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Predicting penetration–aspiration through quantitative swallow measures of children: a videofluoroscopic study

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Abstract

Purpose Quantitative measures have improved the reliability and accuracy in interpretation and reporting of videofluoroscopy (VFSS). Associations between quantitative VFSS measures and swallow safety in children are not widely reported. The ability to predict aspiration in children, even if not observed during brief VFSS, will improve diagnostic reporting and potentially reduce the need for extended radiation time. The aims of this study were to determine associations between quantitative fluoroscopic swallow measures and penetration–aspiration and to predict likelihood of penetration–aspiration.

Methods We selected videofluoroscopic data of 553 children from a pediatric hospital database for this single-center retrospective observational study. A standard protocol of VFSS administration was used and data were recorded at 30 frames-per-second. A set of quantitative and descriptive swallow measures was obtained using a specialized software with satisfactory inter-rater and intra-rater reliability. Binomial logistic regression with backward likelihood ratio was conducted, while controlling for age, gender, and etiology.

Results We found bolus clearance ratio (BCR), pharyngeal constriction ratio (PCR), duration to hyoid maximal elevation (Hdur), and total pharyngeal transit time (TPT) to be predictive of penetration–aspiration in children. PCR was the most predictive of penetration–aspiration in children (61.5%). Risk of aspiration was more than 100 times, when BCR = ≥ 0.1, TPT = ≥ 2 s, Hdur = > 1 s or PCR = ≥ 0.2 ($p < 0.05$ for all measures).

Conclusion The results confirm the potential of objective quantitative swallow measures in predicting the risk of aspiration in children with dysphagia. These parameters provide predictive measures of aspiration risk that are clinically useful in identifying children of concern, even if no aspiration is observed during VFSS.

Keywords Dysphagia · Deglutition disorders · Fluoroscopy · Swallowing disorders · Aspiration · Children

Introduction

Videofluoroscopic study of swallowing (VFSS) is one of the most common instrumental swallowing assessment tools employed to evaluate swallowing in children [1]. It allows clinicians to observe oral, pharyngeal, and esophageal phases of swallowing and airway simultaneously [2]. Penetration and aspiration are considered the most severe complications of oropharyngeal dysphagia [3]. Previously, clinicians have at times used VFSS as a binary study to screen only for aspiration during swallowing [4]. This narrow focus ignores potential for a more comprehensive biomechanical assessment. It may result in missing pre-swallow and/or post-swallow aspiration due to truncated screening and thus reduce the benefit of these studies [5]. This leaves clinicians with doubts on whether oral feeding should be continued or what particular bolus sizes/consistencies are safe to swallow. Because fluoroscopy exposes individuals to ionizing radiation, it is clinically and ethically imperative to not only report swallow safety, i.e., incidence of penetration–aspiration [6], but to maximize the amount of swallowing biomechanical information gathered to aid clinical decision-making [7]. Although, standard rating protocols such as the MBSImP [8] and the BaByVFSSImP [9] have

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improved agreement of VFSS analysis, such ordinal visuo-perceptual VFSS observations lack objective quantification.

The development of objective quantitative VFSS measures in adults by Leonard and Kendall in the early 2000s [10–13] has led a number of researchers to explore the use of these measures in children [7, 14–18]. Such studies have improved our understanding of pediatric swallow mechanisms across a diverse range of ages, aetiologies, and instrumentation types. The ability to anticipate penetration–aspiration in children, even when it is not observed directly, would strengthen the value of VFSS as an assessment. Even though clear associations between quantitative swallow measures and disordered swallow mechanics have been studied in adults [3, 19–23], these are yet to be described in children. We hypothesized that predicting penetration–aspiration is possible through quantitative measures. In this study, we measured a selected set of objective quantitative VFSS measures in a large, heterogenous group of children from 0 to 21 years presenting with swallowing or feeding concerns. Our aims were to: (1) determine associations between objective quantitative VFSS measures and penetration–aspiration and (2) predict likelihood of penetration–aspiration using this set of objective quantitative VFSS measures.

