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Classification of high-resolution manometry data according to videofluoroscopic parameters using pattern recognition

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Abstract

Objective—To determine if pattern recognition techniques applied to high-resolution manometry (HRM) spatiotemporal plots of the pharyngeal swallow can identify features of disordered swallowing reported on the Modified Barium Swallow Impairment Profile (MBSImP).

Study Design—Case series evaluating new method of data analysis.

Setting—University hospital.

Subjects and Methods—Simultaneous HRM and videofluoroscopy was performed on 30 subjects (335 swallows) with dysphagia. Videofluoroscopic studies were scored according to the MBSImP guidelines while HRM plots were analyzed using a novel program. Pattern recognition using a multilayer perceptron artificial neural network (ANN) was performed to determine if seven pharyngeal components of the MBSImP as well as penetration/aspiration status could be identified from the HRM plot alone. Receiver operating characteristic (ROC) analysis was also performed.

Results—MBSImP parameters were identified correctly as normal or disordered at an average rate of approximately 91% (area under the ROC curve ranged from 0.902 to 0.981). Classifications incorporating two MBSImP parameters resulted in classification accuracies over 93% (area under the ROC curve ranged from 0.963 to 0.989).

Conclusion—Pattern recognition coupled with multiparameter quantitative analysis of HRM spatiotemporal plots can be used to identify swallowing abnormalities which are currently assessed using videofluoroscopy. The ability to provide quantitative, functional data at the bedside while avoiding radiation exposure make HRM an appealing tool to supplement and, at times, replace traditional videofluoroscopic studies.

Keywords

High-resolution manometry; pharyngeal swallow; MBSImP; videofluoroscopy

INTRODUCTION

Swallowing is a modifiable patterned response requiring complex organization and action. Disordered swallowing results from diverse etiologies and can carry significant morbidity

and mortality.¹ Videofluoroscopy is a primary examination tool providing information on bolus transit, residue, and aspiration, and is often used to guide assessment and therapy.²

While videofluoroscopy is certainly valuable, examination requires radiation exposure and associated risk to patients.³ Additionally, examination requires the patient be moved to the radiology suite and is a relatively poor predictor of aspiration pneumonia.^{4,5} Thus, it would be beneficial to develop an assessment which can provide information similar to that provided by videofluoroscopy but does not require radiation exposure and can also be performed easily at the bedside.⁶ Such an assessment would also be amenable to serial measurements and evaluation of patient progress over time, as the exam could be performed quickly and accumulative radiation would not be a concern. Fiberoptic endoscopic evaluation of swallowing (FEES) meets these criteria and has been shown to be valuable in detecting secretions not visualized on videofluoroscopy⁷ as well as silent aspiration,⁸ but does not provide quantitative information on the changes in pressure underlying bolus transit.

Swallowing is a pressure-driven process;⁹ accordingly, detailed measurement and analysis of the changes in pressure underlying bolus transit can provide valuable information on swallowing physiology. High-resolution manometry (HRM) uses a catheter which spans the length of the pharynx and provides spatial resolution of one centimeter. The large amount of information produced by HRM and the complexity of its spatiotemporal plots are ideally suited to analysis by pattern recognition. Pattern recognition techniques such as artificial neural networks (ANNs) are powerful mathematical models which use nonlinear statistical analysis to classify large datasets into groups.^{10,11} We previously applied ANNs to classify HRM data into normal and disordered swallows¹² as well as identify penetration and aspiration.¹³ While application to identify clinically significant events currently assessed on videofluoroscopy such as aspiration is an important step in the development of HRM, videofluoroscopy can assess much more than aspiration status.

The Modified Barium Swallow Impairment Profile (MBSImP) represents an advance which could help standardize videofluoroscopic assessment.² It consists of 17 components describing the oral, pharyngeal, and esophageal phases of swallowing. The initial study demonstrated the potential of this tool to guide videofluoroscopic swallowing analysis in a reliable and repeatable fashion. Subsequent studies determined that the MBSImP protocol does not prolong radiation exposure¹⁴ and that abnormal esophageal clearance is correlated with abnormal findings on esophageal manometry with impedance.¹⁵ Simultaneous pharyngeal HRM and videofluoroscopy with MBSImP analysis has not been performed and, importantly, it has not been investigated whether HRM alone can be used to identify pharyngeal swallow abnormalities reported using the MBSImP.

