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Three-dimensional analysis of pharyngeal high-resolution manometry data

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Abstract

Objective—High-resolution manometry (HRM) represents a critical advance in the quantification of swallow-related pressure events in the pharynx. Previous analyses of the pressures measured by HRM, though, have been largely two-dimensional, focusing on a single sensor in a given region. We present a method a three-dimensional approach which combines information from adjacent sensors in a region. Two- and three-dimensional approaches were compared for their ability to classify data correctly as normal or disordered.

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

Methods—1,324 total swallows from 16 normal subjects and 61 subjects with dysphagia were included. Two-dimensional single sensor integrals of the area under the curves created by rises in pressure in the velopharynx, tongue base, and UES were calculated. Three-dimensional multi-sensor integrals of the volume under all curves corresponding to the same regions were also computed. The two sets of measurements were compared for their ability to classify data correctly as normal or disordered using an artificial neural network (ANN).

Results—Three-dimensional parameters yielded a maximal classification accuracy of $86.71 \pm 1.47\%$, while two-dimensional parameters achieved a maximum accuracy of $83.36 \pm 1.42\%$. When combining two- and three-dimensional parameters with all other variables, including three-dimensional parameters yielded a classification accuracy of $96.99 \pm 0.51\%$, and including 2-dimensional parameters yielded a classification accuracy of $96.32 \pm 1.05\%$.

Conclusion—Three-dimensional analysis led to improved classification of swallows based on pharyngeal HRM. Artificial neural network performance with both two-dimensional and three-dimensional analyses was effective, classifying a large percentage of swallows correctly, thus demonstrating its potential clinical utility.

Keywords

high-resolution manometry; swallowing; pharynx; dysphagia

INTRODUCTION

Traditional measurement of pharyngeal pressures during swallowing used manometric catheters containing 3–5 unidirectional sensors spanning the upper esophageal sphincter.^{1–3}

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While early manometric studies provided valuable information on UES function during swallowing, technological limitations precluded the creation of a comprehensive pressure pattern spanning the entire pharynx. Additionally, problems were encountered with measurement accuracy as the UES moves rostrally 2–3 cm during the swallow.¹ More detailed information on the pressures which drive bolus transport through the asymmetric pharynx was desirable.

The application of high-resolution manometry (HRM) to study the pharyngeal swallow represents a key advance in the investigation of normal and disordered swallowing physiology. While HRM had previously been used in the esophagus,⁴ it is perhaps better suited to the pharynx due to the comparative complexity of pharyngeal pressure patterns. The pharyngeal swallow is a complex neuromuscular event requiring precise coordination of muscular contractions to generate pressure gradients which drive bolus passage from the mouth to esophagus.^{5–7} The asymmetric structure of the pharynx and intricate skeletal muscle contractions preclude accurate assessment with traditional manometric technology.⁸ HRM uses 25–36 circumferential sensors which span the entire length of the pharynx, allowing for accurate quantification of pressure patterns created during swallowing.

Since its initial application to normal swallowing,⁸ pharyngeal HRM has been applied to investigate the influence of posture,⁹ maneuvers,^{10–11} and bolus volume¹² on swallowing physiology. Recently, HRM was also applied to quantify the effects of cricopharyngeal myotomy on a patient with amyotrophic lateral sclerosis.¹³ As pharyngeal HRM is further developed and applied clinically, it is important to develop simple and effective methods of analyzing the great deal of information provided by this technology.

We presented a method of performing automated analysis of pharyngeal HRM data and found that it could reliably analyze data from both normal and disordered subjects.¹⁴ Importantly, more complex analyses also allow for measurement of new parameters, such as line and area integrals. While adding these new parameters resulted in higher rates of correctly classifying swallows as normal or disordered,¹⁵ measurements were still primarily based on single sensor recordings and did not take full advantage of the spatial resolution offered by HRM. These measurements can be thought of as two-dimensional, based on the dimensions of time and pressure.

In this study, we present a new method of analyzing pressure and timing data recorded by pharyngeal HRM. Use of this new program requires only three mouse clicks by the user and provides data on the three-dimensional characteristics of the pressure patterns created in the velopharynx, hypopharynx, and upper esophageal sphincter (UES). By including data from all sensors in a region rather than just a single sensor, the third dimension of space is added to the original two dimensions of time and pressure. We applied this new method to a large set of normal and disordered swallows and hypothesized that inclusion of three-dimensional parameters would result in superior classification rates compared to those offered by two-dimensional parameters.

