
Khan et al. [47]	LRM	Amplitude of esophageal contraction	Not further defined	↓*
Nishimura et al. [48]	LRM	Amplitude of peristaltic contraction	Measured at 5 cm and 10 cm above LES	↓
Cock et al. [45]	HRIM	PNadImp	Pressure at nadir impedance	↑
Cock et al. [45]	HRIM	IBP	Intrabolus pressure	↑
Cock et al. [45]	HRIM	IBP slope	Intrabolus pressure slope (reflecting the rate at which pressure increases)	↑
Cock et al. [45]	HRIM	TNIPP	Time of nadir impedance to peak pressure: latency from bolus distension to esophageal contraction	↑
Nishimura et al. [48]	LRM	Duration of peristaltic contraction	Time difference between the onset and offset of each contraction wave	–
Khan et al. [47]	LRM	Duration of contraction and relaxation phases	Not further defined	–
Khan et al. [47]	LRM	Resting esophageal pressure	Not further defined	–**
Cock et al. [45]	HRIM	PFI	Pressure-flow index	–
Cock et al. [45]	HRIM	IR	Impedance ratio: ratio of nadir impedance to impedance at the time of peak pressure	↑
Chicago variables				
Cock et al. [45]	HRIM	IRP4	4-second integrated relaxation pressure	↑
Cock et al. [45]	HRIM	ICD	Isocontour defect/peristaltic break length: axial length of defects in the 20-mmHg isobaric contour	↑
Cock et al. [45]	HRIM	CFV	Contractile front velocity: slope of the tangent approximating the 30 mmHg isocontour between the proximal transition zone and contractile deceleration point	↑
Cock et al. [45]	HRIM	DCI	Distal contractile integral: distal esophageal segment as amplitude × duration × length of the contraction in excess of 20 mmHg	–
Cock et al. [45]	HRIM	DL	Distal latency: time from swallow onset (either through UES relaxation or the onset of impedance drop at the most proximal channel) to the contractile deceleration point	–
LES				
Nishimura et al. [48]	LRM	Resting LES pressure	Not further defined	–
		Nadir LES pressure on relaxation	Mean of LES pressure at relaxation in ten wet swallows	–
Khan et al. [47]	LRM	Amplitude of LES contraction	Amplitude of LES contraction in response to deglutition	↓
		LES relaxation	Amplitude of LES relaxation in response to deglutition	–
Esophagogastric junction metrics				
Cock et al. [49]	HRIM	IRP4	Esophagogastric junction relaxation pressure: integrated relaxation pressure in four seconds	↑
Cock et al. [49]	HRIM	GasP	Not further defined	↑
Cock et al. [49]	HRIM	BFT	Bolus flow time	↓
Cock et al. [49]	HRIM	BPT	Bolus presence time: bolus presence in the distal esophagus	↓

↑Statistically significant increase observed in older adults; ↓statistically significant decrease observed in older adults; – no significant age-related change; *significantly reduced in lower and upper thirds of esophagus; **significant increase for older females

Table 10 Description of penetration and aspiration events detected in studies

Study	Assessment	Penetration	Old age	Aspiration	Old age
Dejaeger et al. [31]	LRM VFS	Unknown	/	Younger: not detected Older: 1/16 participants	*
Martin-Harris et al. [34]	VFS	Most participants in this study did not demonstrate laryngeal penetration	*	Most participants in this study did not demonstrate aspiration	*
Martin-Harris et al. [35]	VFS	Unknown	/	Not detected	–
Yoshikawa et al. [23]	VFS	Younger: 0/14 Older: 6/19	↑	Not detected	–
Daggett et al. [50]	VFS	All PAS 2. By swallow: < 50 years: 4.8% 50+ years: 13.2% (60–69 years: 10.7% 70–79 years: 14.4% 80–89 years: 15.6% 90+ years: 11.3%)	*	Not detected	–
Martin-Harris et al. [24]	VFS	PAS 2 for 2/43 delayed in trial 1 and 6/51 delayed in trial 2 PAS 3 for 1/43 in trial 1 and 1/51 in trial 2	*	PAS 6 for 1/43 delayed in trial 1	*
McCullough et al. [25]	VFS	Single bolus, 21–39 years: at least one PAS 2 for 5/20 participants, PAS 3 for 1/20. ≥ 80 years: at least one PAS 2 for 12/20 3 oz test, 21–39 years: PAS ≥ 2 for 9/20. ≥ 60 years: PAS 2–3 for 23/40	↑	Single bolus, 21–39 years: > PAS 3 for 0/20 ≥ 80 years: ≥ PAS 3 for 7/12 participants, maximum PAS 7	↑
Kelly et al. [51]	FEES	32/2448 (1.3%) by 21 young and 11 elderly, all coating or mild residue	*	Not detected	–
Butler et al. [52]	FEES LRM	82/545 swallows (15%)	*	18/545 swallows (3%)	*
Ayala and Logemann [26]	VFS	Young: 7.9% Old: 19.1% Very old: 17.5%	*	Young: 1 participant Old: 0 Very old: 3 (5 swallows)	↑
Butler et al. [53]	FEES	462/2432 swallows (19%)	*	83/2432 swallows (3%) 51/83 swallows silent aspiration	*
Kurosu and Logemann [42]	VFS	Younger: 0 participants Middle-aged: 1 Older: 3	*	Not detected	–
Butler et al. [27]	FEES	Unknown	/	Aspiration detected in following no. participants 70–79 years: 4/18 80–89 years: 8/26 90 years: 11/32	↑
Butler et al. [54]	FEES LRM	Unknown	/	22/748 swallows by 7 participants 19/22 silent aspiration	*
Butler et al. [55]	FEES	601/6404 swallows (9.4%) 71–80 years and 81–90 years had five-fold increased odds vs 51–60 years	↑	104/6404 swallows (1.6%) 81–90 years had 13.6-fold increased odds vs 21–30 years. 27/36 participants: silent aspiration	↑
Jardine et al. [39]	VFS	Younger: not detected Older: 3 (5.4%) participants	*	Not detected	–
Molfenter et al. [56]	VFS	Eight scores of PAS 3 8/372 swallows (2.2%)	*	One score of PAS 5 1/372 swallows	*