We performed simultaneous videofluoroscopy with HRM on thirty subjects with dysphagia. Videofluoroscopic images were analyzed using the MBSImP and HRM data were analyzed using a novel data extraction program. We hypothesized that pattern recognition using an ANN could be used to classify data into groups based on MBSImP components.

MATERIALS AND METHODS

Equipment

Videofluoroscopy was performed in the lateral plane at 30 frames per second (Axiom Sireskop SD, Siemens, Munich, Germany or OEC 9900, General Electric, Fairfield, CT). Video was digitized and recorded onto a DVD+RW for offline analysis (DVO-1000MD, Sony, Park Ridge, NJ).

A solid-state high-resolution manometer with 36 sensors and outer diameter of 4 mm was used for manometry (ManoScan³⁶⁰ High Resolution Manometry System, Sierra Scientific Instruments, Los Angeles, CA). The catheter was covered with a protective sheath during testing (ManoShield, Sierra Scientific Instruments) and calibrated before each use according to manufacturer specifications. Data were collected at a sampling rate of 50 Hz (ManoScan Data Acquisition, Sierra Scientific Instruments).

Participants

Thirty subjects participated in this study with the approval of the University of Wisconsin-Madison Institutional Review Board. Subjects were comprised of nineteen males and eleven females, with a mean age of 68.0 ± 11.8 years (range: 40 – 87). Clinical descriptions are presented in figure 1.

Procedure

A small amount of topical 2% viscous lidocaine hydrochloride was applied to the nasal passages and catheter to provide local anesthesia and ease catheter insertion. Participants were seated upright within the videofluoroscopic unit for the entire procedure. Boundaries for the videofluoroscopic frame included the incisors anteriorly, cervical vertebrae posteriorly, nasal border of the soft palate superiorly, and cervical esophagus inferiorly. Correct catheter placement was verified on videofluoroscopy. Once the catheter was in place, participants rested for 5–10 minutes to adjust to the catheter before performing experimental swallows.

Participants swallowed between 2 and 30 total boluses of 5 ml, 10 ml, and self-selected amounts of thin-liquid, nectar-thick liquid, honey-thick liquid, or pudding barium sulfate (Varibar, E-Z-EM, Lake Success, NY) based on their ability to safely tolerate those consistencies, as judged by a certified speech-language pathologist. All swallows were performed with the head in a neutral position. Pre-measured boluses were given via syringe and self-selected sips were taken via straw. A straw was used for self-selected sip trials, as it was difficult to drink from a cup without a straw while the catheter was in place. Participants were instructed to hold the bolus in the mouth until cued to swallow by the experimenter.

Data analysis

Videofluoroscopic swallowing data were scored on an adapted version of the MBSImP.² Eight components (table 1) were chosen for this study based on their potential to relate to changes in pressure measured by pharyngeal HRM. Each swallow was also scored using the Penetration-Aspiration Scale¹⁶ (1: no airway invasion; 2–5: penetration; 6–8: aspiration). Each swallow was rated separately by two trained undergraduate research assistants. Disagreements in scores were resolved by a third rater (CAJ), a licensed and certified speech-language pathologist who has completed MBSImP training (Northern Speech Services, Gaylord MI) and also trained the two research assistants on videofluoroscopy analysis.

Data were extracted using a customized MATLAB program (The MathWorks, Inc., Natick, MA). Five regions of interest are identified for each swallow, three which are identified by the user and two which are identified automatically. The five regions are the velopharynx, mesopharynx, upper esophageal sphincter (UES), pre-opening UES pressure peak, and post-closure UES pressure peak. Regions are defined manometrically and described in detail in McCulloch et al.¹⁷ The user selects regions roughly corresponding to the velopharynx, pre-UES opening pressure peak, and post-closure UES pressure peak. Local pressure extrema in the surrounding area are then identified by the program. A box encompassing the region of interest based on predetermined temporal and spatial constraints is generated, and can be

altered by the user if necessary. The mesopharynx and UES are identified automatically by the program based on previous manual region selections. A sample of the user interface is provided in figure 2.

