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Research Article

Quantifying Bolus Residue and Its Risks in Children: A Videofluoroscopic Study

Isuru Dharmarathna,[a,b] Anna Miles,[a] and Jacqui Allen[c]

Purpose: Postswallow residue is a clinical sign of swallow impairment and has shown a strong association with aspiration. Videofluoroscopy (videofluoroscopic study of swallowing [VFSS]) is commonly used to visualize oropharyngeal swallowing and to identify pharyngeal residue. However, subjective binary observation (present or absent) fails to provide important information on volume or location and lacks objectivity and reproducibility. Reliable judgment of changes in residue over time and with treatment is therefore challenging. We aimed to (a) determine the reliability of quantifying pharyngeal residue in children using the bolus clearance ratio (BCR), (b) determine associations between BCR and other timing and displacement measures of oropharyngeal swallowing, and (c) explore the association between BCR and penetration–aspiration in children.
Method: In this single-center retrospective observational study, we obtained a set of quantitative and descriptive VFSS measures from 553 children (0–21 years old) using a standard protocol. VFSS data were recorded at 30 frames per second for quantitative analysis using specialized software.
Results: Good interrater (ICC = .86, 95% CI [.74, .961], $p < .001$) and excellent intrarater reliability was achieved for BCR (ICC = .97, 95% CI [.91, 1.000], p = 001). Significant correlations between BCR and pharyngeal constriction ratio and total pharyngeal transit time were reported ($p < .05$). Using binomial logistic regression modeling, we found BCR was predictive of penetration–aspiration in children, $\chi^2(13) = 58.093$, $p < .001$, 64.9%. Children with BCR of ≥ 0.1 were 4 times more likely to aspirate.
Conclusion: BCR is a reliable, clinically useful measure to quantify postswallow residue in children, which can be used to identify and treat children with swallow impairments, as well as to measure outcomes of intervention.

Pharyngeal residue is bolus material that remains in the pharynx after a swallow (Pearson et al., 2013) and is considered a sign of impaired swallowing. Weak pharyngeal muscle strength, weak bolus propulsion, and impaired upper esophageal sphincter function may result in pharyngeal residue during swallowing (Eisenhuber et al., 2002). Incomplete bolus transit during swallowing in adults has a strong correlation with aspiration (Rommel et al., 2015). When residue remains after a swallow and the pharynx returns to its rest position, the airway opens, and residue can then enter the airway—termed *postswallow aspiration*. However, association between residue and aspiration in children is yet to be studied further.

Videofluoroscopic study of swallowing (VFSS) is one of the most common instrumental swallowing assessment tools employed to visualize the dynamic mechanism of swallowing in children (Dodrill & Gosa, 2015) and to visualize postswallow residue (Logemann, 1998; Rommel et al., 2015). Scales and measures have been developed to quantify postswallow residue observed through VFSS, rather than a binary observation of "present" or "absent." Subjective observational scales have been developed that report presence, absence, and severity of residue (Dejaeger et al., 1997; Eisenhuber et al., 2002; Han et al., 2001; Hind et al., 2001). Some qualitative scales have shown correlations with instrumental measures for validation. The Bolus Residue Scale (BRS) is a qualitative scale to determine residue location (Rommel et al., 2015), and it has shown correlations with the swallow risk index (Omari et al., 2011), which is an objective manometric measure associated with aspiration. Holistic VFSS assessment protocols, such as the Modified Barium Swallow Impairment Profile (Martin-Harris et al., 2008), have severity ratings of pharyngeal residue in their standard protocol. These ordinal visuoperceptual rating scales are reliable and easy to use. Yet, they are limited in their ability to provide cutoff marks for normal ranges of

[a]Speech Science, School of Psychology, Faculty of Science, The University of Auckland, New Zealand
[b]Department of Disability Studies, Faculty of Medicine, University of Kelaniya, Colombo, Sri Lanka
[c]Department of Surgery, The University of Auckland, New Zealand
Correspondence to Isuru Dharmarathna: pdha800@aucklanduni.ac.nz

