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Title: High resolution cervical auscultation to detect swallow kinematic events, part 1: the acoustic signals

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Acknowledgement of financial support: Research reported in this publication was supported by the Eunice Kennedy Shriver National Institute of Child Health and Human Development of the National Institutes of Health under Award Number R01HD074819. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Explanation of any conflicts of interests: The authors have no conflicts to disclose.

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Clinical trial registration number: Not applicable

Title

High resolution cervical auscultation to detect swallow kinematic events, part 1: the acoustic signals

Abstract

Objective: To examine whether there were any associations between high resolution cervical auscultation (HRCA) acoustic signals recorded by a contact microphone and swallowing kinematic events during pharyngeal swallow as assessed by a videofluoroscopic examination.

Design: Prospective pilot study

Setting: University teaching hospital**,** University research laboratories

Participants: 35 patients with stroke who have suspected dysphagia (26 males + 9 females; age = 65.8 ± 11.2).

Methods: Videofluoroscopic recordings of one hundred liquid swallows from 35 stroke patients were analyzed, and a variety of HRCA signal features to characterize each swallow were calculated.

Main Outcome Measure(s): Percent of signal feature maxima (peak) occurring within 0.1 seconds of swallow kinematic event identified from videofluoroscopic recording

Results: Maxima of HRCA signal features, such as standard deviation, skewness, kurtosis, centroid frequency, bandwidth, and wave entropy, were associated with hyoid elevation, laryngeal vestibule closure, and upper esophageal sphincter opening, and the contact of the base of the tongue and posterior pharyngeal wall.

Conclusions: Although the kinematic source of HRCA acoustic signals has yet to be fully elucidated, these results indicate a strong relationship between these HRCA signals and several

swallow kinematic events. There is a potential for HRCA to be developed for diagnostic and rehabilitative clinical management of dysphagia.

Key Words: swallowing, deglutition, deglutition disorders, high resolution cervical auscultation, signal analysis

Abbreviations: Base of the tongue (BOT), Cervical auscultation (CA), Hyoid elevation (HE), High resolution cervical auscultation (HRCA), Laryngeal vestibule (LV), Laryngeal vestibule closure (LVC), Posterior pharyngeal wall (PPW), Speech language pathologist (SLP), Upper esophageal sphincter (UES), Upper esophageal sphincter opening (UESO), Videofluoroscopic studies (VFSS)

Manuscript body

Stroke is the fourth leading cause of death in the U.S. [1], with approximately 800,000 people in the U.S. diagnosed with a new or recurrent stroke each year [2]. Swallowing difficulties or dysphagia, are common in this population [3,4] with more than half of the admitted acute stroke patients showing signs of dysphagia, such as coughing after swallowing during screening and/or aspiration during videofluoroscopic examination of swallowing (VFSS) [3-5]. Stroke patients with dysphagia are three times more likely to develop pneumonia than those without [4]. As a further complication, aspiration pneumonia is associated with substantial morbidity and mortality [6], as well as a financial impact of over $1.3 billion dollars a year in the U.S [7]. In order to efficiently identify the potential risks to the well-being of these patients, a reliable, non-invasive, and inexpensive screening test should be administered [3,5] so that patients with suspected dysphagia can be referred to VFSS, a gold standard objective evaluation of swallowing for further assessments [8].

Stethoscope-based cervical auscultation (CA), one of the screening tests currently used in acute care and rehabilitation clinical settings, is to evaluate swallowing performance based on the acoustic properties [9,10]. However, CA's reliability and validity has been questioned [9,11,12]. There is no consensus on the kinematic source of CA signals, or agreement regarding what the observed sounds represent, which are highly variable among different individuals [10].

High resolution cervical auscultation (HRCA) is a combined hardware-software system that merges electronic transducers with advanced data analysis methods. In the place of a stethoscope, HRCA uses digital electronic transducers, such as a microphone and/or an accelerometer, to record acoustic and vibratory signals caused by movements of the upper aerodigestive tract and boluses during swallowing [13,14]. After the recording of acoustic and vibratory signals, HRCA signal features were extracted. Allowing for a deeper, more detailed analysis unimpeded by the limitations and biases of manual acoustic analysis suggests that HRCA offers greater potential than traditional CA as a dysphagia screening method [13,15,16]. However, similar to the stethoscope CA, the kinematic sources of HRCA acoustic signals recorded during swallowing have not yet been elucidated, because few studies have investigated the sources[17,18].