The box corresponding to the velopharynx has a duration of 1 second (shorter duration of actual pressure activity does not adversely affect measurements). The mesopharynx consists of all sensors between the velopharynx and post-closure UES pressure peak and is identified automatically following user identification of those two regions. Duration of pressure events in the mesopharynx is automatically determined by the program using a 2-second test window and a 2-second background window. The mean and standard deviation of the background noise are calculated in the background window and the mesopharynx is defined as the area with pressure higher than background. The starting and ending time are the first and last points with pressure above baseline. The pre-opening UES pressure peak is identified by the user and represents the maximum pressure occurring in the UES prior to relaxation. This region spans three sensors with duration of 0.5 seconds. The post-closure UES pressure peak is the last user-identified region and represents the maximum UES pressure during closure; the spatial boundary is variable depending on the trial and subject pharynx length, and extends from the point of maximum pressure (selected by user) to the inferior boundary of the pre-opening UES pressure peak region. It has a duration of 1 second. The last region is the UES during relaxation, with temporal constraints of the pre-opening and post-closure pressure peaks, and spatial constraints of the superior-most UES-related sensor and the pre-opening UES pressure peak. This region is identified automatically.

Several parameters are calculated for each region. Maximum pressure, rise time, rise rate, fall time, and duration of pressure above baseline are calculated for the velopharynx and mesopharynx. For the pre-opening and post-closure UES pressure peak regions, maximum pressure is calculated; for the UES, minimum pressure, activity time (duration between pre-opening and post-closure peaks), and nadir pressure duration (bolus passage time) are calculated. Total swallow duration is calculated and defined as the time lapse between onset of velopharyngeal pressure and the postswallow UES pressure peak. For all five regions, two- (total pressure generated in region of one sensor corresponding to maximum pressure in that region) and three-dimensional integrals (defined as the total pressure generated in the entire area spanning all sensors) are also calculated.

Data processing

Artificial neural network (ANN) analysis using MATLAB and the Neural Network Toolbox (The MathWorks, Inc.) was performed to determine if HRM data alone could be used to identify the abnormalities identified using the MBSImP.

In total, 335 swallows from 30 subjects were analyzed. By attaching the classification status of a swallow (i.e., if that swallow exhibits a given abnormality) to the corresponding data, machine learning techniques can be applied to model the relationship between the manometric variables and swallow status. Known swallows (both classification and data are provided) are presented during a training stage and unknown swallows (only data are provided) are presented during a testing stage. Training and testing data are kept separate to increase generalizability of the classification algorithm.

Data were randomly partitioned into a training set (60%), a testing set (20%), and a validation set (20%). A Multi-Layer Perceptron ANN was created using sigmoidal activation functions in one hidden layer, with number of hidden nodes varied from ten to one-half of the total number of samples included to achieve optimal performance. Twenty

replicates were performed at each number of hidden nodes to determine classification accuracy and reliability.

Twelve classifications were performed (table 2). Each classification analysis included equal numbers of samples in each group (normal and disordered). For the class which had more samples in the entire dataset, the samples included in each analysis were varied so that all were included at some point, but each classification was performed with balanced groups. This ensures that the probability of accurately classifying samples by chance is always 50%.

Statistical analysis

Category-specific (i.e., normal or disordered) as well as total classification accuracy for each scheme were determined. Receiver operating characteristic (ROC) analysis was performed to yield ROC curves and area under the curve (AUC) for each category.

RESULTS

A summary of the data used as inputs to the ANN is presented in table 3 (online appendix). Total classification accuracy for individual MBSImP parameters ranged from $86.5 \pm 6.2\%$ for pharyngeal swallow initiation to $94.0 \pm 2.4\%$ for anterior hyoid excursion (table 4). ROC analysis yielded AUC values ranging from 0.902 for pharyngeal swallow initiation to 0.981 for anterior hyoid excursion and pharyngeal residue (table 4, figure 3).

Classifications using a subset of the dataset and incorporating two MBSImP parameters yielded classification accuracies of $91.6 \pm 8.4\%$ (AUC=0.963) when evaluating tongue base retraction in the presence of abnormal PES opening, $92.6 \pm 4.2\%$ (AUC=0.971) when evaluating PES opening in the presence of abnormal hyoid excursion, and $95.2 \pm 1.7\%$ (AUC=0.989) when evaluating hyoid excursion in the presence of delayed pharyngeal swallow initiation (table 4, figure 4).