Materials and methods

This single center retrospective observational study was conducted at a children's hospital. Ethical approval for the study was received from the University of Auckland Human Participants Ethics Committee (application number: 9263). The American Academy of Pediatrics identifies the upper limit of cases termed 'pediatric' as 21 years [24] and the children's hospital adheres to this classification to care for children and adolescents with complex disabilities until developmentally appropriate transition to adult care can be established. Videofluoroscopic data of all children from 0 to 21 years consecutively referred for VFSS from 2016 to early 2020 by their speech-language therapist following a clinical swallowing evaluation were gathered from the hospital database. Common reasons for VFSS referral were poor growth, apparent difficulties with feeding and swallowing, choking, and predisposing medical conditions deemed to put the child at risk of a swallowing problem. Demographic data and medical history were obtained by the primary investigator (ID). Primary medical etiologies were categorized as neurological (e.g., cerebral palsy, stroke), chromosomal (e.g., Prader–Willi syndrome, trisomy 21), anatomical (e.g., tracheomalacia, trachea-oesophageal fistula), respiratory (e.g., chronic lung disease, bronchiolitis), cardiac (e.g., Tetralogy of Fallot, congenital heart disease), gastrointestinal (e.g., toxic ingestion-related injuries, gastroenteritis), multiple (combination of medical aetiologies), and unknown (no known medical etiology).

VFSS administration

The VFSS was conducted in the radiology suite on a Siemens Sireskop radiographic unit (Siemens, Munich, Germany) at the tertiary children's hospital. Children who refused the procedure or did not swallow thin liquids (Level 0 Thin, [25]) were excluded from the study. In 2016, a standardized protocol of obtaining video loops at 30 frames per second was introduced to obtain reliable objective quantitative VFSS measures of children without increasing radiation dose or exposure time [7]. To implement the same protocol, we used Varibar™ barium sulphate contrast (40% w/v) (E-Z-EM Canada Inc, Quebec, Canada) in 50:50 of water/preferred milk/juice:barium to create Level 0 Thin liquids. Children were placed in their usual or recommended feeding posture with or without the support of a caregiver. An in-house speech-language therapist was present to guide the caregiver. Either a radio-paque ring of a known diameter was placed in the child's chin with tape or a ruler-like tool (in pixels) was present in digitalized VFSS images to allow displacement measures.

We obtained 20-s video loops of 'midfeed sucking' in bottle-fed infants using either breast milk or recommended formula combined with barium, according to the particular infant's needs. For younger children who had grown out of bottle drinking, but had not yet established open-cup drinking skills, midfeed cup drinking of sequential swallowing from a sipper cup was recorded. 'Midfeed' was defined as, 'midway through the feed', ensuring that children had established their stable functional feeding pattern. Older children with open-cup feeding skills were asked to swallow two Level 0 Thin Liquid bolus sizes (5 ml, 10 ml) by an open-cup. The VFSS were recorded on an USB external drive in.avi file format at 30 frames per second rate (f/s) for frame-by-frame analysis.

Objective VFSS measures

A comprehensive literature review was undertaken to identify the objective and quantitative VFSS measures and the selected measures were reviewed for their reliability, feasibility, and clinical relevance by a panel of three researchers and three clinicians. We calculated the penetration aspiration scale (PAS) [26] and considered a score of 3 or more as incidents of airway violation (PAS $\geq$ 3) (15, 27, 28) grouping children as aspirators (PAS $\geq$ 3) and non-aspirators (PAS = 1, 2) for analysis. All airway violation (penetration and aspiration) of PAS ≥ 3 will be referred to as penetration–aspiration hereafter. Penetration–aspiration, nasopharyngeal reflux (NPR), esophagopharyngeal reflux (EPR), and post-swallow residue were recorded as binary observations (present/absent). We measured timing and displacement measures of hyoid bone excursion only in children older than 9 months, as visibility of hyoid movements is not reliable until 9 months [15]. Due to the unique coordination of suck-swallow-breathe pattern in bottle-feeding milk-sucking infants [29, 30], a set of suck-swallow timing measures was obtained only from bottle-fed infants (Table 1). Definitions of objective, quantitative swallow measures are given in Appendix 1.