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residue and are subjectively graded (Pearson et al., 2013). They do not provide clinicians and researchers with objective, quantifiable measures to allow tracking of residue over time or comparisons when trialing a compensatory strategy or following an intervention. As these visuoperceptual ordinal measures of residue lack precision, pixel-based methods with stable anatomical references are recommended for precise measurement of residue (Steele, Peladeau-Pigeon, Nagy, & Waito, 2020). Therefore, objective quantitative measures have been developed by manually outlining residue area in relation to known anatomical locations. These include the vallecular residue ratio, a computer-based ratio of the size of residue and the size of the valleculae (Dyer et al., 2008), and the Normalized Residue Ratio Scale, a calculation of residue in the valleculae and pyriform sinuses (Pearson et al., 2013). However, such measures are clinically beneficial when bolus residue is restricted to one or two locations of the pharynx, and measuring can be challenging in patients with residue spread across multiple pharyngeal locations. To overcome this, Leonard (2017) introduced the bolus clearance ratio (BCR), an objective quantitative measure of the residue using a semiautomatic technique, which was found to have excellent intra- and interrater reliability when measured in adults with dysphagia. Due to its ability to quantify bolus residue distributed across multiple regions of the pharynx and the simplicity of the measuring technique, we selected BCR to study in children as an objective quantitative measure of postswallow residue. These quantitative measures of residue have been studied in adults, but exploration in children is scarce. We previously reported obtaining BCR reliably in infants (0–9 months; Dharmarathna et al., 2020). In the current study, we investigated a large, heterogeneous group of children from 0 to 21 years of age presenting with swallowing difficulties. We hypothesized that BCR would be a reliable residue measure in children from 0 to 21 years of age and that BCR would be significantly associated with pharyngeal constriction ratio (PCR) and penetration–aspiration. Our aims were to (a) determine the reliability of quantifying residue in children using the BCR, (b) determine associations between BCR and other timing and displacement measures of oropharyngeal swallowing, and (c) explore the association between BCR and penetration–aspiration in children.

Materials and Method

This single-center retrospective observational study was conducted at a tertiary children's hospital. Ethical approval for the study was received from the University of Auckland Human Participants Ethics Committee (Application No. 9263).

Participants

The American Academy of Pediatrics identifies the upper limit of pediatrics as 21 years of age (Hardin et al., 2017), and the children's hospital adheres to this classification to care for children and adolescents with very complex disabilities up to 21 years of age. The University of Auckland videofluoroscopic database holds data on all children from 0 to 21 years of age consecutively referred for VFSS by their speech-language therapist due to concerns related to feeding/swallowing from 2016 to early 2020 at this children's hospital. From a total of 572 fluoroscopic videos of children obtained during this period, 553 videos of children were included. Exclusions included children who refused the procedure or did not swallow thin liquids (Level 0 thin; International Dysphagia Diet Standardization Initiative, 2016). Demographic data and medical history were obtained by the primary investigator (I. D.). 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 (a combination of medical etiologies), and unknown (no known medical etiology). Key clinical information regarding presence of tracheostomy, presence of a feeding tube, oxygen requirements, and respiratory complications was also collected. Respiratory complications were defined as any respiratory sign, which can result in morbidity and/or mortality of children (Carroll & Agarwal, 2010; von Ungern-Sternberg, 2014). Laryngospasm, bronchospasm, severe persistent cough, partial/complete airway obstruction, apnea, oxygen desaturation, bronchiectasis, and stridor were common respiratory complications identified in children.

VFSS Administration

The VFSS was conducted in the radiology suite on a Siemens Sireskop radiographic unit at the tertiary children's hospital. In 2016, a standardized protocol of obtaining video loops at 30 frames per second was introduced to obtain reliable, objective VFSS measures of children without increasing radiation dose or exposure time (Henderson et al., 2016). We used a standard recipe of Varibar barium sulfate contrast (40% w/v; E-Z-EM Canada, Inc.) 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 and cue older children to swallow when required. Either a radiopaque ring of a known diameter was placed in the child's chin with tape or a rulerlike 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 data were recorded on a USB external drive in .avi file format at 30 frames per second rate for frame-by-frame analysis.

VFSS Measures

We reported binary observation of (present/absent) nasopharyngeal reflux (NPR), along with postswallow residue, to be studied as incomplete bolus transit (Matsuo & Palmer, 2008), since both describe disruption in the flow of the bolus from the mouth to the stomach. Even though aspiration is the most critical risk during swallowing, VFSS should not merely report aspiration (Leonard, 2019). We chose the BRS (Rommel et al., 2015) as a subjective qualitative measure of residue to determine residue location, which was studied in adults previously. BCR (Leonard, 2017) was chosen as an objective quantitative measure of residue. BCR measures the ratio of residue present after a swallow to bolus area as the bolus enters the pharyngoesophageal segment (PES; see Figure 1). To calculate BCR and the other displacement measures, we used the area measurements provided by the presence of calibration ring in 2015–2017 and changed to a pixel ruler in 2018 with the purchase of a software update. We calculated the Penetration–Aspiration Scale (PAS; Rosenbek et al., 1996) as a measure of airway violation, considering a score of 3 or more as airway violation (PAS ≥ 3; Daggett et al., 2006; Riley et al., 2018; Steele & Grace-Martin, 2017). All incidents of airway violation of PAS ≥ 3 will be referred to as *penetration–aspiration* hereafter. We used a comprehensive range of quantitative timing and displacement measures of swallowing to determine associations with BCR (see Table 1). The hyoid bone excursion was only measured in children older than 9 months, as visibility of hyoid movements is not reliable until 9 months (Riley et al., 2018). Definitions of objective, quantitative swallow measures are given in the Appendix.