DISCUSSION

Pattern recognition was applied to classify swallows from patients with dysphagia according to parameters in the MBSImP. The MBSImP was presented as a standardized method of analyzing videofluoroscopy, a valuable and frequently used assessment but one that can lack inter-rater reliability.¹⁸ While videofluoroscopy utility is not disputed, it exposes subjects to radiation and is not ideally suited to serial measurements tracking patient progress over time. An HRM exam, however, is quick, does not require radiation exposure, and can be performed at the bedside. There is certainly potential for increased subject discomfort in the short-term due to presence of the catheter, but this is preferable compared to long-term concerns of increased risk for malignancy.

This is the first study using pharyngeal HRM to identify specific abnormalities visible on videofluoroscopy beyond penetration or aspiration. Differences in classification accuracy were somewhat predictable across parameters. Parameters which do not have an obvious manometric correlate, such as pharyngeal swallow initiation and penetration-aspiration, had the lowest scores. Notably, these parameters were still classified with greater than 80% accuracy and had AUC values greater than 0.9. These results demonstrate the value of multiparameter assessment combined with ANN-based pattern recognition. Provided there are many parameters and a large pool of samples, one can employ machine learning techniques to recognize and classify a wide variety of phenomena. As shown in table 3, numerous parameters can be extracted from HRM spatiotemporal plots. Manual interpretation of all these data would be challenging in a research setting, let alone a clinical setting. Classification using pattern recognition, though, can be done in seconds and

represents a more feasible method of analyzing the large amounts of data produced by HRM.

Events with direct manometric links displayed predictably high classification rates and AUC values. Abnormalities in PES opening are well-suited to examination with manometry^{19,20} and normal opening is easily identified on the HRM spatiotemporal plot as a decrease in pressure at the UES to or below atmospheric pressure. Accordingly, this parameter was classified correctly nearly 93% of the time and had an AUC value of 0.945. Additionally, the pharyngeal stripping wave can be identified as a traveling pressure wave on the HRM plot. This parameter was classified correctly at a rate of 94.0% with an AUC value of 0.971.

While the results of this investigation are encouraging, additional studies are warranted to further assess the value of HRM in identifying clinically relevant swallow abnormalities which are currently evaluated using videofluoroscopy. Importantly, we reduced all parameters to a binary classification scheme (i.e., normal or disordered; table 2). While this scheme is suitable for identifying persons exhibiting a given abnormality, it does not yield insight into the severity of that finding. Machine learning techniques tend to produce better results when provided with more examples from each class of interest. Further subdividing our sample of 335 swallows according to severity would have led to rather small sizes for each group which would likely lead to lower classification rates. As more data are collected and classification algorithms are refined, more precise severity-based classifications will be feasible. Secondly, the classification accuracy of 84.2% observed for penetration-aspiration was based on a binary classification scheme (normal versus penetration+aspiration) and was lower than our previously reported value of 89.4% obtained using a ternary scheme (normal versus penetration versus aspiration).¹³ This disparity may be due to the absence of impedance measurement, which is useful for detecting bolus residue.⁶ Future studies using combined HRM-impedance to identify abnormalities observed on videofluoroscopy may produce even stronger correlations than those observed here. Lastly, only a subset of the MBSImP components was evaluated. While the data collection protocol used in this study would not allow for measurement of oral or esophageal pressure, it could be modified to do so. This will be a focus of additional experiments.

In addition to identifying single MBSImP parameters, we performed three classifications driven by clinical scenarios. The first classified subjects according to anterior hyoid excursion given the presence of delayed pharyngeal swallow initiation. Martin-Harris et al. performed a videofluoroscopic study of normal subjects across a wide age range and found that entry of the bolus into the pharynx prior to hyoid movement alone was not sufficient to cause a swallowing abnormality.²¹ If normal hyoid excursion is preserved, it may allow for normal UES opening and consequent bolus passage without risk of penetration or aspiration. This analysis produced a classification accuracy of 92.6%; such a method could be used to determine if patients with a delayed swallow are at risk for dysphagia or if it is merely a normal variant.

The second scenario evaluated base of tongue retraction given the presence of abnormal PES opening. The tongue plays a critical role in bolus propulsion²² and tongue strengthening exercises can be of benefit in improving swallowing function;²³ however, UES function and tongue strength must be considered before recommending exercise to a patient. When bolus transit is impaired, strengthening exercises may be less helpful for those in whom the primary problem is increased resistance at the bolus head (i.e., inability to relax the cricopharyngeus) rather than decreased propulsive force at the bolus tail. In this group, botulinum toxin injection²⁴ or cricopharyngeal myotomy²⁵ may produce a better outcome. Our analysis yielded a classification accuracy of 91.6%, indicating the potential of HRM to separate these two groups.