MATERIALS AND METHODS

Data collection

Equipment—A solid-state high resolution manometer was used for all data collection (ManoScan³⁶⁰ High Resolution Manometry System, Sierra Scientific Instruments, Los Angeles, CA). The manometric catheter has an outer diameter of 4 mm and 36 circumferential pressure sensors spaced 1 cm apart. The system records pressures between –20 and 600 mmHg with fidelity of 2 mmHg. Data were collected at a sampling rate of 50 Hz (ManoScan Data Acquisition, Sierra Scientific Instruments). Prior to calibration, the

catheter was covered with a protective sheath to preserve sterility without the need to sterilize the catheter between uses (ManoShield, Sierra Scientific Instruments). The catheter was calibrated before each participant according to manufacturer specifications.

Participants—Seventy-seven subjects participated in this study with the approval of the Institutional Review Board of the University of Wisconsin-Madison. Sixteen subjects were without swallowing, neurological, or gastrointestinal disorders, while sixty-one had a swallowing disorder. Disordered subjects reported at least one symptom of dysphagia, such as diet change, food sticking, cough with eating, or globus sensation. Additionally, subjects displayed abnormalities on either fiberoptic endoscopic evaluation of swallowing (FEES) or modified barium swallow study (MBSS), as determined by their medical history. Clinical descriptions of the disordered subjects are presented in figure 1.

Procedure—A small amount of topical 2% viscous lidocaine was applied to the nasal passages with a cotton swab. The manometric catheter was lubricated with a minimal amount of 2% viscous lidocaine to ease passage of the catheter through the pharynx. Passage of the catheter in disordered subjects was guided by endoscopy or videofluorography. Once the catheter was positioned within the pharynx, participants rested for 5–10 minutes to adjust to the catheter prior to performing the experimental swallows. While swallowing is a sensorimotor action and could potentially be affected by the use of topical anesthetic, omitting anesthetic in early pilot trials led to increased gagging and coughing as well as elevated baseline UES pressure. Additionally, mechanoreceptors deep to the mucosa were likely not affected by the anesthetic. The added comfort provided by topical anesthetic may result in an experimental swallow which is more similar to the subject's natural swallow than would otherwise be obtained in an uncomfortable subject.

Subjects swallowed a variety of bolus sizes and consistencies. Bolus size ranged from 1 cc (saliva) to 20 cc. Consistencies included liquid (water) and semi-solid (pudding). Liquid boluses were delivered to the oral cavity via syringe, while semi-solid boluses were delivered to the oral cavity via spoon. All swallows were performed with the head in a neutral position. A total of 1324 swallows were analyzed; this included 662 for normal subjects and 662 for disordered subjects.

Data analysis

Variables of interest—Total pressure generated was calculated for each sensor corresponding to the velopharynx and tongue base. Total pressure generated was also calculated for the UES at two time points: the period immediately preceding opening and the period immediately following closure. Two types of analysis were employed to analyze these calculations. Two-dimensional analysis was performed to determine the integral, or area under the curve, for the sensor in each region that recorded the maximum pressure achieved in the region. A novel three-dimensional analysis was also performed to determine the total pressure generated in the region, including pressures recorded by all sensors located within each region.

Automated data extraction—Data were extracted using a customized MATLAB program (The MathWorks, Inc., Natick, MA). Pattern segmentation is based on the selection of regions, rather than selection of individual sensors within a region, and parameters are then calculated based on the data in the region (3-dimensional parameters).

After loading a data file, two-dimensional plot and three-dimensional contours are presented. Five regions of interest are identified for each swallow, three of which are identified by the user and two of which are identified automatically. The five regions of

interest are the velopharynx, hypopharynx, upper esophageal sphincter (UES), pre-UES opening pressure peak, and post-closure UES pressure peak. The user clicks on 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 modified by the user if so desired. The hypopharynx and UES are identified automatically by the program based on previous region selections by the user. If more than one swallow occurred in quick succession, only the first swallow was analyzed. A sample of the user interface is provided in figure 2.