As the aim of the study was to determine associations with penetration–aspiration, in each child participant we chose the swallow with the highest PAS score for analysis [37]. For example, when an older child swallowed both 5 ml and 10 ml volumes, the swallow with the highest PAS score was chosen for analysis. All videofluoroscopic data were analyzed using a software programme specifically designed for quantitative and objective analysis of VFSS (Swallowtail, Belldev Medical, Illinois, USA). This software application allows frame-by-frame analysis and uses integrated tools to obtain objective timing and displacement measures of the swallow as described by Leonard and Kendall. The primary investigator (ID), an experienced speech-language therapist completed comprehensive face-to-face training on objective quantitative swallow measures and use of the specialized software from the second author (AM). The primary author completed the analysis of all videofluoroscopic data for the study.

Reliability testing

VFSS data of 50 infants (< 9 months) and 116 children (> 1 year) were randomly selected for inter-rater reliability, which was 30% of total cohort. Two experienced raters blinded to each other's scores, medical history and clinical characteristics of the children were used for inter-rater reliability testing. The primary investigator (ID) analyzed the same dataset 10 months after the first rating to calculate intra-rater reliability. An intra-class correlation coefficient (ICC) above 0.75 was considered a good agreement for inter-rater and intra-rater reliability [38]. Intra-rater reliability across all measures were found to have excellent agreement (ICC = ≥ 0.92, 95% CI 0.8–0.96, $p < 0.001$) for both infants (< 9 months) and children. Inter-rater reliability across all measures reported fairly good agreement in infants (ICC = 0.75–0.84, 95% CI 0.3–0.86, $p < 0.001$) and good to excellent agreement in children above 1 year (ICC = 0.77–0.92, 95% CI 0.69–0.95, $p = 0.001$).

Data analysis

Statistical analysis of objective quantitative swallow measures were conducted using the Statistical Package for the

Table 1 Objective and/or quantitative swallow measures of children

Quantitative swallow measures		Descriptive swallow measures
Timing(s) measures	Displacement measures (cm)	
Total pharyngeal transit time (TPT)[1]	Pharyngeal constriction ratio (PCR)[1]	Penetration–aspiration scale (PAS)[5]
Time to airway closure (Airwaycl)[1]	Maximum opening of PES during a swallow (PESmax)[1]	Frequency of penetration-aspiration in 20 s loop[a,9]
Airway closure duration (ACD)[1]	Bolus clearance ratio (BCR)[4]	Time of airway violation (pre-swallow, mid-swallow, post-swallow, multiple)[8]
PES opening duration (PESdur)[1]	Maximal hyoid elevation[b] (Hmax)[1]	Penetration–aspiration (PAS ≥ 3) (±)[6,7]
Coordination of airway closure with bolus transit (BP1AEcl)[1]	Maximum approximation of hyoid bone and larynx[b] (HL)[1]	Post swallow residue (±)[2]
Stage transition duration[b] (STD)[11]		Nasopharyngeal reflux (NPR) (±)[8]
Laryngeal elevation[b] (LE)[1]		Esophagopharyngeal reflux (EPR) (±)[8]
Duration to hyoid maximum elevation[b] (Hdur)[1]		Suck/swallow bolus control[a] (±)[2]
Duration of maximum hyoid displacement[b] (Hm)[1]		Number of swallows in 20 s segment[a,9]
Duration of velopharyngeal closure (VCD)[3]		Number of sucks per swallow[a,2]
Suck time[2,a]		
Tongue–soft palate cycle (T–SP)[a,10]		

[1] [5], [2] [18], [3] [31], [4] [32], [5] [26], [6] [27], [7] [33], [8] [34], [9] [7], [10] [35], [11] [36]

[a]Measured during midfeed sucking of bottle-fed infants only

[b]Measured in children above 9 months-old only. (±) = (present/absent)