Calculations were performed on the swallow with the highest PAS score for each child (Hedström et al., 2017). Therefore, where an older child swallowed both 5- and 10-ml volumes, we chose the swallow with the highest PAS score for analysis. Where a midfeed loop was recorded, again, the swallow with the highest PAS score was chosen for analysis. As we obtained measures of postswallow residue, BCR and BRS were of the residue leftover from the same swallow we selected for objective analysis. All videofluoroscopic data were analyzed using a software program specifically designed for quantitative and objective analysis of VFSS (Swallowtail, Belldev Medical). The primary investigator (I. D.), an experienced speech-language therapist, completed comprehensive face-to-face training on objective quantitative swallow measures and the use of specialized software from the second author (A. M.). The primary author conducted the analysis of all videofluoroscopic data for the study and was blinded to participants' medical history and clinical characteristics.

Reliability Testing

VFSS data of 50 infants (< 9 months) and 116 children (> 1 year) were randomly selected for interrater reliability, which was 30% of the total cohort. The primary investigator (I. D.) measured the same data set of 50 infants (≤ 9 months) and 124 children (> 1 year) twice, with at least 10 months between repeat analyses to calculate intrarater reliability. Measures for interrater reliability were obtained by two raters (L. F. and M. J.) for infant and older children groups, respectively. All timing and displacement measures applicable for each group of children were obtained for reliability. The raters were blinded to each other's scores and medical history and clinical characteristics of the children for objective/quantitative analysis of all videofluoroscopic data.

Data Analysis

Statistical analyses of quantitative swallow measures were conducted using the Statistical Package for the Social

Figure 1. Calculating bolus clearance ratio in a bottle-fed infant (11 months old). (A) Bolus area pre-swallow = 5.67 cm^2, (B) Bolus area post-swallow = .968 cm^2, BCR = .171.

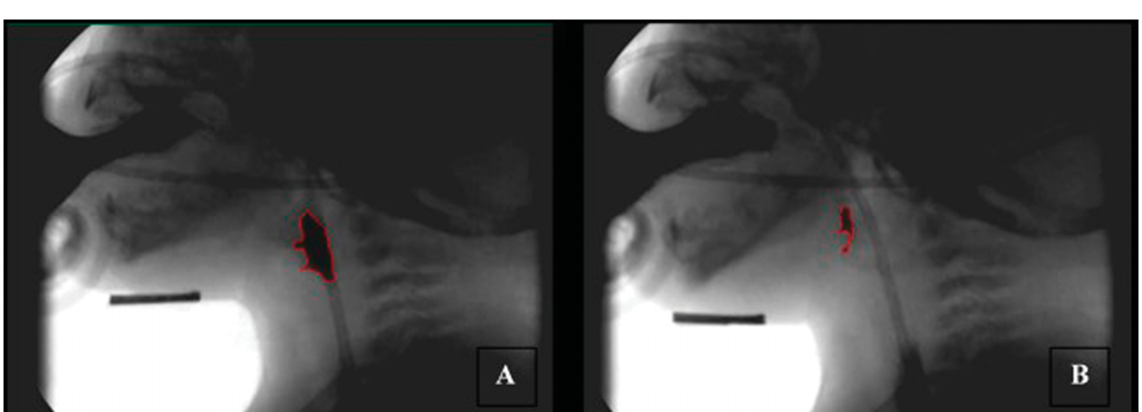


Table 1. Objective and/or quantitative swallow measures of children.

Quantitative swallow measures		Incomplete bolus transit measures
Timing (s) measures	**Displacement measures (cm)**	
Total pharyngeal transit time (TPT)[a]	Pharyngeal area at rest (PAhold)[a]	Bolus residue scale (BRS)[b]
Time to airway closure (Airwaycl)[a]	Pharyngeal area at maximum pharyngeal constriction (PAmax)[a]	Post swallow residue (+/–)[c]
Airway closure duration (ACD)[a]	Pharyngeal constriction ratio (PCR)[a]	Nasopharyngeal reflux (NPR) (+/–)[d]
PES opening duration (PESdur)[a]	Maximum opening of PES during a swallow (PESmax)[a]	Penetration–Aspiration Scale (PAS)[e]
Coordination of airway closure with bolus transit (BP1AEcl)[a]	Bolus clearance ratio (BCR)[f]	
Stage transition duration[g] (STD)[h]	Maximal hyoid elevation[g] (Hmax)[a]	
Laryngeal elevation[g] (LE)[a]	Maximum approximation of hyoid bone and larynx[g] (HL)[a]	
Duration to hyoid maximum elevation[g] (Hdur)[a]		
Duration of maximum hyoid displacement[g] (Hm)[a]		
Duration of velopharyngeal closure (VCD)[i]		

Note. (+/–) = (present/ absent); PES = pharyngoesophageal segment.