Regions of interest were defined manometrically using a method similar to that described by McCulloch et al.¹⁰ The velopharynx is the region of swallow-related pressure change just proximal to the area of continuous nasal cavity quiescence and extending 2 cm distally. The user selects the superior boundary of this region; the nearest sensor and one sensor below that are defined as sensors corresponding to the velopharynx. The box corresponding to this region has a duration of 1 second (duration meant only to ensure all data are recorded, and does not adversely affect temporal or manometric measurements). The hypopharynx is the region of swallow-related pressure change between the velopharynx and UES. It is defined in the program as consisting of all sensors between the velopharynx and the post-closure UES pressure peak; this region is identified automatically by the program. The duration of pressure events in the hypopharynx is automatically detected by the program. A 'test window' with duration of 2 seconds is selected first, followed by a 'background window,' also with duration of 2 seconds. The mean and standard deviation of the background noise are calculated in background window. The hypopharynx region is defined as the continuous area with pressure higher than background. The starting and ending time are the first and last points which are 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 encompasses three sensors and has a duration of 0.5 seconds. The post-closure UES pressure peak is the last region identified by the user and represents the maximum pressure achieved in the UES during closure. This region encompasses a variable number of sensors depending on the individual trial as well as subject pharynx length, and is defined spatially as extending 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 of interest is the UES during sphincteric relaxation, and is defined temporally as the region between the pre-opening and post-closure pressure peaks, with spatial constraints of the superior-most UES-related sensor and the inferior boundary of the pre-opening UES pressure peak. This region is identified automatically by the program.

Several parameters are calculated for each region. Maximum pressure, rise time, fall time, duration of pressure above baseline, and rise rate are calculated for the velopharynx and hypopharynx. Temporal information is calculated using the aforementioned background baseline method. For the pre-opening and post-closure UES pressure peak regions, the maximum pressure and the time it occurs are calculated; for the UES region, the minimum pressure, onset time, UES activity time, and nadir pressure duration (bolus passage time) are calculated. In the calculation of nadir pressure duration, all sensors in the UES are first combined and then the second-order derivative is used to find the onset and offset times of the nadir. Total swallow duration is also calculated which is defined as the time lapse between onset of velopharyngeal pressure and the postswallow UES pressure peak.

For all five regions, two-dimensional pressure integrals (defined as the area under the curve of a single sensor in the region which included the highest recorded pressure) and three-dimensional integrals (defined as the total pressure generated in the entire area spanning all sensors) were calculated.

Data Processing—Artificial neural network (ANN) analysis was performed to determine the classifying ability of individual two- and three-dimensional parameters, two- and three-dimensional parameter sets, as well as two- and three-dimensional parameters in conjunction with all other parameters of interest. ANNs are mathematical models which can classify large amounts of data into groups based on nonlinear statistical analysis.¹⁶

All data processing was completed using MATLAB and the Neural Network Toolbox (The MathWorks, Inc.). In total, 1324 swallows were analyzed and the derived feature sets were used as a basis for determining models of safe swallow, penetration, and aspiration. Of the 1324 swallows, 662 were normal and 662 were disordered. Equal numbers of swallows from each group were included to ensure each swallow had a 50% chance probability of being classified correctly. By attaching the known status of a swallow to its feature vector, machine learning techniques can be applied with the goal of modeling the relationship between the input features and the status of a given swallow. The ANN is first presented with the known data, goes through a training stage, and finally is presented with new data during a test stage. The training and testing data are kept separate to better evaluate the generalizing ability of the classification. Which swallows are used in the training set and testing set changes so all data are used in the test stage at some point. This ensures that the analytic capabilities of the algorithm are not limited to only a select group of swallows.

Data were normalized and each variable in the data set ranged in value from -1 to 1, with a mean of 0 and a standard deviation of 1. Normalizing the data improves algorithm efficiency and accuracy.¹⁷ Additionally, principal component analysis was used to reduce dimensionality and improve generalization. The feature set underwent two levels of reduction, during which variables that contributed minimally to classification ability were removed. This was done because such variables can be detrimental to correct classification rates.