/ unknown; – not detected; *detected but no particular age-related change; ↑ detected and suggested increase with older age

Table 11 Description of pharyngeal residue detected in studies

Study	Assessment	Pharyngeal residue	Old age
Dejaeger et al. [31]	LRM VFS	Younger: not detected Older: vallecular 11/16 participants, pyriform 10/16	↑
Dejaeger et al. [46]	LRM VFS	Younger: not detected Older: diffuse pharyngeal residue in 24/75 swallows, vallecular 15/75, pyriform 13/75	↑
Rademaker et al. [19]	VFS	Oral, 20–39 years: 10.1% swallows 80–89 years: 29.2%	↑
		Pharyngeal, 20–39 years: 18.0% 80–89 years: 38.0%	↑
Logemann et al. [20]	VFS	None or mild for all ages Younger: usually no residue Older: mild residue was noted more often	*
Logemann et al. [21]	VFS	None or mild for all ages	*
Kim et al. [22]	VFS	No residue other than trace coating	*
Yoshikawa et al. [23]	VFS	Oral, Younger: 4/14 Older: 13/19	↑
		Pharyngeal, Younger: 0/14 Older: 8/19	↑
McCullough et al. [25]	VFS	Residue was significantly affected by age, rated 0 (none) for twice as many younger adults as older adults. Residue ratings of 1 (trace residue) were more likely than 0.	↑
Kelly et al. [51]	FEES	Ratings were 0.1 higher in younger participants (coating, mild, moderate)	*
Ayala and Logemann [26]	VFS	Similar and stable across age groups, minimal/trace amounts (0–3%): within normal limits	*
Veiga et al. [37]	FEES	Residue in valleculae and pyriform detected, unknown age correlation	*
Jardine et al. [39]	VFS	Trace residue quantified, no age-related differences	*
Molfenter et al. [56]	VFS	Vallecular and pyriform residue quantified	*

*Detected but no particular age-related change; ↑ detected and suggested increase with older age

85 years old, in some studies the proportion of oldest old was unclear and age distribution was poor. Some studies reported age range without mean age or omitted the age range. This systematic review positively demonstrates an increase in maximum age in research over time, suggesting that researchers are responding to the aging population and the need to recruit adults over 85 years old. Future research should continue to strive for, not only a maximum age in the 90s/100s, but also equal proportions of adults over 85 years old to truly represent aging trends of world societies.

Measuring Swallowing Physiology

From the 1990s through to 2018, VFS was performed in the majority of studies (30/44), demonstrating its ongoing relevance as well as reliability thanks to quantitative analysis [74]. While concurrent VFS and manometry (manofluorography) offers further information (visual physiology and pressure topography), these only featured in earlier studies in this review [31, 32, 46]. HRIM is a novel assessment, with four studies included in this review since 2014. Swallowing tasks (instruction, volume, and viscosity of oral trials) differed across studies. Fewer swallow tasks were performed during VFS compared with FEES, particularly in earlier studies. Less than half of studies (19/44) specified whether swallow tasks were cued or non-cued, despite our understanding of differences in bolus position during cued swallows [75] and impact on analysis, as well as comparison of bolus timing results.

The diverse number of terms and definitions for swallowing measures complicates comparisons across studies (Tables 3, 4, 5, 6, 7, 8, 9, 10, 11), as discussed in previous systematic reviews [76–78]. Standardized procedures and swallowing tasks are needed in future studies to ensure results are comparable, particularly for populations that are difficult to recruit, such as the oldest old.

Table 12 Risk of bias assessment, adapted from the Cochrane Collaboration's tool for assessing risk of bias

Study	Detection	Attrition	Other sources of bias		
			Reliability	Bolus	Instruction
Khan et al. [47]	–	–	–	One bolus size	–
Dejaeger et al. [31]	–	–	–	One bolus size	–
Nishimura et al. [48]	Low	–	–	One bolus size	–
Dejaeger et al. [46]	–	–	✓	One bolus size	Cued
Rademaker et al. [19]	–	–	✓	Standard order	–
Kern et al. [40]	Low	–	✓	–	–
Logemann et al. [20]	–	–	✓	–	–
Yokoyama et al. [32]	–	–	–	One bolus size	–
Logemann et al. [21]	–	–	✓	–	–
Van Herwaarden et al. [44]	–	Low	–	–	–
Kendall et al. [57]	Low	–	–	–	–
Kendall et al. [58]	Low	–	✓	Standard order	Cued
Leonard et al. [33]	–	–	✓	Standard order	–
Kim et al. [22]	–	–	✓	–	–
Martin-Harris et al. [34]	–	Low	–	One bolus size	Uncued
Martin-Harris et al. [35]	–	Low	–	One bolus size	Uncued
Yoshikawa et al. [23]	–	–	Observations discussed	One bolus size	Cued
Daggett et al. [50]	–	–	✓	–	–
Dozier et al. [59]	–	–	–	One bolus size	Uncued
Leonard and McKenzie [60]	–	–	–	Standard order	Cued
Martin-Harris et al. [24]	–	Low	Two observers for agreement	One bolus size	Uncued
McCullough et al. [25]	–	Low	✓	Standard order	–
Mendell and Logemann [61]	Low	–	✓	Standard order	Cued
Kelly et al. [51]	Low	Low	Scored by consensus	Standard order	–
Kim and McCullough [41]	–	–	✓	–	–
Butler et al. [52]	–	Low	–	Randomized	Uncued
Ayala and Logemann [26]	Low	Low	✓	Randomized	Cued
Butler et al. [53]	–	–	–	Randomized	Uncued
Kurosu and Logemann [42]	–	Low	✓	–	Cued
Butler et al. [27]	Low	Low	✓	Randomized	Uncued
Butler et al. [54]	–	Low	–	Randomized	Uncued
Brodsky et al. [62]	–	Low	–	One bolus size	Uncued
Im et al. [36]	–	–	✓	–	Cued
Omari et al. [28]	–	Low	–	Standard order	Cued
Veiga et al. [37]	–	Low	–	Randomized	Uncued
Kagaya et al. [63]	–	–	✓	–	Cued
Cock et al. [45]	–	–	–	–	Cued
Cock et al. [29]	–	–	–	–	Cued
Miles et al. [38]	–	–	✓	Standard order	Cued
Cock et al. [49]	–	–	–	–	Cued
Butler et al. [55]	–	Low	–	Randomized	Uncued
Herzberg et al. [64]	–	Low	✓	Standard order	–
Jardine et al. [39]	–	Low	–	Standard order	–
Molfenter et al. [56]	Low	–	✓	Standard order	Uncued