Social Sciences (SPSS) (IBM Corp. Released 2019. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY: IBM Corp.). According to the central limit theorem, we assumed that with our large sample size ($n > 30$), the sampling distribution of the mean for a variable is approximate to normal distribution [39]. Therefore, parametric tests were conducted to draw statistical significance, using mean to represent the center of the distribution [40]. Since significant differences in aspiration has been evident across bolus sizes in adults [27, 41, 42], we conducted one-way ANOVA to determine the effect of bolus size on PAS scores in this cohort. Independent sample *t* test was performed to compare the means of objective quantitative swallow measures between children with and without penetration–aspiration (PAS ≥ 3), NPR, EPR, and residue. Pearson correlation was performed to determine associations between objective, quantitative swallow measures, and PAS scores. As the clinical value of VFSS interpretation can be enhanced by enabling prediction of penetration–aspiration in children [4], we performed a binomial logistic regression to predict the likelihood of penetration–aspiration based on objective quantitative swallow measures. We used backward likelihood ratio as the method of variable selection to include all the potential explanatory variables controlled for age, gender, and etiology, by removing variables, which did not make significant contribution to the model. We used relative risk (RR) of objective quantitative swallow measures in the regression models to predict the likelihood of penetration–aspiration based on the assumption that odds ratios obtained from logistic regression models of rare outcomes are equal to risk ratio/relative risk [43]. Cut offs for predictive swallow measures are reported with RR as effect size with 95% confidence intervals (CI). A *p* value (significance) of < 0.05 is considered statistically significant.

Results

A total of 553 children between 0 and 21 years (mean = 3.12 year ± 3.86) were recruited. The characteristics of the children are given in Table 2. Due to the absence or lack of visualization of calibration ring, displacement measures were unable to be obtained from 74 children. The total of analysed data included 210 midfeed sucking, 214 midfeed cup drinking, 99 thin liquid 5 ml, and 30 thin liquid 10 ml boluses. PAS scores of children with midfeed sucking were significantly higher than the PAS scores of children with midfeed cup drinking, and 5 ml and 10 ml thin liquid boluses [$F(3, 510) = 9.359$, $p < 0.001$]. No significant differences of PAS scores were observed among midfeed cup drinking, 5 ml and 10 ml thin liquid boluses.

Table 2 Demographics/clinical information

Demographic	Frequency (*n*)	Percentage (%)
Sex		
Female	212	38.3
Male	341	61.7
Age[a]		
0–12 months	184	33.3
1–3 years	183	33.1
3.1–5 years	74	13.4
5.1–12 years	82	14.8
12.1–18 years	29	5.2
18–21 years	1	0.2
Swallow act		
Midfeed drinking	214	38.7
Midfeed sucking	210	38.0
Thin liquid—5 ml	99	17.9
Thin liquid—10 ml	30	5.4
Primary medical etiology		
Respiratory	114	20.6
Neurological	165	29.8
Anatomical	71	12.8
Cardiac	25	4.5
Chromosomal	62	11.2
Multiple	32	5.8
Other	13	2.4
Unknown	71	12.8

[a]Classification of age recognized by the American Academy of Pediatrics [24]

Table 3 Descriptive swallow measures of penetration–aspiration in children

Binary/categorical observations	Frequency (*n*)	Percentage (%)
Penetration–aspiration (PAS ≥ 3)		
Present	210	40.9
Absent	343	59.1
Time of penetration–aspiration[a]		
Pre swallow	63	27.8
Mid swallow	109	48.0
Post swallow	17	7.5
Multiple	38	16.7
Descriptive swallow measures		
Points of the scale	Frequency (*n*)	Percentage (%)
Penetration–aspiration scale (PAS)		
1–2 = safe airway[a]	326	58.9
3–6 = penetration[a]	69	12.5
6–8 = aspiration[a]	158	28.6

[a]Out of 227 children with penetration–aspiration, *PPW* posterior pharyngeal wall, *PS* pyriform sinus, [a] = [15, 27, 28]

Penetration–aspiration (PAS ≥ 3) was reported in 41% of children ($n = 227$). An episode of silent aspiration (PAS = 8) was reported in 136 children (24.6% of total cohort). Compared to penetration–aspiration, NPR (8.7%), EPR (4.6%), and residue (9.9%) were less common (Table 3).