Concurrent HRCA and VFSS studies allow comparing acoustic signal features and swallowing kinematic events identified on videofluoroscopic images. If signal features are temporally associated with a specific swallow kinematic event, then the HRCA signal can be said to be associated with the swallow event that has occurred. For example, in order to correlate the two modalities, we could compare when specific kinematic events occurred to when our chosen mathematical features exhibited a local maximum (peak). Any local maximum that occurred within 0.1 seconds of when a kinematic event occurred, as determined by the concurrent VFSS exam, could be declared as being associated with the event. It's worth noting that 0.1 seconds window is the tolerance range for obtaining high reliability between raters for manual VF analysis [19]. Furthermore, if a local maximum of one specific feature occurs within 0.1 second in the majority of the swallows, we would declare that there is association between the acoustic signal feature itself and the swallow event.

This study serves as a preliminary study to determine whether or not a larger, more detailed investigation of the correlation between HRCA acoustic signals and swallow kinematic events is warranted. The purpose of this preliminary study was to examine whether there are any associations between HRCA acoustic signals recorded by a contact microphone and swallow kinematic events assessed by VFSS. We hypothesized that HRCA acoustic signal features would be associated with laryngeal vestibule closure (LVC), laryngeal vestibule (LV) re-opening, upper esophageal sphincter opening (UESO), and the contact of the base of the tongue (BOT) and posterior pharyngeal wall (PPW) (BOT-PPW contact) [20] which were postulated to be the potential kinematic sources of CA signals. We further hypothesized that acoustic signal features also would be associated with hyoid elevation (HE) which has high correlation between LVC and UESO [21,22], and reported to be the kinematic source of CA signals [23] as well as vibratory signals recorded via an accelerometer [18]

Methods

Ethical considerations

This study was approved by the University of Pittsburgh Institutional Review Board.

Participants

35 patients with stroke (26 males + 9 females; age=65.8 ± 11.2) who were suspected of having dysphagia and who were scheduled for a VFSS at the Presbyterian Hospital of the University of Pittsburgh participated in this study. All participants were referred by their physician for a VFSS because of clinical suspicion of dysphagia based on diagnosis or clinical evaluation. All the participants signed informed consent prior to the study. Table 1 summarizes the patient demographic information.

Data collection

VFSS recording

During the VFSS, patients were instructed to swallow chilled (5 C) thin liquid barium boluses (Varibar thin liquid with < 5 cps viscosity), placed in the patients' mouths with a 5ml tea-spoon by a speech language pathologist (SLP). The bolus volumes were approximately 3ml, though the exact volumes were not measured. Patients also swallowed self-selected comfortable volume boluses of liquid barium from a cup. The bolus volume for the swallows from a cup, bolus consistency, number of swallow trials for each bolus consistency, and the order of the bolus presentation were not controlled for the current study. They were determined by the SLP who administered the VFSS, and our research protocol was intended to avoid interfering with the procedure's clinical purposes in any significant way.

Among the swallows produced by the 35 patients, one hundred liquid swallows produced as a single swallow or the first of multiple swallows per bolus were analyzed. These swallows include 39 thin liquid swallows administered by a tea-spoon and 61 thin liquid swallows from a cup without any swallow maneuvers or postural changes.

VFSS images output by the x-ray machine (Ultimax system, Toshiba, Tustin, CA) were input to a video capture card (AccuStream Express HD, Foresight Imaging, Chelmsford, MA) and recorded with the LabView program Signal Express (National Instruments, Austin TX) at a rate of 30 frames per second.

HRCA signal recording

Concurrent to VFSS, swallowing vibration and acoustic signals were recorded by a tri-axial accelerometer (ADXL 327, Analog Devices, Norwood, MA) which was attached to the participant's anterior neck at the level of the cricoid cartilage. A contact microphone (Model C411L, AKG, Vienna, Austria) was placed below the accelerometer and slightly towards the right lateral side of the trachea [24]. This study includes only the microphone results because the accelerometer and microphone record different signals that are complementary but not comparable to one other [25]. Figure 1 shows the microphone and accelerometer on a VF image. The microphone signals (10Hz to 10k Hz) were unfiltered in order to record the entire dynamic range, and they were sampled at 20 kHz by a custom LabView program. (National Instruments, Austin, TX) and they were sent to a National Instruments 6210 DAQ.

