ORIGINAL ARTICLES

Pressure-Flow Analysis for the Assessment of Pediatric Oropharyngeal Dysphagia

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Objectives To determine which objective pressure-impedance measures of pharyngeal swallowing function correlated with clinically assessed severity of oropharyngeal dysphagia (OPD) symptoms.

Study design Forty-five children with OPD and 34 control children without OPD were recruited and up to 5 liquid bolus swallows were recorded with a solid-state high-resolution manometry with impedance catheter. Individual measures of pharyngeal and upper esophageal sphincter (UES) function and a swallow risk index composite score were derived for each swallow, and averaged data for patients with OPD were compared with those of control children without OPD. Clinical severity of OPD symptoms and oral feeding competency was based on the validated Dysphagia Disorders Survey and Functional Oral Intake Scale.

Results Those objective measures that were markers of UES relaxation, UES opening, and pharyngeal flow resistance differentiated patients with and without OPD symptoms. Patients demonstrating abnormally high pharyngeal intrabolus pressures and high UES resistance, markers of outflow obstruction, were most likely to have signs and symptoms of overt Dysphagia Disorders Survey (OR 9.24, $P = .05$, and 9.7, $P = .016$, respectively).

Conclusion Pharyngeal motor patterns can be recorded in children by the use of HRIM and pharyngeal function can be defined objectively with the use of pressure-impedance measures. Objective measurements suggest that pharyngeal dysfunction is common in children with clinical signs of OPD. A key finding of this study was evidence of markers of restricted UES opening. *(J Pediatr 2016;177:279-85).*

Safe, effective, and efficient swallowing throughout development relies on intricate sensory development, fine motor coordination of the swallowing musculature, and maturation of feeding skills to ensure airway protection and full bolus clearance from the oropharyngeal segment.[1-3] Physiologically, pressure changes across the pharyngoesophageal segment drive bolus movement during the swallowing process. Stimulation of mechanoreceptors in the base of tongue during bolus propulsion and afferent pathways stimulated by bolus advancement into the oropharynx trigger the pharyngeal swallow response.[4] The soft palate elevates to seal the nasal cavity; the cricopharyngeus muscle, which primarily generates the upper esophageal sphincter (UES) high-pressure zone, relaxes in coordination with hyolaryngeal excursion to enable concomitant airway protection and UES opening. The pharyngeal stripping wave follows to clear any bolus residue.

In cases in which there is restriction at the level of the UES, bolus outflow from the pharynx is obstructed and intrabolus pressures increase, making post-swallow residue and risk of mid or post-swallow aspiration more likely. Children with developmental disorders, neurologic conditions, respiratory or cardiac problems, esophageal dysmotility, or structural deficits such as cleft palate are at risk for oropharyngeal dysphagia (OPD) and potentially aspiration.[5-12]

Objective assessment of oropharyngeal swallowing is challenging because of its mechanically complex nature.[12] High-resolution, solid-state manometry with impedance (HRIM) is a catheter-based diagnostic modality that overcomes some of

DDS	Dysphagia Disorders Survey
FI	Flow interval
FOIS	Functional Oral Intake Scale
HRIM	High-resolution, solid-state manometry with impedance
OPD	Oropharyngeal dysphagia
PFA	Pressure-flow analysis
PNI	Pressure at nadir impedance
PP	Peak pressure
PSIR	Post-swallow impedance ratio
SRI	Swallow risk index
TNIPP	Time from nadir impedance to peak pressure
UES	Upper esophageal sphincter
UESNI	Upper esophageal sphincter nadir impedance
UESRES	Upper esophageal sphincter intrabolus pressure during relaxation
VFSS	Videofluoroscopy swallow study

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the inherent limitations of existing assessment techniques. Used as an adjunct to videofluoroscopy swallow studies (VFSS), HRIM enhances biomechanical evaluation of oropharyngeal swallowing and, furthermore, pressure and impedance recordings generated during HRIM-measured swallows can be analyzed with pressure-flow analysis (PFA).[2,13-19] Published studies in adults and, to a lesser extent, in children with pharyngeal dysphagia have shown individual PFA measures and a global composite score of swallowing dysfunction, called the swallow risk index (SRI), are able to discriminate consequences of swallowing pathophysiology, such as risk of aspiration, the presence of post-swallow residue, and abnormal pharyngeal distension-contraction timing in circumstances of poor oral containment and/or delayed swallow trigger.[2,13,18,19] Although PFA measures differ in relation to the radiologic picture of severity, it remains to be determined which PFA measures correlate with the degree of swallowing impairment determined by accepted clinical assessment scales that are used widely among speech-language pathologists.