[a]Leonard and Kendall (2019). [b]Rommel et al. (2015). [c]Gosa et al. (2015). [d]Dodds et al. (1990). [e]Rosenbek et al. (1996). [f]Leonard (2017). [g]Measured in children above 9 months old only. [h]Byeon and Koh (2016). [i]Logemann et al. (1995).

Sciences (SPSS; IBM Corp. Released 2019, IBM SPSS Statistics for Windows, Version 26.0, 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 a normal distribution (Kwak & Kim, 2017). Therefore, parametric tests were conducted to draw statistical significance, using the mean to represent the center of the distribution (Chin & Lee, 2008). Statistical analyses conducted to achieve the research objectives are given below. Reliability of measures were obtained through intraclass correlation coefficient (ICC). ICC above .75 was considered a good agreement for interrater and intrarater reliability for ratings (Koo & Li, 2016). Pearson correlation test was conducted to determine the association of BCR with other objective quantitative measures and the association of BCR with PAS scores. One-way analysis of variance was used to determine differences in the distribution of PAS scores across the 6 points of BRS. Bonferroni post hoc test was used for pairwise comparisons in one-way analysis of variance test. An independent-sample t test was used to compare the differences of objective quantitative measures in children with and without NPR. Lastly, we explored whether BCR as an objective quantitative measure of residue could predict penetration–aspiration in children. BCR was entered into a binomial logistic regression model while being controlled for age, sex, bolus volume, and etiology to determine BCR's ability to predict penetration–aspiration in children. PAS score was used to group children as aspirators (PAS ≥ 3) and nonaspirators (PAS = 1, 2; Daggett et al., 2006; Riley et al., 2018; Steele & Grace-Martin, 2017). We used the relative risk of BCR in the regression model based on the assumption that odds ratio obtained from logistic regression models of rare outcomes are equal to risk ratio/relative risk (Diaz-Quijano, 2012). Cutoffs for BCR is reported with relative risk as effect size with 95% confidence intervals (CIs). A p value (significance) of $< .05$ is considered statistically significant.

Results

Descriptive Statistics

A total of 553 children ($n = 341$, 61% male) between 0 and 21 years of age ($M = 3.12$ year ± 3.86) were recruited. The characteristics of the children are given in Table 2. Due to the absence or lack of visualization of the calibration ring or the pixel ruler, displacement measures were unable to be obtained from 74 children.

Mean BCR of this cohort of children was 0.033 ($SD = 0.134$, range: 0–0.973). Categorical and ordinal measures of penetration–aspiration and incomplete bolus transit (presence of postswallow residue, BRS, and NPR), along with PAS scores are reported in Table 3.

Reliability of Quantifying Residue in Children

Interrater reliability across all measures was found to have good agreement in infants (ICC =.75–.84, 95% CI [.3, .86], $p < .001$) and good to excellent agreement in children above 1 year (ICC = .77–.92, 95% CI [.69, .95], $p = .001$). Intrarater reliability of all quantitative measures was above .9, indicating excellent agreement ($p < .05$). BCR showed good interrater reliability (ICC = .86, 95% CI [.74, .961], $p < .001$).

Association of BCR With Timing and Displacement Swallow Measures

Significant differences between BCR and other quantitative swallow measures were found. BCR was significantly

Table 2. Demographics/clinical information.

Demographic		Frequency (*n*)	Percent
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
Sex	Female	212	38.3
	Male	341	61.7
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
Respiratory complications	Yes	217	39.2
	No	336	60.8
Oxygen requirements	Yes	23	4.2
	No	530	95.8
Tracheostomy	Yes	35	6.3
	No	518	93.7
Alternative feeding at the time of procedure	Nasogastric tube	107	19.4
	Percutaneous endoscopic gastrostomy	51	9.2
	None	395	71.4

[a]Classification of age recognized by the American Academy of Pediatrics (Hardin et al., 2017).

positively correlated with BRS, $r(552) = .765$, $p < .001$, and PCR, $r(552) = .219$, $p < .001$. Significant positive correlations were seen between BCR and total pharyngeal transit time (TPT), $r(552) = .174$, $p < .001$; BP1AEcl, $r(552) = .167$, $p < .001$; and pharyngeal area at maximum constriction, $r(478) = .211$, $p < .001$. Significant negative correlation was found between BCR and duration of PES opening, $r(552) = -.1$, $p = .023$; maximum opening of PES during swallowing (PESmax), $r(478) = -.109$, $p = .023$; stage transition duration, $r(512) = -.263$, $p < .001$; airway closure

Table 3. Descriptive swallow measures of children.