Measurements

VFSS and acoustic signal data were analyzed step by step. Figure 2 indicates the flowchart of the data analysis. Figure 3 illustrates the VFSS images and the concurrent acoustic signal after filtering noise artifacts from a single swallow.

Swallow kinematic temporal analysis

First, in order to properly analyze the acoustic signals, the onset and offset of each pharyngeal swallow were identified. Table 2 indicates the definition of the time points of the swallow kinematic analysis [13,26,27]. Next, the nine measures listed in Table 2 that were related to HE, LVC, UESO, and BOT-PPW contact were obtained from the VF recording by the primary rater. All time points were identified from the VF recording of each swallow in a lateral view played both in slow motion and frame-by-frame by the primary rater, an experienced SLP (1st author). Ten percent of all measures were randomly selected and repeated by the same rater as well as the 2nd rater (2nd author), who also is an experienced SLP, to determine intra-rater and inter-rater reliability. Both raters were blinded to the acoustic signal data. The intraclass correlation coefficient both for the intra- and inter- rater reliability was 1.0. All videofluoroscopic images were analyzed with Image J software (Image J, National Institutes of Health, Bethesda, MD).

Acoustic signal processing and analysis

After filtering noise artifacts from acoustic signals, several HRCA signal features were computed. First, time domain features, which were (1) standard deviation, (2) skewness, (3) kurtosis, (4) entropy rate, and (5) Lempel-Ziv complexity were calculated to analyze each swallow [28]. Second, frequency domain features, which were (1) peak frequency, (2) centroid frequency, (3) bandwidth, and (4) wavelet entropy, also were calculated. All the features were calculated, not as a single value, but as time-varying parameters by applying 100 msec sliding non-overlapping window to our signals. Finally, local maxima (peak) that occurred within 0.1 seconds of each of the nine swallowing events were identified for each signal feature. Table 3 indicates the definitions of the statistical features and equations used to calculate them.

Statistical analysis

Binomial tests were used to test whether the proportions of the occurrence of a local maximum for each swallow event were statistically significant. The cutoff point was set to be 60% in order to minimize the effect of noise and random chance on our results. $p<0.05$ was accepted as significant for all the tests. IBM SPSS statistics 23.0 (IBM Corporation, Armonk, NY) was used for the statistical analyses. Maxima occurring within 0.1 seconds of a swallow event indicated that the event and feature were associated.

Results

Swallow kinematic analysis

None of the participants showed anatomical abnormalities. Among the 100 swallows, there were 11 swallows with aspiration and 57 swallows with laryngeal penetration. LVC onset and LV re-open from three swallows, UESO onset and UES re-closure from two swallows, and BOT-PPW contact onset and BOT-PPW re-open from two swallows were excluded from analysis because they could not be identified on VF images.

Acoustic signal analysis

Local maxima of Lempel-Ziv complexity and entropy rate were not observed within 0.1 seconds of any of the swallow events (0%; $p<.0001$). Peak frequency maxima did not demonstrate statistical significance at the 60% level on any swallow events. Figure 4 indicates the percent of signal feature maxima occurring within 0.1 seconds of each swallow kinematic event.

As can be appreciated in Figure 4, there were several associations between signal features and swallow kinematic events. Standard deviation maxima were associated with hyoid onset (61%; p<.0001) and UESO onset (76%; p< .0001). Skewness maxima were associated with all swallow kinematic events in more than 80% of the cases (p< .0001). Kurtosis maxima were associated with LVC onset (70%; p= .02), LV re-open (69%; p= .048), and UESO onset (72%; p= .01). Centroid frequency maxima were associated with hyoid rest (75%; p< .0001), LVC onset (71%; p= .01), and UESO onset (66%; p< .0001). Bandwidth maxima were associated with hyoid max (71%; p=.02), hyoid rest (75%; p< .0001), LVC onset (71%; p= .01), UESO onset (68%; p< .0001), and BOT-PPW contact onset (69%; p= .04). Wavelet entropy maxima were associated with hyoid onset (60%; p< .0001) and UESO onset (60%; p< .0001). No other features demonstrated statistical significance at the 60% level.

Discussion

The purpose of this preliminary study was to test whether there were any associations between HRCA acoustic signals and swallow kinematic events as assessed by HRCA and VFSS in one hundred liquid swallows produced from 35 patients with stroke who have suspected dysphagia. We compared nine acoustic signal features to nine kinematic swallow events and found strong associations between several pairs of signal features (i.e., standard deviation, skewness, kurtosis, centroid frequency, bandwidth, and wavelet entropy) and HE, LVC, UESO, and BOT-PPW contact related swallow kinematic events. The probability that any one signal maximum would co-occur with any one single kinematic swallow event is one in nine or 11.1%, any two physiologic events is 1.23%, and so on. Hence our 60% cutoff demonstrates strong associations for the signal-kinematic pairs.