The aim of this study was to perform HRIM with PFA in a heterogeneous group of children with clinically recognized signs of OPD to investigate potential correlations with established clinical assessment scales, namely the Dysphagia Disorders Survey (DDS)[20] and the Functional Oral Intake Scale (FOIS).[21] We hypothesized that PFA metrics would differentiate patients with OPD from control children without OPD and correlate with DDS and FOIS scores.

Methods

All investigations were performed in the Gastroenterology Department at the Women's and Children's Hospital in Adelaide, Australia. Children older than 2 years of age with symptoms of dysphagia were recruited between December 2011 and June 2015. The Women's and Children's Health Network Human Research Ethics Committee approved the study protocol (HREC1367). Informed consent was obtained from the primary caregiver for all participants. Because of ethical concerns, healthy children were not studied; instead, children who were referred for manometric investigation of esophageal motility were recruited as control children without OPD. If needed, these children were given extra boluses with the catheter repositioned to capture pharyngeal motor patterns.

A 10-French HRIM catheter was used that incorporated 25 1 cm-spaced unidirectional pressure sensors and 12 adjoining impedance segments, each of which were 2 cm in length (Unisensor AG, Attikon, Switzerland). The catheter was positioned transnasally, with sensors straddling the entire pharyngoesophageal segment from velopharynx to proximal esophagus. A small amount of water-based lubricant was used at the tip and shaft of the catheter to assist with passage. Once positioned, the catheter was taped to the participant's cheek. The pressure and impedance data were acquired at 20 Hz (Solar GI acquisition unit; Medical Measurement Systems, Enschede, The Netherlands).

Patients were seated upright/semireclined for all swallows. The swallow material was offered via syringe or spoon, and cervical auscultation was used to confirm the onset of swallow after bolus administration to the mouth. Liquid bolus swallows (saline 0.9% NaCl) of 2-5 mL were recorded in each patient. Swallows acquired and analyzed from HRIM recordings were for liquid swallows without thickener modifications. (Note: the volume and number of boluses administered were determined on clinical grounds by the attending speech-language pathologist.)

Patient recordings were included in this study if at least 3 swallows of 2 mL of saline were acquired. All controls provided at least 4 × 5 mL liquid (saline 0.9% NaCl) swallows. Saline was used to enhance conductivity for reliable impedance measurements. To investigate the effects of age and volume on the PFA measures, in this cohort patients were grouped for age (2-5 years, 6-10 years, 11-14 years, or 15-18 years) and volume (2-3 mL or 4-5 mL).

Acquired HRIM Recordings

Pressure recordings during swallows are displayed as color isobaric-contour plots (**Figure 1**), which provide a graphical representation of pressure changes in real time, from the velopharynx to the proximal esophagus during a swallow. Simultaneously acquired impedance measurements detect the movement of the propelled bolus through the pharynx and UES.

Pressure-Flow Analysis

After HRIM recordings were acquired, pressure and impedance data for each swallow were exported (.csv file) and opened with purpose-designed MATLAB-based software for PFA. (AIMplot.v1 software, copyright T Omari, created in Matlab version 7.9.0.529; MathWorks Inc, Natick, Massachusetts). AIMPlot is used to derive swallow function metrics and a SRI. Derivation of metrics and the SRI have been described previously.[2,13-19] To summarize in brief, specific landmarks on the pressure topography space-time plot were selected (**Figure 1**) to define specific regions of interest for analysis (**Figure 2**; available at www.jpeds.com). The landmarks selected were: (1) onset of swallow, (2) position of the UES proximal margin post-swallow, and (3) position of the velopharynx during the swallow.

Within each region of interest, swallow function metrics were derived with the use of automated algorithms. These metrics are pharyngeal peak pressure (PP), defined as the maximum contraction of the pharynx during the swallow; the pharyngeal nadir impedance reading, defined as a marker of the center and diameter of the main body of the swallowed bolus; the pressure at nadir impedance (PNI), measuring the intrabolus pressure during maximal pharyngeal distension; the time from nadir impedance to peak pressure (TNIPP), measuring the time from bolus distension of the pharynx to the maximum pharyngeal contraction during the stripping wave; and the flow interval (FI), defining pharyngeal bolus dwell time.[14] We also measured the upper esophageal sphincter nadir impedance (UESNI) as a marker of UES opening diameter[13] and the upper esophageal sphincter resistance (UESRES), defined by UES intrabolus pressures over the relaxation period.[22] The post-swallow impedance ratio (PSIR) is an integrated ratio that