Descriptive swallow measures	Points of the scale	Frequency (*n*)	Percent
Penetration–Aspiration Scale	1–2 = safe airway[a]	326	58.9
	3–5 = penetration[a]	69	12.5
	6–8 = aspiration[a]	158	28.6
Residue location rating			
Bolus Residue Scale	1 = no residue	498	90.1
	2 = residue in valleculae	16	2.9
	3 = residue in PPW or PS	11	1.9
	4 = residue in valleculae and PPW or PS	15	2.7
	5 = residue in PPW and PS	7	1.3
	6 = residue in valleculae, PPW and PS	6	1.1
Binary observations		**Frequency (*n*)**	**Percent**
Post swallow residue	Present	55	9.9
	Absent	498	90.1
Nasopharyngeal reflux	Present	48	8.7
	Absent	505	91.3

Note. PPW= posterior pharyngeal wall; PS= pyriform sinus.

[a]Daggett et al. (2006), Riley et al. (2018), Steele and Grace-Martin (2017).

duration, $r(512) = -.153$, $p = .001$; and laryngeal elevation, $r(512) = -.139$, $p = .039$.

NPR and Quantitative Swallow Measures

Significantly more elevated PAS scores were observed in children with NPR ($Mdn = 5$, $SE = .496$), compared to children without NPR ($Mdn = 2$, $SE = .137$), $t(50.904) = 2.385$, $p = .021$. Children with NPR demonstrated significantly elevated BCR scores ($M = 0.152 \pm 0.287$), compared to children without NPR ($M = 0.023 \pm 0.109$), $t(45.22) = 2.986$, $p = .005$. Significant differences in quantitative swallow measures between children with and without NPR were found (see Table 4).

Residue and Penetration–Aspiration

PAS scores significantly positively correlated with BCR, $r(552) = .128$, $p = .004$, indicating elevated (worse) BCR scores in children with more severe PAS scores. Significant differences in the distribution of PAS scores across 6 points of BRS were observed, $F(5, 516) = 6.292$, $p < .001$, indicating an association between penetration–aspiration and location of residue in children (see Figure 2). Bonferroni test revealed that the PAS score was significantly higher (more severe) in children with residue in posterior pharyngeal wall/pyriform sinus (BRS = 3, $M = 6.45 \pm 2.423$) than in children with no residue ($M = 3.35 \pm 2.962$). Moreover, children with residue in all three residue locations (valleculae, posterior pharyngeal wall, and pyriform sinus, BRS = 6) reported significantly higher PAS scores ($M = 8 \pm 0$) than children with no residue ($M = 3.35 \pm 2.962$).

The mean BCR was 0.07 (± 0.06) for children who did not aspirate and 0.32 (± 0.17) for children who aspirated. After adjusting for age, sex, bolus volume, and etiology, the multiple logistic regression analysis revealed that the BCR was significantly predictive of penetration–aspiration in children ($p < .001$). The binomial logistic regression model was statistically significant, $\chi^2(13) = 58.093$, $p < .001$, and the model correctly classified 64.9% of cases. According to the odds ratios, children with a BCR of ≥ 0.1 were 4 times more likely to aspirate (95% CI [1.02, 16.429], $p = .047$).

Table 4. Significant differences in quantitative swallow measures in relation to nasopharyngeal reflux (NPR).

Measure	NPR	*M*	*SD*	*t*	*df*	Sig.
BCR	Present	0.152	0.287	2.986	45.22	.005
	Absent	0.023	0.109			
BRS	Present	2.000[a]	0.247[b]	3.272	45.268	.002
	Absent	1.000[a]	0.030[b]			
PCR	Present	0.341	0.227	4.32	47.475	< .001
	Absent	0.187	0.184			
PESmax	Present	0.376	0.208	3.613	437	< .001
	Absent	0.515	0.234			
PESdur	Present	0.340	0.214	2.114	512	.035
	Absent	0.400	0.178			
ACD	Present	0.405	0.259	2.172	511	.03
	Absent	0.490	0.248			

Note. *df* = degree of freedom; Sig. = significance/*p* value; BCR = bolus clearance ratio; BRS = Bolus Residue Scale; PCR = pharyngeal constriction ratio; PESmax = maximum opening of PES during swallowing; PESdur = duration of PES opening; ACD = airway closure duration.