– Unclear risk of bias; ✓ tested

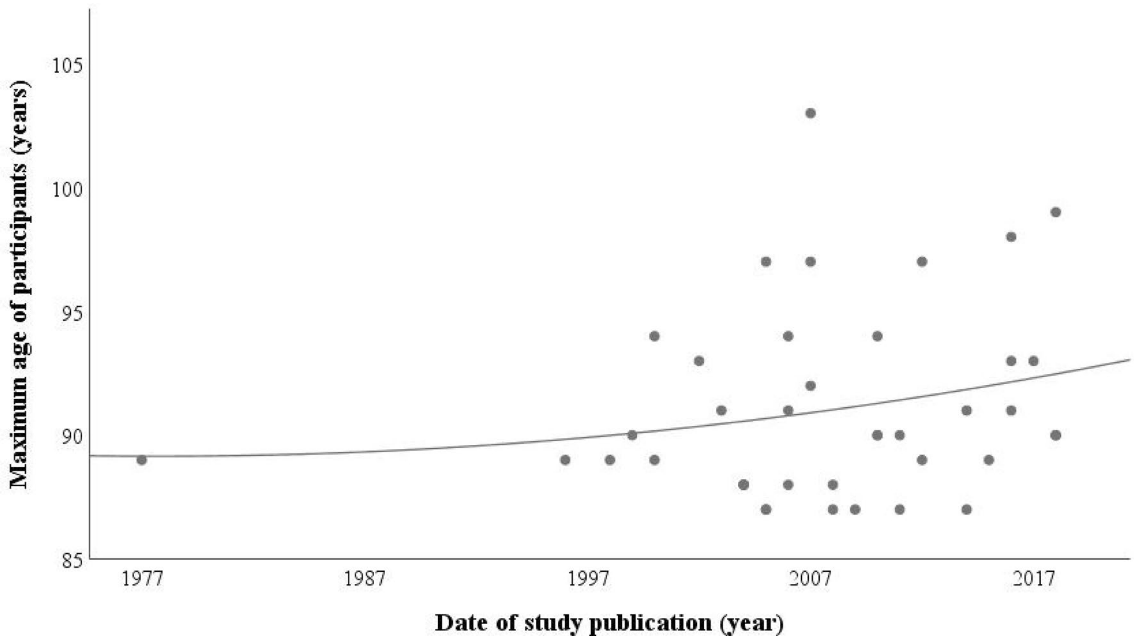

Fig. 3 Distribution of maximum ages across included studies and year of publication

Limitations

Our search was limited to original articles, published in English and performed by one author. However, all data were assessed by a second author. Age filters were applied instead of an additional age-related search term, which may have affected results. No software was used to compile this systematic review; data collection process, data extraction, and bias and quality assessment were performed by hand. Measures reported in tables were selected by the authors, in order to present the most similarly reported results across studies. However, a number of single measures from included studies remain unreported.

Conclusions

This systematic review identified subtle age-related swallowing changes: increased delay in the timing of bolus entry into the pharynx in relation to swallow onset; bolus transit times; duration of UES opening; pressure above the UES; UES relaxation pressure; and reduced pressure at the UES. There is insufficient evidence that these changes worsen for the healthy oldest old. There is a large body of literature reporting age-related swallowing changes, attributed to neurological, anatomical and physiological factors. However, swallowing efficiency prevails with age. This review suggests that markers of risk, such as aspiration and pharyngeal residue may occasionally occur but are not synonymous with aging. Substantial deviations from published normative swallowing measures in older adults should not be regarded as a consequence of typical aging. When considering specific changes for the oldest old in deglutition research, results are limited by the extent to which adults over 85 years old are represented, as well as study design and bias. Given the globally aging population, we need to further develop our knowledge of swallowing in the oldest old. It is essential that future studies plan to recruit healthy adults and adults with dysphagia, who are over 85 years old.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Appendix 1: Details of Included Studies