The data set was randomly partitioned into a training set (60%), a testing set (20%), and a validation set (20%). A Multi-Layer Perceptron ANN, the most commonly used ANN in medical applications,¹⁸ was employed. The number of nodes in the hidden layer was varied from 10 to 660 in increments of 10 to attain better performance. The maximum number of nodes evaluated was selected as it is approximately one-half of the total number of samples. Twenty replicates were performed at each number of hidden nodes to determine the average classification accuracy at that level as well as the reliability of that classification.

Statistical analysis

Classification accuracy for each category (normal, disordered) was determined for each set of parameters collectively (i.e., all 2-dimensional integrals or all 3-dimensional integrals) as well as each parameter individually. Receiver operating characteristic (ROC) analysis was performed to yield ROC curves and area under the curve (AUC) for each category. Statistical analysis (e.g., t-test, analysis of variance) was not performed due to the wide variety of disorders present in the disordered group. Different disorders are expected to influence manometric variables in different ways, with resulting large intra-group variability potentially concealing the diagnostic value of a given parameter.

RESULTS

Summary data from normal and disordered subjects are presented in table 1. When performing ANN analysis using either only all 2-dimensional parameters or only all 3-dimensional parameters as inputs, 3-dimensional parameters produced consistently higher classification accuracies (figure 3). A maximal total classification accuracy of $86.71 \pm 1.47\%$ was achieved with 3-dimensional parameters, while 2-dimensional parameters yielded a

maximum accuracy of $83.36 \pm 1.42\%$ (table 2). ROC analysis demonstrated an area under the curve (AUC) of 0.896 for two-dimensional and 0.922 for three-dimensional parameters (figure 4).

Individual parameter classification rates did not vary greatly across parameters, with most classifying approximately 65% of swallows correctly (table 2). The post-swallow UES pressure peak had the highest classification accuracy of $67.90 \pm 8.67\%$ for three-dimensional analysis, while the hypopharynx had the highest classification accuracy for two-dimensional analysis at $66.65 \pm 2.36\%$ (table 2).

When combining the 2-dimensional or 3-dimensional parameters with all other variables in the feature set, classification accuracy improved, but relative superiority of one or the other was less apparent (figure 5). Using 3-dimensional parameters in the feature set led to a maximal classification rate of $96.99 \pm 0.51\%$, and including 2-dimensional parameters led to a rate of $96.32 \pm 1.05\%$ (table 2). ROC analysis demonstrated an AUC of 0.987 for the feature set including two-dimensional parameters and 0.989 for the feature set including three-dimensional parameters (figure 6).

DISCUSSION

This study addresses several of the limitations present in previous studies using HRM to evaluate the pharyngeal swallow. First, a large sample of both normal and disordered subjects was included. Relevant to the ANN methodology employed and use of classification accuracy as an outcome measure, both groups were also represented equally. The total classification accuracy thus has a chance level of 50% and there is not potential for artificial inflation due to unbalanced classes. Second and most importantly, three-dimensional analysis truly takes advantage of the multi-sensor capabilities of HRM. While our previous studies used the multiple sensors included in HRM to our benefit by selecting the single sensor in each region of interest which captured the highest pressure achieved in that region, we did not use the information captured by the other sensors. The analysis presented here uses information from nearly every sensor obtained from the most rostral aspect of the velopharynx to the most caudal aspect of the UES.

Both two- and three-dimensional parameters led to high classification results, though three-dimensional parameters typically led to consistently higher classification accuracy. While the absolute increase observed (approximately 3%) is not extremely large, it does not require any additional effort on the part of the user to obtain it. Determining values for all 26 parameters analyzed requires only three mouse clicks. This is similar to the level of user intervention required in our previous method of analysis.¹⁴ The magnitude of the added benefit of three-dimensional parameters was less apparent when including all other parameters in the analysis, with the absolute increase less than 1%; however, values were still consistently higher. If applied on a large scale over time, a seemingly small increase of 1–3% could have an impact on the assessment of a significant number of patients. Additionally, more refined classification of subjects with dysphagia according to etiology may be facilitated by a more comprehensive analysis.

Selection of three points can be complicated by severely disordered swallows (figure 7), such as those with an absent velopharyngeal pressure (precluding user knowledge of superior extent of pharynx) or extremely low resting UES pressure (precluding accurate identification of pre- and post-swallow pressure peaks). This potential problem can be addressed using elementary knowledge of pharyngeal anatomy and manometric patterns. As the anatomic relationships among the structures do not change, the user knows where the velopharynx and UES are approximately located and can select those regions accordingly.