[a]Median. [b]Standard error.

Discussion

This retrospective, observational study reliably obtained BCR, an objective quantitative residue measure, in a large pediatric caseload. We believe this is one of the largest reports of quantitative swallow measures of residue in children to date. We found BCR to have good interrater reliability and excellent intrarater reliability when measuring in infants and children. Similar excellent interrater reliability of BCR has been reported in adults (Leonard, 2017; Leonard & Kendall, 2019). Considering the difficulties of visualizing swallowing in anatomically different developing children (Newman et al., 1991), these interrater reliability results are a positive indication of their potential use in children.

Residue and Pharyngeal Constriction

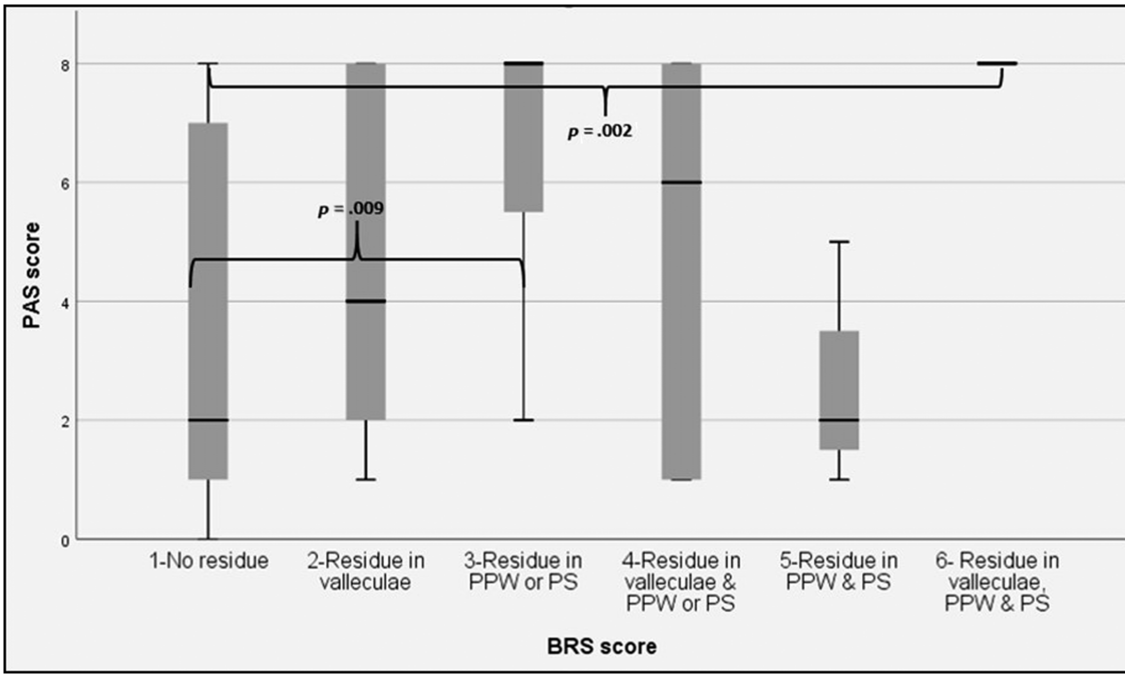
PCR is a surrogate measure of pharyngeal constriction and a ratio derived from measures of the pharyngeal area at rest and the pharyngeal area at maximum constriction (Leonard et al., 2011). In our study, elevated PCR was reported in children with elevated BCR. Weak pharyngeal constriction (measured as elevated PCR) leads to an inability to push the whole bolus down through the pharynx, resulting in postswallow residue, which may later enter into the airway, causing airway violation. Significant associations between pharyngeal constriction and residue are also found in adults (Stokely et al., 2015).

Residue and Other Objective Measures

Children with elevated (worse) BCR reported a significantly narrower PESmax and shorter duration of PES opening, indicating that residue is associated with a dysfunctional pharynx. PESmax was narrower in children with elevated BCR. If the PES does not open widely or for long enough, the whole bolus may not make it through to the esophagus before the PES closes again, resulting in pharyngeal residue, which can then be aspirated. Higher velocity of flow is required across a narrowed or short duration of opening PES to allow the same volume to pass. Compensation by increasing pharyngeal pressures may assist PES flow or may cause bolus to escape to other areas with lower pressures, such as the airway and nasal cavity, causing airway violation and NPR, respectively (Rommel et al., 2015).