Study (in chronological order)	Age range	Participant groups (*n*)	Oldest group (mean, SD)	How deemed 'healthy'?	Medications?	Instrumental assessment	Swallow tasks (bolus size, texture)	Study aim
Khan et al. [47]	20–89 years	20–39 years (43) 60–89 years (49)	Not stated	Interview: 'carefully questioned'	Not stated	LRM	5 ml boluses of water, total unclear	Effect of age on esophageal motility
Dejaeger et al. [31]	Not stated	Healthy volunteers (20) Elderly (16)	80 years, 5 years	No relevant history	Not stated	VFS LRM	At least 3 × 10 ml liquid barium	Effect of age on quantitative and qualitative swallowing measures
Nishimura et al. [48]	23–89 years	< 49 years (11) 50–59 years (15) 60–69 years (11) > 70 years (10)	Not stated	No relevant history	Screened	LRM	10 × 3–5 ml tap water	Effect of age on esophageal motility
Dejaeger et al. [46]	Not stated	Young (18) Elderly (25)	80 years, 7 years	No relevant history	Screened	VFS LRM	3 × 10 ml liquid barium	Quantitative differences in swallowing between swallows with and without pharyngeal residue
Rademaker et al. [19]	20–89 years	20–39 years (61) 40–59 years (45) 60–79 years (38) 80–89 years (23)	Not stated	No relevant history	Screened	VFS	2 × 1, 3, 5 and 10 ml liquid barium	Effect of age and bolus size on healthy swallowing function
Kern et al. [40]	24–90 years	Young (14) Elderly (14)	75 years, 2.8 years	Not stated: 'without any swallowing difficulties'	Not stated	VFS LRM	3 × 5 and 10 ml liquid barium	Effect of age on timing, width and pressure of UES opening, and associated biomechanical events
Logemann et al. [20]	21–94 years	21–29 years (8) 80–94 years (8)	Not stated	No relevant history	Screened	VFS	2 × 1 and 10 ml liquid barium	Effect of age on swallowing timing and biomechanics
Yokoyama et al. [32]	21–89 years	21–31 years (32) 61–74 years (12) 75–89 years (12)	Not stated	Not stated: 'non-dysphagic'	Not stated	LRM VFS	10 ml liquid barium	Effect of age on swallowing pressure and function
Logemann et al. [21]	21–93 years	21–29 years (8) 80–93 years (8)	Not stated	No relevant history	Screened	VFS	2 × 1 and 10 ml liquid barium	Effect of age on swallowing function
Van Herwaarden et al. [44]	18–91 years	< 60 years (61) > 60 years (23)	71.3 years	No relevant history	Screened	LRM	3 × at least 4 swallows of 5 ml water, 5 ml pudding and ¼ cookie	Effect of age and gender on UES and pharyngeal manometric parameters
Kendall et al. [57]	18–88 years	Young (60) Old (63)	Not stated	Self–reported, no relevant history	Not stated	VFS	1 and 20 ml liquid barium	Coordination between structural movements relative to bolus movements before UES opening

Study (in chronological order)	Age range	Participant groups (*n*)	Oldest group (mean, SD)	How deemed 'healthy'?	Medications?	Instrumental assessment	Swallow tasks (bolus size, texture)	Study aim
Kendall et al. [58]	65–88 years	No medical problems (23) Medical conditions (63)	Not stated	No relevant history, head and neck exam	Screened: taken for chronic older conditions	VFS	1 and 20 ml liquid barium	Effect of medical conditions on swallowing in older adults
Leonard et al. [33]	18–88 years	Nonelderly (84) Elderly (88)	Median 70 years	Interview, HEENT exam, dietary questionnaire	Screened: taken for chronic older conditions	VFS	Lateral: 1 and 3 ml paste, 20 ml liquid bolus. Anterior–posterior: 20 ml liquid bolus	Effect of age on UES opening. Relationship between UES opening and swallowing events
Kim et al. [22]	21–87 years	Younger (20) Older (20)	Not stated	Questionnaire, cranial nerve exam	Not stated	VFS	2 × 5 and 10 ml thin liquid. Puree and solid not analyzed	Effect of age and gender on swallowing timing
Martin-Harris et al. [34]	Not stated	All healthy (76)	Not stated ≥ 81 years	Interview, questionnaire	Screened	VFS	2 × 5 ml liquid barium	Normative respiratory patterns and temporal coordination of breathing and swallowing
Martin-Harris et al. [35]	21–97 years	21–40 years (21) 41–59 years (21) 61–80 years (19) 81–97 years (21)	86 years	Interview, questionnaire	Screened	VFS	2 × 5 ml liquid barium	Effect of age on swallowing and interdependence of temporal onsets of swallowing events
Yoshikawa et al. [23]	24–87 years	Young (14) Elderly (19)	81.2 years	Questionnaire, interview, repetitive saliva swallowing test	Not stated	VFS	3 ml barium solution, 3 × 10 ml barium solution	Effect of age on swallowing
Daggett et al. [50]	20–94 years	< 30 years (13) 30–39 years (14) 40–49 years (13) 50–59yrs (13) 60–69 years (15) 70–79 years (13) 80–89 years (13) 90+ years (4)	Not stated	No relevant history	Screened	VFS	2 × thin liquid (1, 3, 5, 10 ml, own sip from cup), 3 ml pudding, ¼ cookie, bite of apple	Effect of age, bolus type and volume on severity of penetration
Dozier et al. [59]	23–91 years	All healthy (70)	Not stated	Interview, questionnaire	Screened	VFS	50 ml of liquid barium	Comparison of respiratory patterns during sequential swallowing to single liquid swallows
Leonard and McKenzie [60]	18–88 years	Nonelderly (63) Elderly (88)	Median 70 years	No relevant history	Screened: taken for chronic older conditions	VFS	Lateral: 1 and 3 ml paste, 20 ml liquid bolus. Anterior–posterior: 20 ml liquid bolus	Relationship between bolus transit and hyoid displacement

Study (in chronological order)	Age range	Participant groups (n)	Oldest group (mean, SD)	How deemed 'healthy'?	Medications?	Instrumental assessment	Swallow tasks (bolus size, texture)	Study aim
Martin–Harris et al. [24]	21–97 years	All healthy (76)	Not stated	Interview, questionnaire	Screened	VFS	2 × 5 ml liquid barium	Effect of age on bolus head location and temporal measures
McCullough et al. [25]	21–103 years	21–39 years (20) 40–59 years (20) 60–79 years (20) 80+ years (20)	Not stated	Questionnaire, cranial nerve, oral motor and structural exam	Not stated	VFS	3 × 5 and 10 ml thin, 2 × 20 ml thin, 2 × 5 ml puree, 2 × cookie, 3 oz thin liquid sequential	Effect of age, gender and bolus on swallowing function, residue, penetration and aspiration
Mendell and Logemann [61]	22–92 years	20–29 years (20) 40–49 years (20) 60–69 years (20) 70–79 years (20) 80+ years (20)	Not stated	No relevant history from database	Screened	VFS	2 × 3 and 10 ml liquid barium, 1x 3 ml paste barium	Description of swallowing event sequencing
Kelly et al. [51]	23–88 years	Young (21) Elderly (30)	75 years	No relevant history	Screened	FEES	5, 10 ml and large mouthful liquid, 10 ml yogurt, 10 ml chopped banana, 3x3 cm sandwich	Effect of age on amount and location of pharyngeal residue from unmodified boluses
Kim and McCullough [41]	21–87 years	Young (20) Old (20)	77.2 years, 6.85 years	Questionnaire, cranial nerve exam, oral motor/structural exam	Not stated	VFS	2 × 5 and 10 ml thin liquid barium	Effect of age on hyoid movement
Butler et al. [52]	69–87 years	Healthy older adults (20)	78.9 years	Questionnaire	Screened	FEES LRM	Catheter in vs out (5 ml water and 10 ml milk); 10 ml water vs milk vs barium; cup vs syringe (5 and 10 ml milk); 5 ml milk vs pudding vs 2 g cracker	Effect of catheter, bolus (type, volume, viscosity), delivery method or gender on penetration and aspiration in healthy older adults
Ayala and Logemann [26]	20–90 years	20–30 years (10) 60–70 years (10) 80–90 years (10)	83.7 years	Self–reported	Not stated	VFS	45 total swallows, including cold, thin, paste, sour, sweet, cold and sour, water	Effect of sensory bolus characteristics (temperature, taste, viscosity) and continuous use on swallowing