Lastly, we evaluated PES opening given abnormal hyoid excursion to determine if decreased hyoid excursion impaired PES opening and is thus the likely etiology of dysphagia, or if PES opening is preserved. For patients with impaired PES opening, exercises such as the Shaker exercise²⁶ could alleviate the swallowing problem. In patients with preserved PES opening, exercises may be less helpful. The importance of hyoid excursion in UES opening is well-documented^{27,28} and impaired hyoid excursion can lead to aspiration.^{29,30} However, additional factors such as cricopharyngeal tonicity and UES compliance are also relevant. Interestingly, of the 213 swallows in our dataset exhibiting disordered hyoid excursion, 135 had normal PES opening. A total classification accuracy of 92.6% was achieved in this scheme, demonstrating the ability to stratify this group of subjects.

As additional data are incorporated into the machine learning process, classification accuracy can be expected to increase. While values reported in this study were fairly high, none achieved 100% agreement with videofluoroscopy. Modifications to both data collection and analysis to incorporate more structures and variables in the analysis will be explored, with the ultimate goal of creating a data analysis platform which can be used by clinicians to identify swallow impairments with the same accuracy as videofluoroscopy.

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Figure 1.

Etiologies of dysphagia. “Other” includes recurrent hiatal hernia, idiopathic muscular atrophy, Schatzki’s ring, post-myocardial infarction, and Hodgkin’s lymphoma. CP = cricopharyngeus; Zenker’s = Zenker’s diverticulum; HNC = head and neck cancer.

Figure 2.

User interface display for one swallow. A = velopharynx; B = mesopharynx; C = pre-upper esophageal sphincter (UES) opening pressure peak; D = UES opening; E = UES post-closure pressure peak.

Figure 3. Receiver operating characteristic (ROC) curves for single Modified Barium Swallow Impairment Profile parameter classifications. Area under the curve (AUC) varied from 0.902 (pharyngeal swallow initiation) to 0.981 (pharyngeal residue).

Figure 4.

Receiver operating characteristic (ROC) curves for penetration-aspiration scale and two-parameter classifications. Area under the curve (AUC) varied from 0.911 (penetration-aspiration scale) to 0.989 (anterior hyoid excursion given presence of delayed pharyngeal swallow initiation).

Table 1

Adapted version of the Modified Barium Swallow Impairment Profile.

Component Number	Description	Score Range
6	Initiation of Pharyngeal Swallow	0–4
8	Laryngeal Elevation	0–3
9	Anterior Hyoid Excursion	0–2
10	Epiglottic Movement	0–2
12	Pharyngeal Stripping Wave	0–2
14	Pharyngoesophageal Segment Closing	0–3
15	Tongue Base Retraction	0–4
16	Pharyngeal Residue	0–4

Table 2

Classification schemes.

Data included	Parameter	NORMAL		DISORDERED	
		MBSImP score	n	MBSImP score	n
All data included	Pharyngeal swallow initiation	0	132	1-4	203
All data included	Laryngeal elevation	0	202	1-3	133
All data included	Anterior hyoid excursion	0	122	1-2	213
All data included	Epiglottic movement	0	193	1-2	132
All data included	Pharyngeal stripping wave	0	167	1-2	168
All data included	PES opening	0-1	249	2-3	86
All data included	Tongue base retraction	0-1	173	2-3	162
All data included	Pharyngeal residue	0-1	101	2-4	234
All data included	Penetration-aspiration scale	1	171	2-8	164
Abnormal initiation	Anterior hyoid excursion	0	92	1-2	111
Abnormal PES opening	Tongue base retraction	0-1	26	2-3	60
Abnormal hyoid excursion	PES opening	0-1	135	2-3	78

MBSImP = modified barium swallow impairment profile; n = number of swallows in dataset; PES = pharyngoesophageal segment. Classes (normal and disordered) were balanced in each analysis; thus, there was no potential for biased classification results based on unequal sample sizes.

Table 3

Summary data separated according to MBSImp parameter.