Penetration–aspiration and quantitative VFSS measures

PAS scores of children were positively correlated with bolus clearance ratio (BCR) [r (552) = 0.158, $p < 0.001$], as well as pharyngeal constriction ratio (PCR) [r (552) = 0.166, $p < 0.001$]. Reduced maximum opening of the pharyngoesophageal segment (PES) (PESmax) was significantly correlated with higher PAS scores [r (478) = −0.104, $p = 0.03$]. The timing measure of bolus movement in relation to airway closure (BP1Aecl) significantly correlated with PAS scores [r (552) = 0.134, $p = 0.002$], indicating when bolus arrives at the PES before airway closure, there is a greater risk of penetration–aspiration and, therefore, PAS scores are higher. The total duration of airway closure (ACD) was significantly negatively correlated with PAS scores. PAS scores are lower when the airway is closed for a longer time offering greater airway protection [r (512) = − 0.13, $p = 0.003$]. Moreover, PAS scores were more elevated in children with longer duration of velopharyngeal closure (VCD) [r (552) = 0.095, $p = 0.034$] and longer laryngeal elevation (LE) [r (512) = 0.177, $p = 0.009$]. The longer it took for the hyoid bone to reach maximal elevation (Hdur), the greater (worse) the PAS scores [r (512) = 0.146, $p = 0.03$]. Furthermore, children with significantly shorter duration of maximum hyoid displacement (Hm) [r (512) = − 0.202, $p = 0.003$] also demonstrated elevated PAS scores.

Table 4 Prediction accuracy of quantitative swallow measures in predicting penetration–aspiration in children

Measure	Prediction accuracy (%)	Sensitivity (%)	Specificity (%)	Sig. (p)
For each swallow measure				
BCR	60.1	59.1	47.6	0.013
TPT	59.4	59.4	49.1	0.032
Hdur	61.0	65.7	62.2	0.012
PCR	61.5	61.9	58.2	< 0.001
All measured combined				
BCR, TPT, Hdur, and PCR	70.5	61.7	63.9	< 0.001

Predictors of penetration–aspiration in children

Table 4 presents classification of penetration–aspiration in children using binary logistic regression with a single quantitative measure, which showed significant correlations with PAS scores, along with gender and age. All of these measures were combined into a binomial logistic regression model, which was statistically significant [X^2 (4) = 20.128, $p < 0.001$] and the model correctly classified 70.5% of cases. After adjusting for age, gender, and etiology, the logistic regression analysis revealed that PCR, TPT, BCR, and Hdur were significant predictors of penetration–aspiration risk in children. Individually, the highest prediction value was achieved for PCR, 61.5% and the predictive accuracy was improved to 70.5% with all variables combined.

Mean scores of predictive variables for children with and without penetration–aspiration, as well as the risk ratios (RR) for each measure are presented in Table 5. Of the objective measures of predictive ability, BCR (RR = 19.582) reported the largest risk ratio, indicating that there was a 20-fold increased risk of penetration–aspiration when BCR was increased by one point. The regression model for combined factors explains that the risk of penetration–aspiration was 100 times greater, when BCR = ≥ 0.1, TPT = ≥ 2 s, Hdur = > 1 s, and PCR = ≥ 0.2. In children with several measures elevated, the risk of penetration–aspiration climbed steeply, with a 100 times greater risk in those with combined presence of elevated bolus constriction ratio, prolonged pharyngeal transit time, poor pharyngeal constriction, and delay in maximum hyoid elevation. Figures 1, 2, 3 and 4 illustrate the swallow gesture times on VFSS to obtain BCR, TPT, Hdur, and PCR, respectively, in children.