Study (in chronological order)	Age range	Participant groups (*n*)	Oldest group (mean, SD)	How deemed 'healthy'?	Medications?	Instrumental assessment	Swallow tasks (bolus size, texture)	Study aim
Butler et al. [53]	61–90 years	61–70 years (18) 71–80 years (28) 81–90 years (30)	83.8 years, 2.3 years	Self-reported	Not stated	FEES	5, 10, 15 and 20 ml × water, skim milk, 2% milk, whole milk via straw and cup	Effect of age, sex, liquid type, delivery method and volume on penetration and aspiration
Kurosu and Logemann [42]	22–94 years	Young (20) Middle-aged (20) Older (20)	84.5 years	Questionnaire	Screened	VFS	2 × 1, 3, 5, 10 ml and self-selected sip liquid barium, 2 × 3 ml barium paste, ¼ cookie with paste	Effect of age and gender on airway closure and UES opening
Butler et al. [27]	61–90 years	61–70 years (18) 71–80 years (26) 81–90 years (33)	83.6 years, 2.4 years	Self-reported	Not stated	FEES	5, 10, 15 and 20 ml × water, skim milk, 2% milk, whole milk via straw and cup; soy milk (5, 10, 15 and 20 ml straw); puree (5, 10 ml applesauce and pudding); 2 g cracker	Effect of age, sex, liquid type, delivery method and viscosity on bolus dwell times
Butler et al. [54]	69–87 years	Healthy older adults (19)	79.2 years	Questionnaire	Screened	FEES LRM	Catheter in: 5 and 10 ml water and milk Catheter out: 5 and 10 ml water and milk via syringe; 5, 10, 15 ml water and milk via cup	Effect of aspiration status, sensor location, liquid type and volume on pharyngeal and UES pressures
Brodsky et al. [62]	21–97 years	21–40 years (21) 41–60 years (21) 61–80 years (19) > 81 years (21)	Not stated	Interview, questionnaire	Screened	VFS	2 × 5-ml liquid barium	Relationship between swallow non-inspiratory flow and swallowing events, and effect of age
Im et al. [36]	21–89 years	Younger (20) Older (20)	77.25 years, 8.4 years	Cranial nerve exam, questionnaire	Not stated	VFS	2 × 5 ml thin liquid, thick liquid, puree	Effects of age, gender and bolus consistency on swallowing

Study (in chronological order)	Age range	Participant groups (n)	Oldest group (mean, SD)	How deemed 'healthy'?	Medications?	Instrumental assessment	Swallow tasks (bolus size, texture)	Study aim
Omari et al. [28]	20–91 years	20–39 years (15) 40–59 years (15) 60–79 years (18) 80+ years (20)	84 years	Self-reported, questionnaire	Screened	HRIM	5 × 5 ml and 10 ml saline, 5 ml and 10 ml viscous bolus	Effect of age on automated impedance manometry (AIM) analysis and the swallow risk index
Veiga et al. [37]	62–87 years	Elderly (30)	72.8 years, 7 years	No relevant history	Not stated	FEES	100 ml water via cup and via straw	Effect of cup or straw during sequential swallowing by healthy elderly
Kagaya et al. [63]	25–89 years	Younger < 60 years (28) Older ≥ 60 years (25)	Median 70 years	No relevant history	Not stated	VFS	10 ml liquid barium, 8 g corned beef, 5 ml liquid barium with 4 g corned beef	Effect of age and bolus type on occurrence of isolated pharyngeal swallow
Cock et al. [45]	20–93 years	Younger (30) Older (15)	85 years, 4 years	No relevant history, questionnaire	Screened	HRIM	5 × 5 and 10 ml liquid and viscous bolus	Effect of age on bolus clearance and esophageal propulsive physiology
Cock et al. [29]	20–91 years	Younger (50) Older healthy (16) Patients (27)	85 years, 4 years	Interview, questionnaire	Screened	HRIM	5 × 5 ml liquid and viscous boluses	Comparison of UES function in patients (with restricted UES opening) to healthy controls across ages
Miles et al. [38]	20–98 years	< 40 years (36) 40–59 years (27) 60–79 years (32) 80+ years (13)	Not stated	Questionnaire	Not stated	VFS	20 ml fluid bolus, barium tablet, 5 ml paste	Esophageal bolus transit times in healthy adults for a normative database
Cock et al. [49]	20–93 years	Younger (30) Older (15)	85 years, 4 years	No relevant history, questionnaire	Screened	HRIM	5 × 5 and 10 ml liquid and viscous bolus	Evaluation of esophago-gastric junction function and effect of age
Butler et al. [55]	20–90 years	20–30 years (27) 31–40 years (29) 41–50 years (30) 51–60 years (27) 61–70 years (28) 71–80 years (31) 81–90 years (31)	84 years, 2.2 years	Self-reported	Not stated	FEES	4 liquid types (water, skim milk, 2% milk and whole milk) with 4 bolus volumes (5, 10, 15, and 20 ml) using 2 delivery methods (straw vs cup)	Effect of age, sex, liquid type, bolus volume and bolus delivery on penetration and aspiration
Herzberg et al. [64]	22–90 years	Young (20) Older (23)	74.7 years	No relevant history	Not stated	VFS	3 × 5 and 20 ml thin liquid barium, 5 ml nectar thick barium	Effect of age on swallowing event sequencing