Our results support our a priori hypothesis that HRCA acoustic signals were associated LVC, LV re-open, UESO, and BOT-PPW contact. These results corresponded with the cardiac analogy hypothesis that suggests that CA acoustic signals are generated via vibrations caused by valve and pump systems within the aerodigestive tract including LVC, LV-reopen, UESO, and BOT-PPW contact [20]. The results agreed with the data from Moriniere and colleagues (2007) that indicated the association between CA acoustic signals and LV re-open in 15 healthy adults, although they did not measure the exact onset times [23]. Our results indicating the association between feature maxima and UES re-closure did not correspond with the data from Perlman and colleagues (2005) that indicated no correlation between acoustic peak and UES complete closure defined as the time point when the bolus has just passed UES [29]. However, Perlman et al. (2005) examined the acoustic peaks and their association with swallow events while we analyzed signal features of the acoustic signals. The results also did not correspond with the data from Moriniere and colleagues (2007) that reported CA acoustic sound was observed during UESO and the bolus passing through UES [23]. Yet, they examined the sounds during the bolus passing through UES whereas the current study measured the UES re-closure which occurs after the bolus passes UES. These experimental condition differences may explain the discrepancy in the results.

Our results also support our a priori hypothesis that HRCA acoustic signals were associated with HE. These results corresponded with the data from Moriniere and colleagues (2007) that indicate the association between CA acoustic signals and HE in 15 healthy adults, although the exact onset time of the acoustic signals or swallow events were not measured in their study [23].

Zoratto and colleagues (2010) indicated the correlation between hyolaryngeal excursion, i.e., the displacement of the hyoid and arytenoids, and HRCA vibratory signals [18]. However, it is not clear whether HRCA acoustic and vibratory signals share the same kinematic sources.

Reduced HE and LVC result in penetration and/or aspiration before, during, and/or after the swallow [21], and are prevalent in a number of neurogenic populations with dysphagia including lateral medullary and other cerebral infarctions, Parkinson disease, iatrogenic and pathology-related peripheral nerve injury and others [21]. Reduced UESO also causes laryngeal penetration, aspiration of post-swallow residue [30], and contributes to significant post-onset morbidity in these populations [21]. Reduced BOT-PPW contact may result in residue in the vallecular that also may cause penetration and/or aspiration after the swallow [21]. As can be appreciated in Figure 4, some HRCA acoustic signal features were associated with specific swallow kinematic events stronger than other signals: skewness maxima were associated with all the swallow events whereas other feature maxima were associated with selected swallow events. There results suggest that, if implemented with the aid of advanced computer analysis, the combination of HRCA acoustic signal features may potentially contribute to efforts to identify impairments of swallow kinematic events that may cause reduced airway protection when imaging studies are unavailable. If so, this could lead to HRCA offering several advantages over traditional CA and other swallow screening techniques. HRCA potentially add diagnostic information to traditional dysphagia screening techniques which are unable to identify asymptomatic penetration/aspiration or the kinematic explanations for aspiration that is the most salient target of rehabilitative intervention for people with dysphagia. Indeed, previous studies indicated that HRCA could grossly discriminate swallows with and without deep penetration/aspiration with high sensitivity [13,31]. Further studies are needed to investigate HRCA's capability of detecting penetration/aspiration.

Nevertheless, several sequential cascading neuromuscular events, such as HE, LVC, UESO, and BOT-PPW contact, occur when the pharyngeal swallow is triggered [21]. It is not clear whether observed signal feature maxima were truly the results of each swallow physiological event or combinations of several events, or another phenomenon. There were several other bolus movements in the aerodigestive tract, such as residue in the valleculae and/or pyriform sinuses and penetration/aspiration, which may have caused a local maximum for some of the signal features. Although the results are promising, further studies with larger sample size are needed to specify the relationship between feature maxima and swallow kinematic events. Furthermore, although we have found associations between signal features and swallow events, the kinematic nature of these differences in time and frequency domains of these signals remain unclear.