Importantly, any region exhibiting such an abnormality would only aid in the classification of a swallow as disordered, due to low values for both two- and three-dimensional pressure measurements. Future investigations will evaluate the ability of novice users to identify regions and perform analysis correctly for normal and disordered swallows.

Subjects swallowed a variety of bolus consistencies (liquid or semi-solid) and volumes (saliva, 5 cc, 10 cc, and 20 cc). While changes in bolus characteristics can affect pharyngeal pressure,^{12,19–20} this did not adversely affect our ability to classify swallows. Central to our method of classifying swallows is the application of pattern recognition, a means by which we can perform a global assessment of pressure-related characteristics. Maintaining a high classification rate regardless of bolus type is clinically relevant, as some patients may be able to swallow a given bolus more safely than another type. For example, patients with dysphagia due to glottic insufficiency may aspirate on thin liquids²¹ and patients with pharyngeal weakness may require a small bolus to avoid residue and aspiration.²² The effects of impaired glottic closure or pharyngeal weakness would still be evident on the HRM plot, but performing the assessment would not require compromising the subject's safety or management plan. Additionally, analysis which is not dependent on specific bolus characteristics is more generalizable across clinician, institution, and testing protocols.

Based on the results obtained from individual parameter analysis, UES-related parameters appeared to have accounted for the observed difference in three-dimensional versus two-dimensional classification rates. This is likely due to the inclusion of a relatively large number of patients with cricopharyngeal disorders. Utilizing multi-sensor three-dimensional analysis may also be more important in this region as the UES is mobile during swallowing.¹ Two-dimensional classification rates for the velopharynx and hypopharynx were generally higher across the various number of hidden nodes analyzed, though maximum classification accuracy observed was highest for three-dimensional in the hypopharynx and approximately equal for two- and three-dimensional analyses of the velopharynx. For pre- and post-swallow UES pressure peaks, classification accuracies were routinely higher for three-dimensional assessment, with maximum values being 2–3% higher relative to two-dimensional analysis.

A characteristic of artificial neural networks which makes them well-suited for application to HRM is that classification accuracy tends to improve as more parameters are included in the analysis. Improvements were seen in this study by including three-dimensional parameters; however, simply adding more information may also improve our ability to classify swallows based only on manometric characteristics.

CONCLUSION

A new method of analyzing pharyngeal HRM data is presented that better utilizes the measurement capabilities of HRM catheters. By combining multiple sensors in the same region for parameters of interest, improved classification of swallows as normal or disordered was achieved. Applying this method to classify disorders according to specific characteristics will be the subject of future research. This study adds to the evidence demonstrating the clinical utility of HRM for assessment of oropharyngeal dysphagia.