Study (in chronological order)	Age range	Participant groups (n)	Oldest group (mean, SD)	How deemed 'healthy'?	Medications?	Instrumental assessment	Swallow tasks (bolus size, texture)	Study aim
Jardine et al. [39]	20–99 years	Younger (45) Older > 70 years (59) Patients (55)	81.2 years, 8.18 years	Questionnaire	Not stated	VFS	Lateral view: 1, 3, 20, 100 ml liquid barium, 3 ml barium paste. A-P view: 20 ml liquid barium, 3 ml paste, pill	Comparison of quantitative swallowing measures in healthy adults vs older patients with new onset dysphagia
Molfenter et al. [56][a]	> 65 years	Healthy seniors (44)	76.9 years, 7.1 years	Interview, oral motor sensory exam, questionnaire	Not stated	VFS	12 self-administered, uncued barium boluses. 9 for this study: 3 × 5 ml and 20 ml thin liquid, nectar thick liquid	Effect of pharyngeal volume on pharyngeal swallowing biomechanics and residue in healthy aging

[a]In December 2018 this article was accessible early online

Appendix 2: Adapted checklist from the Critical Appraisal Skills Programme

1. Was the cohort recruited in an acceptable way?
2. Was the outcome accurately measured to minimize bias?
3. Have the authors identified all important confounding factors, and included these in the design and/or analysis?
4. Do the results include quantitative measures of swallowing or swallowing parameters?
5. Are the results plausible?
6. Does the study include participants over 85 years old?
7. Do the results develop our understanding of swallowing in advanced age?
8. Does the study report clinical implications?

References

1. Jaul E, Barron J. Age-related diseases and clinical and public health implications for the 85 years old and over population. Front Public Heal. 2017;5(December):1–7.
2. Madhavan A, Lagorio A, Crary M, Dahl W, Carnaby G. Prevalence of and risk factors for dysphagia in the community dwelling elderly: a systematic review. J Nutr Heal Aging. 2016;20(8):806–15.
3. Leder SB, Suiter DM, Agogo GO, Cooney LM. An epidemiologic study on ageing and dysphagia in the acute care geriatric-hospitalized population: a replication and continuation study. Dysphagia. 2016;31(5):619–25.
4. Marik PE, Kaplan D. Aspiration pneumonia and dysphagia in the elderly. Chest. 2003;124(1):328–36.
5. Sura L, Madhavan A, Carnaby G, Crary MA. Dysphagia in the elderly: management and nutritional considerations. Clin Interv Aging. 2012;7:287–98.
6. Chen P, Golub J, Hapner E, Johns M. Prevalence of perceived dysphagia and quality-of-life impairment in a geriatric population. 2009;24:1–6.
7. Namasivayam-MacDonald A, Shune S. The burden of dysphagia on family caregivers of the elderly: a systematic review. Geriatrics. 2018;3(2):30.
8. Plowman EK, Humbert IA. Elucidating inconsistencies in dysphagia diagnostics: redefining normal. Int J Speech Lang Pathol. 2018;20(3):310–7.
9. Forster A, Samaras N, Gold G, Samaras D. Oropharyngeal dysphagia in older adults: a review. Eur Geriatr Med. 2011;2(6):356–62.
10. Gleeson DCL. Oropharyngeal swallowing and aging. A review. J Commun Disord. 1999;32(6):373–96.
11. Logemann JA, Curro FA, Pauloski B, Gensler G. Aging effects on oropharyngeal swallow and the role of dental care in oropharyngeal dysphagia. Oral Dis. 2013;19(8):733–7.
12. Robbins JA. Old swallowing and dysphagia: thoughts on intervention and prevention. Nutr Clin Pract. 1999;14(5):S21–6.
13. Sonies BC, Parent LJ, Morrish K, Baum BJ. Durational aspects of the oral-pharyngeal phase of swallow in normal adults. Dysphagia. 1988;3(1):1–10.
14. Tracy JF, Logemann JA, Kahrilas PJ, Jacob P, Kobara M, Krugler C. Preliminary observations on the effects of age on oropharyngeal deglutition. Dysphagia. 1989;4:90–4.
15. Ward SA, Parikh S, Workman B. Health perspectives: international epidemiology of ageing. Best Pract Res Clin Anaesthesiol. 2011;25(3):305–17.