Table 5 Relative risk of predictive swallow measures of penetration–aspiration

Predictive measure	Mean (μ)		SD		Relative risk (RR)	95% CI		Sig. (p)
	Pen-Asp	NonAs*p*	Pen-Asp	NonAs*p*		Lower	Upper	
BCR	0.052	0.022	0.170	0.111	19.582	1.313	292.122	0.031
TPT	1.340	1.208	1.141	1.017	14.777	1.982	110.183	0.009
Hdur	0.667	0.0801	1.249	1.251	13.514	1.788	102.116	0.012
PCR	0.231	0.174	0.173	0.195	7.640	1.054	55.352	0.044

Pen-Asp children with PAS ≥ 3, *NonAsp* children with PAS = 1 or 2, *SD* standard deviation, *CI* confidence interval

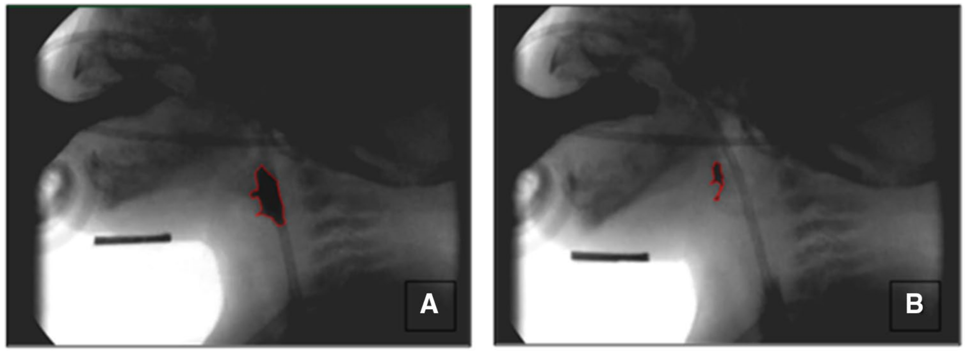

Fig. 1 Calculating BCR in a bottle-fed infant (11 months old). **a** Bolus area pre-swallow, **b** bolus area post-swallow, BCR = B/A

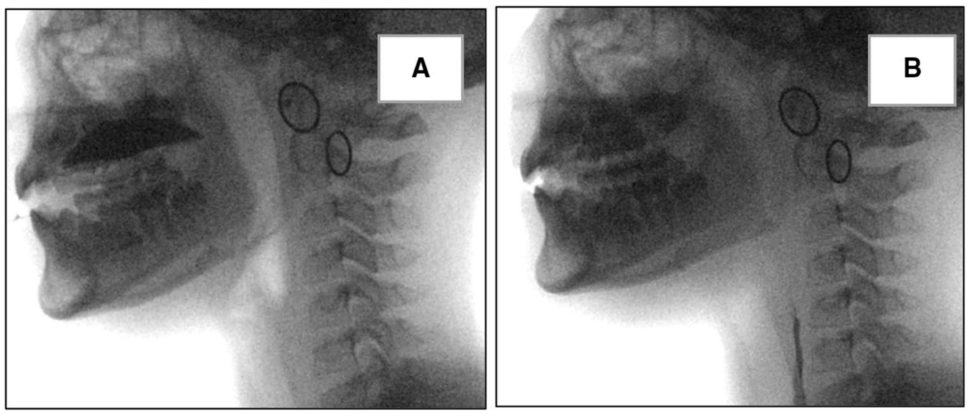

Fig. 2 Calculating TPT in a child. **a** Bolus head passing posterior nasal spine (B1), **b** bolus head passing posterior nasal spine (B1), TPT = BP2 − B1

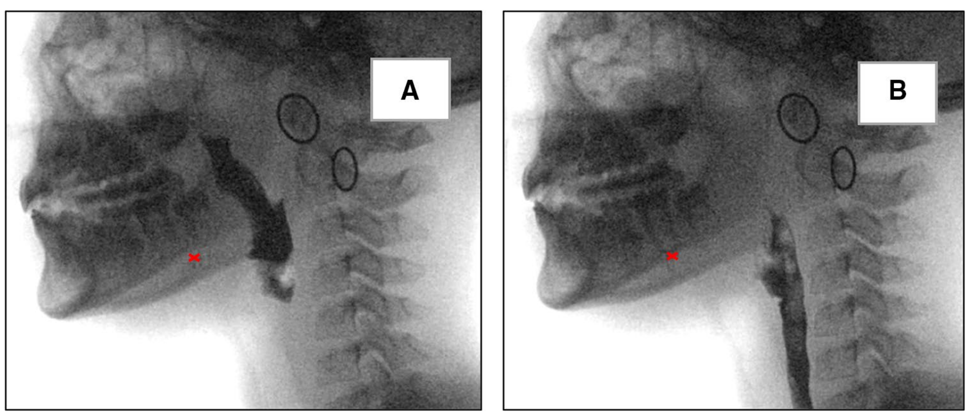

Fig. 3 Calculating Hdur in a child (> 9 months old), hyoid bone is marked in red. **a** First displacement of the hyoid bone to initiate a swallow (H1), **b** maximum elevation of the hyoid bone during swallowing (H2)