Parameter	Swallow initiation		Laryngeal elevation		Hyoid excursion		Epiglottic movement		Stripping wave		PES opening		BOT retraction		Pharyngeal residue	
	N	D	N	D	N	D	N	D	N	D	N	D	N	D	N	D
<i>Velopharynx</i>																
Duration (s)	0.78±0.21	0.83±0.20	0.82±0.19	0.78±0.23	0.84±0.20	0.79±0.21	0.83±0.16	0.76±0.25	0.79±0.22	0.82±0.20	0.79±0.21	0.85±0.18	0.85±0.16	0.76±0.24	0.85±0.15	0.79±0.23
Rise time (s)	0.31±0.18	0.37±0.18	0.36±0.17	0.36±0.21	0.37±0.15	0.35±0.20	0.35±0.16	0.36±0.21	0.35±0.17	0.37±0.19	0.35±0.17	0.39±0.22	0.38±0.16	0.33±0.20	0.38±0.15	0.35±0.20
Rise rate (mmHg/s)	629±597	535±531	473±416	722±700	478±506	625±582	513±426	675±713	626±656	517±439	599±588	492±459	508±563	640±549	438±409	629±604
Fall time (s)	0.47±0.18	0.44±0.17	0.46±0.17	0.43±0.17	0.47±0.19	0.44±0.16	0.48±0.16	0.40±0.17	0.44±0.19	0.46±0.15	0.45±0.18	0.45±0.15	0.47±0.17	0.43±0.17	0.47±0.18	0.44±0.17
Max pressure (mmHg)	126±38	148±39	130±38	154±38	133±42	143±38	138±46	141±31	146±44	133±34	142±41	131±35	140±44	138±35	135±48	141±36
2D integral (mmHg*s)	55±28	74±31	61±29	75±32	62±28	69±32	63±30	70±31	66±29	67±33	64±28	75±36	68±29	64±33	63±29	68±32
3D integral (mmHg*s)	97±46	132±51	114±53	125±50	120±53	117±51	117±54	118±49	119±49	117±55	114±50	129±56	124±50	111±53	115±52	119±52
<i>Mesopharynx</i>																
Duration (s)	0.83±0.31	0.79±0.35	0.81±0.34	0.79±0.32	0.75±0.37	0.84±0.31	0.84±0.32	0.74±0.34	0.77±0.36	0.84±0.30	0.78±0.34	0.88±0.31	0.85±0.33	0.75±0.33	0.88±0.30	0.77±0.34
Rise time (s)	0.41±0.23	0.43±0.23	0.42±0.23	0.42±0.23	0.43±0.22	0.41±0.24	0.42±0.23	0.40±0.23	0.45±0.23	0.39±0.23	0.42±0.23	0.41±0.25	0.47±0.20	0.36±0.25	0.50±0.18	0.39±0.24
Rise rate (mmHg/s)	579±1861	806±4605	476±599	1081±5929	484±695	850±4695	777±4711	672±1909	437±550	994±5286	798±4360	480±499	382±437	1074±5385	289±203	901±4497
Fall time (s)	0.42±0.24	0.36±0.23	0.39±0.23	0.37±0.23	0.32±0.21	0.42±0.24	0.41±0.24	0.35±0.21	0.33±0.21	0.44±0.24	0.36±0.23	0.47±0.21	0.38±0.21	0.39±0.25	0.38±0.20	0.39±0.24
Max pressure (mmHg)	122±85	125±65	117±49	135±98	112±40	131±86	126±71	124±78	118±29	130±99	124±76	124±65	128±49	120±92	113±31	129±85
2D integral (mmHg*s)	50±64	50±90	43±27	60±123	36±16	58±100	52±94	46±59	40±18	60±112	48±91	54±35	48±29	52±112	42±18	53±96
3D integral (mmHg*s)	123±122	124±115	117±92	134±148	96±38	140±142	131±138	116±84	108±41	140±160	119±115	138±125	140±97	106±135	112±45	129±138
<i>Pre UES</i>																
Max pressure (mmHg)	91±41	105±127	99±127	100±45	117±159	89±43	93±46	106±153	94±44	105±138	108±115	76±42	99±45	101±140	103±49	98±118
2D integral (mmHg*s)	22±16	31±62	26±63	29±15	34±79	24±16	23±14	33±77	26±14	29±69	31±57	18±12	25±13	30±70	28±14	27±59
3D integral (mmHg*s)	48±32	61±68	53±68	60±32	66±82	50±33	50±30	62±81	55±28	56±75	62±62	37±28	53±28	59±76	60±32	54±64
<i>Post UES</i>																
Max pressure (mmHg)	145±71	183±128	171±133	164±61	210±152	144±66	165±70	169±154	191±61	146±140	184±118	121±65	186±56	149±146	193±57	157±125
2D integral (mmHg*s)	57±40	74±87	65±89	70±35	85±108	57±37	59±39	77±104	73±40	61±94	75±80	44±35	70±36	65±97	70±35	66±84
3D integral (mmHg*s)	216±131	264±151	235±156	260±126	298±149	214±134	244±124	231±166	294±107	196±161	277±137	151±127	283±104	205±170	292±92	224±159
<i>UES</i>																
Min pressure (mmHg)	-7±20	0±12	-3±17	-3±14	3±11	-7±17	-4±18	-2±12	-2±15	-4±17	-2±14	-5±21	-6±20	-1±10	-1±16	-4±16
Activity time (s)	0.90±0.32	0.94±0.39	0.87±0.36	1.00±0.36	0.93±0.37	0.92±0.36	0.90±0.36	0.94±0.37	0.99±0.39	0.86±0.32	0.96±0.36	0.80±0.35	0.92±0.36	0.93±0.37	1.01±0.40	0.89±0.34
Nadir duration (s)	0.45±0.22	0.48±0.27	0.46±0.23	0.47±0.27	0.51±0.20	0.44±0.27	0.46±0.23	0.48±0.28	0.49±0.24	0.44±0.26	0.48±0.23	0.42±0.29	0.48±0.23	0.45±0.27	0.51±0.21	0.44±0.26
2D integral (mmHg*s)	34±29	47±161	42±162	42±27	57±206	33±29	29±24	61±198	35±26	48±177	47±146	27±27	33±24	51±180	33±22	46±151
3D integral (mmHg*s)	75±64	90±170	78±170	94±63	102±212	74±64	65±55	109±207	81±61	87±185	94±155	56±61	74±53	95±190	78±59	87±161