The hyoid and laryngeal elevation contributes to PES opening during swallowing (Cook et al., 1989; Dodds et al., 1990; Jacob et al., 1989). Due to pharyngeal and laryngeal anatomy, hyoid bone, larynx, and the upper

Figure 2. Distribution of Penetration–Aspiration Scale (PAS) scores across 6-point Bolus Residue Scale (BRS). PPW = posterior pharyngeal wall; PS = pyriform sinus.



esophageal sphincter operate as one mobile unit during swallowing (Jacob et al., 1989). Parallel superior laryngeal and superior hyoid movements were observed during swallowing in adults (Jacob et al., 1989). Difficulties in hyoid elevation have often been accompanied by reduced PES opening (Leonard & Kendall, 2019). This unique association of hyoid bone, larynx, and the upper esophageal sphincter function may explain our finding of a negative correlation between BCR, with timing measures of hyoid and laryngeal movements such as stage transition duration, airway closure duration, and laryngeal elevation. In addition, we found TPT was longer in children with elevated BCR. Longer transit time may be an indicator of weak pharyngeal musculature and inability to drive bolus transit (Leonard, 2019).

Residue and Penetration–Aspiration

As one of our aims was to identify the associated risk of residue presence with penetration–aspiration, we used only BCR in our logistic regression model. To our knowledge, this is the first study to predict the likelihood of penetration–aspiration using BCR in children. In this study, we provided a threshold score of BCR to predict penetration–aspiration: Children with a BCR of 0.1 or above are 4 times more likely to aspirate than children with a BCR of < 0.1. This confirms that an elevated BCR increased the risk to aspirate due to residue and inability to clear the bolus completely from the pharynx in a timely manner. As normative scores in children are unavailable, scores higher than the BCR threshold scores can be considered red flags for impaired swallowing and increased penetration–aspiration risk in children.

With the model predicting 64.9% of the penetration–aspiration, it is evident that pharyngeal residue alone is not the cause of all incidents of airway violation in children. As we would expect, other timing and displacement components of dynamic swallowing processes play significant roles in airway protection but were not the focus in this particular article. An elevated BCR means a larger volume of residue remained in the pharynx following the swallow, and it is clear that the larger volume of residue leads to a greater risk of penetration–aspiration. Similarly, previous studies have found that larger volumes of residue can overflow into the airway after a swallow resulting in postswallow aspiration (Dodds et al., 1990; Eisenhuber et al., 2002). Recently, a study on adults at risk of dysphagia reported a pharyngeal residue threshold of 1% $(C2\text{-}4)^2$, as a cutoff point for increased risk of airway violation on a subsequent swallow (Steele, Peladeau-Pigeon, Barrett, & Wolkin, 2020), further confirming the association between increased residue volumes and a higher risk of penetration–aspiration.

BRS was used as a subjective rating scale to identify the location of residue, and it also provided interesting insights regarding residue in the pyriform fossae. We found that diffuse residue resulted in a higher risk of penetration–aspiration. As reported through higher BRS, residue located closer to the airway entrance showed significantly greater (worse) PAS scores. That is, residue located in the pyriform sinus was more likely to be associated with penetration–aspiration than residue located in the valleculae. Similar findings were reported in adults with dementia, where a higher risk of penetration–aspiration was found when pyriform residue was seen (Namasivayam-MacDonald & Riquelme, 2019).

Objective VFSS measures not only identify penetration–aspiration, but give us the opportunity to predict penetration–aspiration and evaluate residue critically so that it might also guide treatment options. Our findings on postswallow residue and other signs of incomplete bolus transit in children clearly align with adult swallow impairment literature. Our study adds clinically useful threshold scores of BCR in children, which may signal an increased risk of penetration–aspiration. Threshold scores of BCR may be used as outcome measures in intervention studies to track the effects of an intervention.

Limitations

We acknowledge a number of limitations to this study. 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, we may have missed postswallow residue and penetration–aspiration in some instances. Due to a diverse range of etiologies reported in these children, details of comorbidities, diagnosis of dysphagia, the severity of illness, and medications are not provided for stratification. Although evidence on differences of postswallow residue across bolus volumes and consistencies is available on adult swallowing (Kendall & Leonard, 2001; Leonard et al., 2006; Stokely et al., 2015), studying the effect of bolus volume and consistency was beyond the scope of this study. Further exploration of the effect of bolus volume and consistencies on pharyngeal constriction and residue across a range of bolus sizes may add value in future studies. We acknowledge the limitation of VFSS procedure being a two-dimensional representation of the three-dimensional swallow mechanism. Due to the nature of lateral VFSS, we could only investigate postswallow residue from a lateral view of VFSS as a two-dimensional representation. Therefore, we are unable to determine how residue is lateralized between the right and left sides of the pharynx, which may be useful in providing intervention. In addition, we acknowledge the potential limitation of using the BRS in this pediatric cohort as a qualitative rating scale, which has only been validated in adults.