16. da Costa Santos CM, de Mattos Pimenta CA, Nobre MR. The PICO strategy for the research question construction and evidence search. Rev Lat Am Enfermagem. 2007;15(3):508–11.
17. Higgins J, Green S. Cochrane handbook for systematic reviews of interventions (Internet). The Cochrane Collaboration; 2011. www.handbook.cochrane.org.
18. Balshem H, Helfand M, Schünemann HJ, Oxman A, Kunz R, Brozek J, et al. GRADE guidelines: 3. Rating the quality of evidence. J Clin Epidemiol. 2011;64(4):401–6.
19. Rademaker A, Pauloski B, Colangelo L, Logemann JA. Age and volume effects on liquid swallowing function in normal women. J Speech Lang Hear Res. 1998;41(2):275–84.
20. Logemann J, Pauloski B, Rademaker A, Colangelo L, Kahrilas P, Smith C. Temporal and biomechanical characteristics of oropharyngeal swallow in younger and older men. J Speech Lang Hear Res. 2000;43(5):1264–74.
21. Logemann J, Pauloski BR, Rademaker AW, Kahrilas PJ. Oropharyngeal swallow in younger and older women: videofluoroscopic analysis. J Speech Lang Hear Res. 2002;45(3):434–45.
22. Kim Y, McCullough GH, Asp CW. Temporal measurements of pharyngeal swallowing in normal populations. Dysphagia. 2005;20(4):290–6.
23. Yoshikawa M, Yoshida M, Nagasaki T, Tanimoto K, Tsuga K, Akagawa Y, et al. Aspects of swallowing in healthy dentate elderly persons older than 80 years. J Gerontol A Biol Sci Med Sci. 2005;60(4):506–9.
24. Martin-Harris B, Brodsky MB, Michel Y, Lee F-S, Walters B. Delayed initiation of the pharyngeal swallow: normal variability in adult swallows. J Speech Lang Hear Res. 2007;50(3):585.
25. McCullough GH, Rosenbek JC, Wertz RT, Suiter D, McCoy SC. Defining swallowing function by age: promises and pitfalls of pigeonholing. Top Geriatr Rehabil. 2007;23(4):290–307.
26. Ayala KJ, Logemann JA. Effects of altered sensory bolus characteristics and repeated swallows in healthy young and elderly subjects. J Med Speech Lang Pathol. 2010;18(3):34–58.
27. Butler SG, Maslan J, Stuart A, Leng X, Wilhelm E, Lintzenich CR, et al. Factors influencing bolus dwell times in healthy older adults assessed endoscopically. Laryngoscope. 2011;121(12):2526–34.
28. Omari TI, Kritas S, Cock C, Besanko L, Burgstad C, Thompson A, et al. Swallowing dysfunction in healthy older people using pharyngeal pressure-flow analysis. Neurogastroenterol Motil. 2014;26(1):59–68.
29. Cock C, Besanko L, Kritas S, Burgstad CM, Thompson A, Heddle R, et al. Maximum upper esophageal sphincter (UES) admittance: a non-specific marker of UES dysfunction. Neurogastroenterol Motil. 2016;28(2):225–33.
30. Omari TI, Dejaeger E, Van Beckevoort D, Goeleven A, Davidson GP, Dent J, et al. A method to objectively assess swallow function in adults with suspected aspiration. Gastroenterology. 2011;140(5):1454–63.
31. Dejaeger E, Pelemans W, Bibau G, Ponette E. Manofluorographic analysis of swallowing in the elderly. Dysphagia. 1994;9(3):156–61.
32. Yokoyama M, Mitomi N, Tetsuka K, Tayama N. Role of laryngeal movement and effect of aging on swallowing pressure in the pharynx and upper esophageal sphincter. Laryngoscope. 2000;110(3):434–9.
33. Leonard R, Kendall K, McKenzie S. UES opening and cricopharyngeal bar in nondysphagic elderly and nonelderly adults. Dysphagia. 2004;19(3):182–91.
34. Martin-Harris B, Brodsky MB, Michel Y, Ford CL, Walters B, Heffner J. Breathing and swallowing dynamics across the adult lifespan. Arch Otolaryngol Head Neck Surg. 2005;131:762–70.
35. Martin-Harris B, Michel Y, Castell DO. Physiologic model of oropharyngeal swallowing revisited. Otolaryngol Head Neck Surg. 2005;133(2):234–40.
36. Im I, Kim Y, Oommen E, Kim H, Ko MH. The effects of bolus consistency in pharyngeal transit duration during normal swallowing. Ann Rehabil Med. 2012;36(2):220–5.
37. Veiga HP, Fonseca HV, Bianchini EMG. Sequential swallowing of liquid in elderly adults: cup or straw? Dysphagia. 2014;29(2):249–55.
38. Miles A, Clark S, Jardine M, Allen J. Esophageal swallowing timing measures in healthy adults during videofluoroscopy. Ann Otol Rhinol Laryngol. 2016;125(9):764–9.
39. Jardine M, Miles A, Allen J. Dysphagia onset in older adults during unrelated hospital admission: quantitative videofluoroscopic measures. Geriatrics. 2018;3(4):66.
40. Kern M, Bardan E, Arndorfer R, Hofmann C, Ren J, Shaker R. Comparison of upper esophageal sphincter opening in healtly asymptomatic young and elderly volunteers. Ann Otol Rhinol Laryngol. May 1994;1999:982–9.
41. Kim Y, McCullough GH. Maximum hyoid displacement in normal swallowing. Dysphagia. 2008;23(3):274–9.
42. Kurosu A, Logemann JA. Gender effects on airway closure in normal subjects. Dysphagia. 2010;25(4):284–90.
43. Leonard R, Belafsky PC, Rees CJ. Relationship between fluoroscopic and manometric measures of pharyngeal constriction: the pharyngeal constriction ratio. Ann Otol Rhinol Laryngol. 2006;115(12):897–901.
44. Van Herwaarden MA, Katz PO, Gideon RM, Barrett J, Castell JA, Achem S, et al. Are manometric parameters of the upper esophageal sphincter and pharynx affected by age and gender? Dysphagia. 2003;18(3):211–7.
45. Cock C, Besanko L, Kritas S, Burgstad CM, Thompson A, Heddle R, et al. Impaired bolus clearance in asymptomatic older adults during high-resolution impedance manometry. Neurogastroenterol Motil. 2016;28(12):1890–901.
46. Dejaeger E, Pelemans W, Ponette E, Joosten E. Mechanisms involved in postdeglutition retention in the elderly. Dysphagia. 1997;12(2):63–7.
47. Khan TA, Shragge BW, Crispin JS, Lind JF. Esophageal motility in the elderly. Am J Dig Dis. 1977;22(12):1049–54.
48. Nishimura N, Hongo M, Yamada M, Kawakami H, Ueno M, Okuno Y, et al. Effect of aging on the esophageal motor functions. J Smooth Muscle Res. 1996;32(2):43–50.
49. Cock C, Besanko LK, Burgstad CM, Thompson A, Kritas S, Heddle R, et al. Age-related impairment of esophagogastric junction relaxation and bolus flow time. World J Gastroenterol. 2017;23(15):2785–94.
50. Daggett A, Logemann J, Rademaker A, Pauloski B. Laryngeal penetration during deglutition in normal subjects of various ages. Dysphagia. 2006;21(4):270–4.
51. Kelly AM, Macfarlane K, Ghufoor K, Drinnan MJ, Lew-Gor S. Pharyngeal residue across the lifespan: a first look at what's normal. Clin Otolaryngol. 2008;33(4):348–51.
52. Butler SG, Stuart A, Markley L, Rees C. Penetration and aspiration in healthy older adults as assessed during endoscopic evaluation of swallowing. Ann Otol Rhinol Laryngol. 2009;118(3):190–8.
53. Butler SG, Stuart A, Leng X, Rees C, Williamson J, Kritchevsky SB. Factors influencing aspiration during swallowing in healthy older adults. Laryngoscope. 2010;120(11):2147–52.
54. Butler SG, Stuart A, Wilhelm E, Rees C, Williamson J, Kritchevsky S. The effects of aspiration status, liquid type, and bolus volume on pharyngeal peak pressure in healthy older adults. Dysphagia. 2011;26(3):225–31.
55. Butler SG, Stuart A, Markley L, Feng X, Kritchevsky SB. Aspiration as a function of age, sex, liquid type, bolus volume, and bolus delivery across the healthy adult life span. Ann Otol Rhinol Laryngol. 2018;127(1):21–32.