Discussion

VFSS and high resolution manometry are the two most commonly used instrumental swallow assessment tools in the pediatric research literature [44]. Due to limited access and expertise, high resolution manometry is less commonly utilized in clinical practice. We used the most commonly available swallow assessment tool, VFSS, to obtain objective quantitative swallow measures in a large cohort of children to predict the risk of penetration–aspiration. To our knowledge, this is the largest cohort of quantitative swallow measures of children to date. Unlike the literature on quantifying adult swallowing, the pediatric literature is scarce. A few studies have significantly contributed to objective and quantitative VFSS analysis of swallowing in children in the recent past [7, 9, 14–18]. The heterogenous study populations, study protocols used and differing swallow measures restrict clinicians' ability to apply findings to their practice.

Penetration–aspiration is the most common observation of swallowing impairment reported in research and clinically is considered the most significant 'abnormality' of pharyngeal phase of swallowing [34]. We found penetration–aspiration

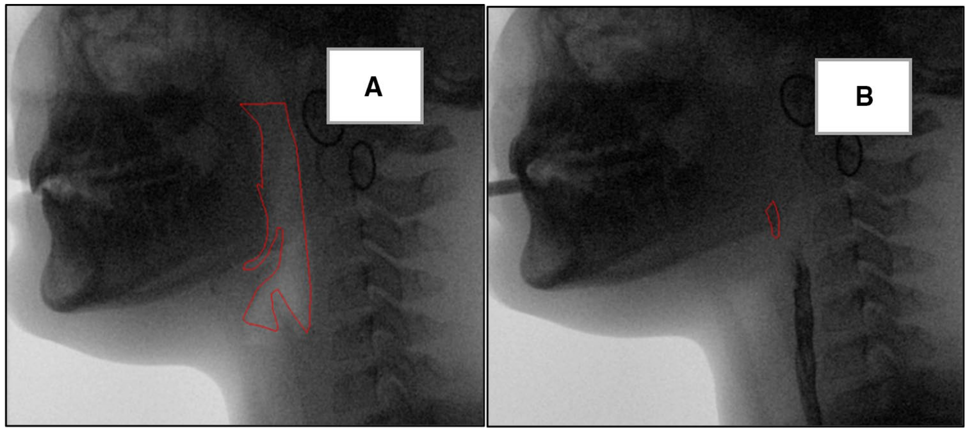

Fig. 4 Calculating PCR in a child. **a** Pharyngeal area at rest (PAs), **b** pharyngeal area at maximum constriction (PAmax), PCR = PAmax/ PAs

to be the most common swallow impairment in this cohort of children and it was more prevalent than post-swallow residue, NPR, and EPR. Bolus residual remaining in the pharynx after a swallow creates a greater risk of bolus material entering the airway post-swallow, resulting in penetration or aspiration [45]. BCR measures the ratio of residue present after a swallow to bolus area as the bolus enters the PES [32]. In children with higher PAS scores, worse BCR was reported, indicating clear association between penetration–aspiration and post-swallow residue in children. This is similar to evidence on swallowing dysfunction in adults [34, 46, 47]. Furthermore, we found PCR, an objective measure of pharyngeal constriction [48] significantly correlated with PAS scores in children. This emphasizes that pharyngeal weakness can result in residue, which may compromise airway safety during swallowing in children. These findings align with studies on adults with swallowing difficulties [4, 23, 49]. Our data indicate the importance of these same strength measures in describing biomechanics of swallowing in children, as they are also evident in children with penetration–aspiration.