Conclusions

Quantifying bolus residue in children is reliable and feasible. Objective quantitative swallow measures are capable of describing pediatric swallow parameters such as residue, NPR, and penetration–aspiration. Threshold scores of BCR in children aid in identifying children at risk of penetration–aspiration secondary to postswallow residue allowing for early intervention. Due to associations between penetration–aspiration and incomplete bolus transit, it is important to report reflux and residue in children. BCR, PCR, PESmax, duration to hyoid maximum elevation, and TPT are valuable quantitative swallow measures to obtain during pediatric VFSS in order to describe and predict the biomechanics of swallowing in children.

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Appendix

Swallowing Measures and Definitions

Objective quantitative measure	Definition
Timing(s)/coordination	
Total pharyngeal transit time (TPT)	Represents the total time of the bolus passage through the pharynx, from when the bolus head passes the posterior nasal spine (B1) to the time at which the bolus tail completely clears the PES (BP2) *Total pharyngeal transit time = BP2 – B1*
Time to airway closure (Airwaycl)	Time taken to total arytenoid-epiglottis approximation to close supraglottic airway *Airway start (AEs) – airway close (Acl)*
Airway closure duration (ACD)	The duration of total airway closure, from the approximation of the elevated arytenoids with the down folding epiglottis (AEc) to the first frame in which the epiglottis has returned to its preswallow position (Em) *Airway closure time = Em – AEc*
PES opening duration (PESdur)	The duration of PES opening from the first frame in which it opens (Pop) to when it closes behind the bolus tail (Pcl) *PES opening time = Pcl – Pop*
Coordination of airway closure with bolus transit (BP1AEcl)	Airway closure time (Aec) in relation to bolus reaching PES (BP1) *Coordination of airway closure with bolus transit = BP1 – Acl*
Stage transition duration (STD)	First upward movement of the hyoid (H1) in relation to bolus head passes the posterior nasal spine (B1)
Laryngeal elevation (LE)	First upward movement of the hyoid (H1) in relation to first upward movement of the arytenoids
Duration to hyoid maximum elevation (Hdur)	The duration from the first upward movement of the hyoid (H1) to its maximum anterior–superior displacement (H2) *Hdur = H2 – H1*
Duration of maximum hyoid displacement (Hm)	The duration hyoid remains in its maximum elevation. From the first frame of maximum elevation (H2) to the first frame, hyoid begins to retract from its maximum elevation (H3). *Hm = H3 – H2*
Duration of velopharyngeal closure (VCD)	The number of video frames exhibiting contact of the velum to the posterior pharyngeal wall multiplied by the duration of one video frame
Displacement measures (cm)	
Maximum pharyngeal area at rest (PAhold)	Measured when the pharynx is at rest, either prior to or following a swallow. The pharyngeal area is outlined by the posterior pharyngeal wall extending from the midportion of the tubercle of the atlas to the top of the arytenoid cartilages, anteriorly over the arytenoids to outline the epiglottis, valleculae and tongue base up to the soft palate (Yip et al., 2006).
Pharyngeal area at maximum constriction (PAmax)	The same pharyngeal area as outlined in the maximum pharyngeal area was measured again, but at the point of maximum constriction during a swallow.
Pharyngeal constriction ratio (PCR)	The ratio of pharyngeal area at maximum constriction to the area of the pharynx at rest *PCR = PAhold / PAmax*
PES max opening (PESmax)	The width of the pharyngoesophageal segment was measured at the point of maximum opening during the swallow.
Bolus clearance ratio (BCR)	Pharyngeal clearance ratio (before and after swallow). Area 1-bolus area during a swallow immediately prior to the UES. Area2- bolus area/any material in pharynx immediately after UES closure BCR = Area2 / Area1
Maximum elevation of hyoid bone (Hmax)	The change in hyoid position from a referent frame (hold) to its maximum anterior–superior displacement (H2)
Maximum approximation of the hyoid and larynx (HL)	The difference in distance between hyoid bone and larynx at hold position and at their point of maximum approximation (HLmax) during the swallow
Incomplete bolus transit measures	
Penetration–Aspiration Scale (PAS)	1–8
Post swallow residue	Presence or absence of residue, marked as (+) or (–)
Bolus Residue Scale (BRS)	1–6 scale
Nasopharyngeal reflux (NPR)	Presence or absence of NPR, marked as (+) or (–)