56. Molfenter SM, Lenell C, Lazarus CL. Volumetric changes to the pharynx in healthy aging: consequence for pharyngeal swallow mechanics and function. Dysphagia. 2019;34(1):129–37.
57. Kendall KA, Leonard RJ, McKenzie S. Airway protection: evaluation with videofluoroscopy. Dysphagia. 2004;19(2):65–70.
58. Kendall KA, Leonard RJ, McKenzie S. Common medical conditions in the elderly: impact on pharyngeal bolus transit. Dysphagia. 2004;19(2):71–7.
59. Dozier TS, Brodsky MB, Michel Y, Walters BC, Martin-Harris B. Coordination of swallowing and respiration in normal sequential cup swallows. Laryngoscope. 2006;116(8):1489–93.
60. Leonard R, McKenzie S. Hyoid-bolus transit latencies in normal swallow. Dysphagia. 2006;21(3):183–90.
61. Mendell DA, Logemann JA. temporal sequence of swallow events during the oropharyngeal swallow. J Speech Lang Hear Res. 2007;50(5):1256.
62. Brodsky M, McFarland D, Michel Y, Orr S, Martin-Harris B. Significance of nonrespiratory airflow during swallowing. Dysphagia. 2012;27(2):178–84.
63. Kagaya H, Yokoyama M, Saitoh E, Kanamori D, Susa C, German RZ, et al. Isolated pharyngeal swallow exists during normal human feeding. Tohoku J Exp Med. 2015;236(1):39–43.
64. Herzberg EG, Lazarus CL, Steele CM, Molfenter SM. Swallow event sequencing: comparing healthy older and younger adults. Dysphagia. 2018;33(6):759–67.
65. Humbert IA, Fitzgerald ME, McLaren DG, Johnson S, Porcaro E, Kosmatka K, et al. Neurophysiology of swallowing: effects of age and bolus type. Neuroimage. 2009;44(3):982–91.
66. Moon HI, Jung Y, Eng M, Choi S. Effect of age on cortical activation during swallowing: an fMRI study. J Korean Dysphagia Soc. 2016;6:26–33.
67. Malandraki GA, Perlman AL, Karampinos DC, Sutton BP. Reduced somatosensory activations in swallowing with age. Hum Brain Mapp. 2011;32(5):730–43.
68. Dodds RM, Granic A, Davies K, Kirkwood TBL, Jagger C, Sayer AA. Prevalence and incidence of sarcopenia in the very old: findings from the Newcastle 85+ study. J Cachexia Sarcopenia Muscle. 2016;8(2):229–37.
69. Zhao W-T, Yang M, Wu H-M, Yang L, Zhang X, Huang Y. Systematic review and meta-analysis of the association between sarcopenia and dysphagia. J Nutr Heal Aging. 2018;22(8):1003–9.
70. Molfenter SM, Amin MR, Branski RC, Brumm JD, Hagiwara M, Roof SA, et al. Age-related changes in pharyngeal lumen size: a retrospective MRI analysis. Dysphagia. 2015;30(3):321–7.
71. Yin T, Jardine M, Miles A, Allen J. What is a normal pharynx? A videofluoroscopic study of anatomy in older adults. Eur Arch Otorhinolaryngol. 2018;275(9):2317–23.
72. Sergi G, De Rui M, Sarti S, Manzato E. Polypharmacy in the elderly: can comprehensive geriatric assessment reduce inappropriate medication use? Drugs Aging. 2011;28(7):509–18.
73. Gallagher L, Naidoo P. Prescription drugs and their effects on swallowing. Dysphagia. 2009;24(2):159–66.
74. Kendall KA, Ellerston J, Heller A, Houtz DR, Zhang C, Presson AP. Objective measures of swallowing function applied to the dysphagia population: a one year experience. Dysphagia. 2016;31(4):538–46.
75. Nagy A, Leigh C, Hori SF, Molfenter SM, Shariff T, Steele CM. Timing differences between cued and noncued swallows in healthy young adults. Dysphagia. 2013;28(3):428–34.
76. Cock C, Omari T. Systematic review of pharyngeal and esophageal manometry in healthy or dysphagic older persons (> 60 years). Geriatrics. 2018;3(4):67.
77. Namasivayam-MacDonald AM, Barbon CEA, Steele CM. A review of swallow timing in the elderly. Physiol Behav. 2018;184:12–26.
78. Winiker K, Gillman A, Guiu Hernandez E, Huckabee ML, Gozdzikowska K. A systematic review of current methodology of high resolution pharyngeal manometry with and without impedance. Eur Arch otorhinolaryngol. 2019;276(3):631–45.

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