We explored the ability of quantitative swallow measures to predict risk of penetration–aspiration in children. To our knowledge, this is the first study to predict likelihood of penetration–aspiration using a set of quantitative swallow measures in children. Our findings align with the previous research in adults, by supporting the value of objective quantitative swallow measures in predicting penetration–aspiration [3, 19–23]. In this study, BCR, TPT, PCR, and Hdur were all predictors of penetration–aspiration in children. Risk of penetration–aspiration was markedly increased when a child has a BCR of ≥ 0.1, TPT of ≥ 2 s, PCR of ≥ 0.2, and Hdur of > 1 s. These threshold values can be used clinically to identify children 'at risk' of aspiration, even though penetration–aspiration is not evident during VFSS. Clinicians must look for children presenting with more than one measure significantly elevated/reduced and be prepared for airway violation. As normative measures in children are unavailable, parameters measured above these threshold scores can be considered red flags of compromised swallow safety in children. As an individual measure, PCR was the most predictive of penetration–aspiration with an accuracy rate of 61.5%, where three out of five cases of penetration–aspiration in this cohort of children was accurately predicted by an elevated PCR. No other published studies were found in children assessing these predictive measures, but a recent study on predicting aspiration in adults with dysphagia reported PCR to be the most predictive measure of aspiration (74.6%) [4]. This study by Leonard also identified Hmax, HL, PESmax, and TPT as the other predictors of aspiration in adults, matching our current data. TPT was predictive of penetration–aspiration in our study. This suggests the longer the bolus stays in the oropharynx, the greater the risk of penetration–aspiration in children. This is confirmed in adults, where prolonged transit times have been significantly associated with aspiration and aspiration pneumonia [50] and prolonged TPT was associated with swallowing difficulties [51]. Restricted displacement of the hyoid (Hmax) has been related to aspiration in adults [4] whereas in our pediatric cohort the duration of maximum hyoid elevation (Hdur) was the predictor of airway risk (penetration–aspiration) rather than displacement. Our study findings that TPT and Hdur are predictive of penetration–aspiration in children may suggest that timing of events are more crucial in airway safety for children, possibly due to the higher rate of sequential swallows. Similar findings were observed in our study on young infants below 9 months [52]. We found TPT and suck:swallow coordination were predictive measures of penetration–aspiration in infants.

Our findings align with adult swallow impairment literature. Our study adds clinically useful threshold values of predictive measures of penetration–aspiration in children, which will allow more individualized approaches for assessment and treatment of children with swallowing difficulties. These objective VFSS measures, therefore, help identify and predict penetration–aspiration, shed light on the causes of penetration–aspiration and dysphagia, and guide with treatment options, maximizing the benefit of a fluoroscopic study.

Limitations

Due to the radioactive nature of VFSS, we are observing videofluoroscopic recordings of limited time portions (20 s loops and volume-based single bolus swallows), to limit radiation exposure of children. Therefore, some instances of swallow impairments may not have been observed. Textures were not evaluated in this study and further exploration of larger and solid boluses would add to the evidence-base. Determining the differences of quantitative timing and displacement measures across bolus sizes was beyond the scope of this study. However, we acknowledge this as an interesting area to explore in pediatric populations. The literature on adult swallowing is enriched with evidence of bolus-volume dependent airway safety [41, 42, 53, 54]. Effect of bolus size on airway safety in pediatrics is very scarce [55]. As this cohort may not represent the typical development of swallowing, statistical analysis was not performed to identify potential differences across gender and age, however, gender, age and etiology were controlled to reduce the risk of confounding.

Conclusion

Profiling objective quantitative swallow measures in children is reliable. These swallow measures have shown their potential to describe pediatric swallow biomechanics and predict the risk of penetration–aspiration in children. PCR, BCR, BP1AEcl, Hdur, and TPT are valuable quantitative swallow measures that can be obtained reliably during pediatric VFSS. Due to associations between residue and reflux (NPR and EPR), and airway violation, it is important to identify these findings in children. Threshold scores for predictive measures related to penetration–aspiration in children aid clinicians in identifying children at risk of aspiration for early intervention.

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Compliance with ethical standards

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

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