Parameter	Swallow initiation		Laryngeal elevation		Hyoid excursion		Epiglottic movement		Stripping wave		PES opening		BOT retraction		Pharyngeal residue	
	N	D	N	D	N	D	N	D	N	D	N	D	N	D	N	D
Swallow duration (s)	0.99±0.29	0.99±0.27	0.97±0.26	1.03±0.31	1.01±0.24	0.98±0.30	0.96±0.23	1.01±0.32	0.99±0.27	0.99±0.29	1.00±0.26	0.96±0.32	0.99±0.27	0.99±0.29	1.01±0.24	0.98±0.29

All data (335 swallows) are included for each parameter, and values are presented as mean±standard deviation. Manual interpretation of this amount of data would be challenging and is facilitated by the use of pattern recognition. N = normal; D = disordered. (*Note: this should only appear as an online appendix.*)

Table 4

Classification accuracies for each analysis.

Classification	Nodes	Normal	Disordered	Total	AUC
Pharyngeal swallow initiation	110	88.5±5.1	84.4±10.3	86.5±6.2	0.902
Laryngeal elevation	120	89.2±8.7	90.4±4.0	89.8±5.2	0.944
Anterior hyoid excursion	110	93.2±4.8	94.9±2.4	94.0±2.4	0.981
Epiglottic movement	120	92.0±3.4	93.0±3.6	92.5±2.5	0.956
Pharyngeal stripping wave	50	92.9±4.5	95.1±2.1	94.0±2.5	0.971
PES opening	50	94.4±3.6	91.2±6.8	92.8±4.0	0.945
Tongue base retraction	130	90.2±3.4	89.4±4.7	89.8±3.4	0.963
Pharyngeal residue	70	92.7±2.6	92.3±3.6	92.5±2.5	0.981
Penetration-aspiration scale	160	84.2±5.9	84.1±5.2	84.2±4.1	0.911
Anterior hyoid excursion with delayed initiation	60	94.3±3.0	96.1±2.2	95.2±1.7	0.989
Tongue base retraction with abnormal PES opening	15	93.3±7.8	90.0±11.5	91.6±8.4	0.963
PES opening with abnormal hyoid excursion	79	93.5±3.5	91.8±6.1	92.6±4.2	0.971