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References

1. Isberg A, Nilsson ME, Schiratzki H. The upper esophageal sphincter during normal deglutition. A simultaneous cineradiographic and manometric investigation. *Acta Radiol Diagn (Stockh)*. 1985; 26:563–568. [PubMed: 4072751]
2. Castell, JA.; Castell, DO.; Duranceau, CA.; Topart, P. Manometric characteristics of the pharynx, upper esophageal sphincter, esophagus, and lower esophageal sphincter in patients with oculopharyngeal muscular dystrophy.
3. Cerenko D, McConnel F, Jackson RT. Quantitative assessment of pharyngeal bolus driving forces. *Otolaryngol Head Neck Surg*. 1989; 100:57–63. [PubMed: 2493617]
4. Fox MR, Bredenoord AJ. Oesophageal high-resolution manometry: moving from research into clinical practice. *Gut*. 2008; 57:405–423. [PubMed: 17895358]
5. Kim SM, McCulloch TM, Rim K. Pharyngeal pressure analysis by the finite element method during liquid bolus swallow. *Ann Otol Rhinol Laryngol*. 2000; 109:585–589. [PubMed: 10855571]
6. McConnel FM. Analysis of pressure generation and bolus transit during pharyngeal swallowing. *Laryngoscope*. 1988; 98:71–78. [PubMed: 3336265]
7. Cook IJ. Normal and disordered swallowing: new insights. *Baillieres Clin Gastroenterol*. 1991; 5:245–267. [PubMed: 1912651]
8. Takasaki K, Umeki H, Enatsu K, Tanaka F, Sakihama N, Kumagami H, Takahashi H. Investigation of pharyngeal swallowing function using high-resolution manometry. *Laryngoscope*. 2008; 118:1729–1732. [PubMed: 18641532]
9. Takasaki K, Umeki H, Kumagami H, Takahashi H. Influence of head rotation on upper esophageal sphincter pressure evaluated by high-resolution manometry system. *Otolaryngol Head Neck Surg*. 142:214–217. [PubMed: 20115977]
10. McCulloch T, Hoffman MR, Ciucci MR. High resolution manometry of pharyngeal swallow pressure events associated with head turn and chin tuck. *Ann Otol Rhinol Laryngol*. 2010 Jun; 119(6):369–76. [PubMed: 20583734]
11. Umeki H, Takasaki K, Enatsu K, Tanaka F, Kumagami H, Takahashi H. Effects of a tongue-holding maneuver during swallowing evaluated by high-resolution manometry. *Otolaryngol Head Neck Surg*. 2009; 141:119–122. [PubMed: 19559970]
12. Hoffman MR, Ciucci MR, Mielens JD, Jiang JJ, McCulloch TM. Pharyngeal swallow adaptations to bolus volume measured with high resolution manometry. *Laryngoscope*. In press., 2010.3 auto.
13. Takasaki K, Umeki H, Enatsu K, Kumagami H, Takahashi H. Evaluation of swallowing pressure in a patient with amyotrophic lateral sclerosis before and after cricopharyngeal myotomy using high-resolution manometry system. *Auris Nasus Larynx*. 2010; 37:644–7. [PubMed: 20172669]
14. Mielens JD, Hoffman MR, Ciucci MR, Jiang JJ, McCulloch TM. Automated analysis of pharyngeal pressure data obtained with high-resolution manometry. *Dysphagia*. 2011 Mar; 26(1): 3–12. [PubMed: 21264672]
15. Mielens JD, Hoffman MR, Ciucci MR, McCulloch TM, Jiang JJ. Application of classification models to pharyngeal high-resolution manometry. *J Speech Lang Hear Res*. 2012 Jun; 55(3):892–902. [PubMed: 22232390]
16. Cross SS, Harrison RF, Kennedy RL. Introduction to neural networks. *The Lancet*. 1995 Oct 21; 346(8982):1075–9.
17. Saarinen S, Bramley R, Cybenko G. Ill-conditioning in neural network training problems. *SIAM Journal on Scientific Computing*. 1993; 14:693–714.
18. Bishop, CM. *Neural networks for pattern recognition*. Oxford: Oxford University Press; 1995.
19. Perlman AL, Schultz JG, VanDaele DJ. Effects of age, gender, bolus volume, and bolus viscosity on oropharyngeal pressure during swallowing. *J Appl Physiol*. 1993; 75:33–37. [PubMed: 8376283]
20. Butler SG, Stuart A, Castell D, Russell GB, Koch K, Kemp S. Effects of age, gender, bolus condition, viscosity, and volume on pharyngeal and upper esophageal sphincter pressure and temporal measurements during swallowing. *J Speech Lang Hear Res*. 2009; 52:240–253. [PubMed: 19064903]

21. Ekberg O, Lindgren S, Schultze T. Pharyngeal swallowing in patients with paresis of the recurrent nerve. *Acta Radiol Diagn (Stockh)*. 1986 Nov-Dec;27(6):697–700.
22. Logemann, JA. Therapy for oropharyngeal swallowing disorders. In: Perlman, Adrienne; Schulze-Delrieu, Konrad, editors. *Deglutition and Its Disorders: Anatomy, Physiology, Clinical Diagnosis, and Management*. Singular Publishing Group, Inc; San Diego, CA: 1997. p. 449-461.

Figure 1.

Summary characteristics of disordered group. HNC = head and neck cancer; CP = cricopharyngeal. The “other” group includes subjects with the following disorders: cervical web, esophageal dysmotility, recurrent hiatal hernia, idiopathic muscle atrophy, and Schatzki’s ring.

Figure 2. Display of user interface portraying normal swallow. A = velopharynx; B = hypopharynx; C = pre-upper esophageal sphincter (UES) opening pressure peak; D = UES opening; E = UES post-closure pressure peak.

Figure 3. Classification accuracies for analyses including all two- or three-dimensional parameters over various levels of hidden nodes.

Figure 4. Receiver operating characteristic (ROC) curves for analyses including all two-dimensional (left) or three-dimensional (right) parameters. Area under the curve (AUC) is 0.896 for two-dimensional and 0.922 for three-dimensional parameters.

Figure 5. Classification accuracies for analyses including two- or three-dimensional parameters as well as all other parameters in the feature set over the various levels of hidden nodes.

Figure 6.

Receiver operating characteristic (ROC) curves for analyses including two-dimensional (left) or three-dimensional (right) parameters as well as all other parameters in the feature set. Area under the curve (AUC) is 0.987 for the feature set including two-dimensional parameters and 0.989 for the feature set including three-dimensional parameters.

Figure 7.
Examples of disordered swallows. Characteristic pressure patterns present in normal swallow are obscured, but regions can still be selected using knowledge of anatomy.

Table 1

Summary data for the normal and disordered groups.

Parameter	Normal	Disordered
VP duration (s)	0.70±0.16	0.67±0.25
VP rise time (s)	0.28±0.15	0.31±0.19
VP rise rate (mmHg/s)	712±2578	671±1023
VP fall time (s)	0.42±0.12	0.36±0.17
VP maximum pressure (mmHg)	139±33	145±45
VP 2-D integral (mmHg*s)	52±18	64±30
VP 3-D integral (mmHg*s)	93±33	108±50
HP duration (s)	0.67±0.18	0.76±0.36
HP rise time (s)	0.39±0.17	0.38±0.26
HP rise rate (mmHg/s)	476±682	1010±5689
HP fall time (s)	0.28±0.11	0.38±0.24
HP maximum pressure (mmHg)	134±66	122±57
HP 2-D integral (mmHg*s)	39±20	43±26
HP 3-D integral (mmHg*s)	114±58	119±82
UES pre-opening maximum pressure (mmHg)	108±54	95±59
UES pre-opening peak 2-D integral (mmHg*s)	33±21	25±17
UES pre-opening peak 3-D integral (mmHg*s)	69±35	52±33
UES post-closure maximum pressure (mmHg)	213±84	204±129
UES post-closure peak 2-D integral (mmHg*s)	115±79	84±60
UES post-closure peak 3-D integral (mmHg*s)	318±120	251±149
Minimum UES pressure (mmHg)	-1±6	0±13
UES activity time (s)	1.06±0.34	0.95±0.36
Nadir duration (s)	0.54±0.18	0.48±0.29
UES 2-D integral (mmHg*s)	60±55	48±39
UES 3-D integral (mmHg*s)	124±103	102±81
Swallow duration (s)	1.03±0.25	0.98±0.38

Table 2

Optimal classification accuracies for each analysis. Values are presented as mean±standard deviation and represent classification accuracy over twenty iterations at the specified number of hidden nodes. UES = upper esophageal sphincter.

Parameters	Hidden nodes	Normal (%)	Disordered (%)	Total (%)
3-dimensional	640	90.62±2.71	82.79±3.29	86.71±1.47
2-dimensional	580	87.57±1.57	79.15±2.41	83.36±1.42
3-dimensional + other	620	97.43±0.59	96.54±0.91	96.99±0.51
2-dimensional + other	640	96.27±2.03	96.37±0.66	96.32±1.05
3-D velopharynx	600	64.90±8.00	66.43±6.43	65.66±2.48
2-D velopharynx	660	70.69±9.59	60.99±5.82	65.84±3.46
3-D hypopharynx	540	71.41±5.18	62.33±4.27	66.87±1.74
2-D hypopharynx	620	68.87±7.44	64.43±6.77	66.65±2.36
3-D pre-opening peak	600	64.00±6.47	68.94±6.68	66.47±1.63
2-D pre-UES peak	580	64.65±6.50	63.29±6.80	63.97±2.30
3-D post-closure peak	660	73.50±7.56	62.29±6.91	67.90±8.67
2-D post-closure peak	660	65.83±6.77	65.05±6.49	65.44±2.02
3-D UES	580	64.72±3.78	65.40±3.70	65.06±2.03
2-D UES	620	62.98±5.62	65.99±5.05	64.49±2.70