Study limitations

There are limitations to the current study. The sample size is small because this study was designed as a preliminary analysis. Patients' age, sex, and lesion sites, which may influence the swallow kinematic analysis [21,26,32-34] and acoustic signals [14] were not controlled. The number of swallows made by each participant and the exact bolus volume for each swallow also was not measured due to the limitations of our data collection methods and our imperative to avoid interference with the administration and clinical purposes of the VFSS. However, our sample accurately represents the real-world conditions in which HRCA would be deployed as a swallow screening method and so should provide comparable results. Finally, all data were obtained from stroke patients. The results of the study may not represent swallow acoustic signals in healthy participants [17].

Future research

Currently, we are investigating the association between HRCA vibratory signals and swallow kinematic events. The results will be published separately.

Conclusions

In this study, we sought to compare the timing of several notable swallow kinematic events with the corresponding HRCA acoustic swallowing profile in stroke patients. We found that some of the higher-level signal features of HRCA acoustic signals were associated with certain swallow kinematic events. Although the kinematic source of HRCA acoustic signals has yet to be fully elucidated, these results indicate a strong relationship between these HRCA signals and several swallow kinematic events. We advocate for further research into this subject in order to further understand the nature of HRCA and correlation between HRCA and swallow kinematic events, and the potential for HRCA as an adjunct to rehabilitation of dysphagia.

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Figure legends

Figure 1. The accelerometer and microphone on a videofluoroscopic image.

Figure 2. Data analysis flowchart.

Figure 3. Illustration of the concurrent acoustic signal and VFSS images from a single swallow.

Figure 4. Percent of the signal feature maxima occurring within 0.1 seconds of each swallow kinematic event.

Figures

Figure 1. The accelerometer and microphone on a videofluoroscopic image.

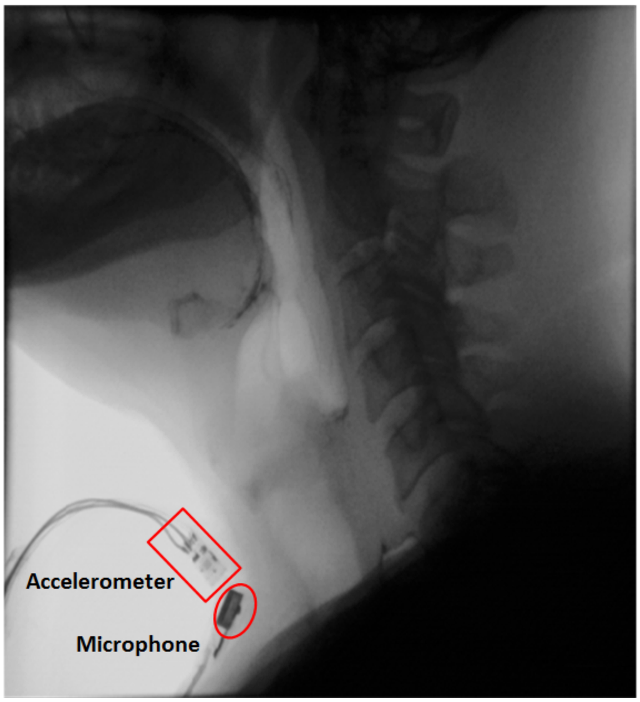


Figure 2. Data analysis flowchart.

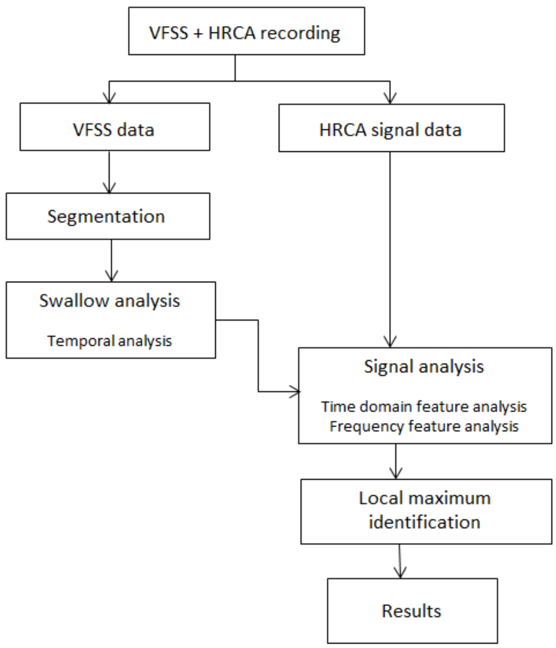
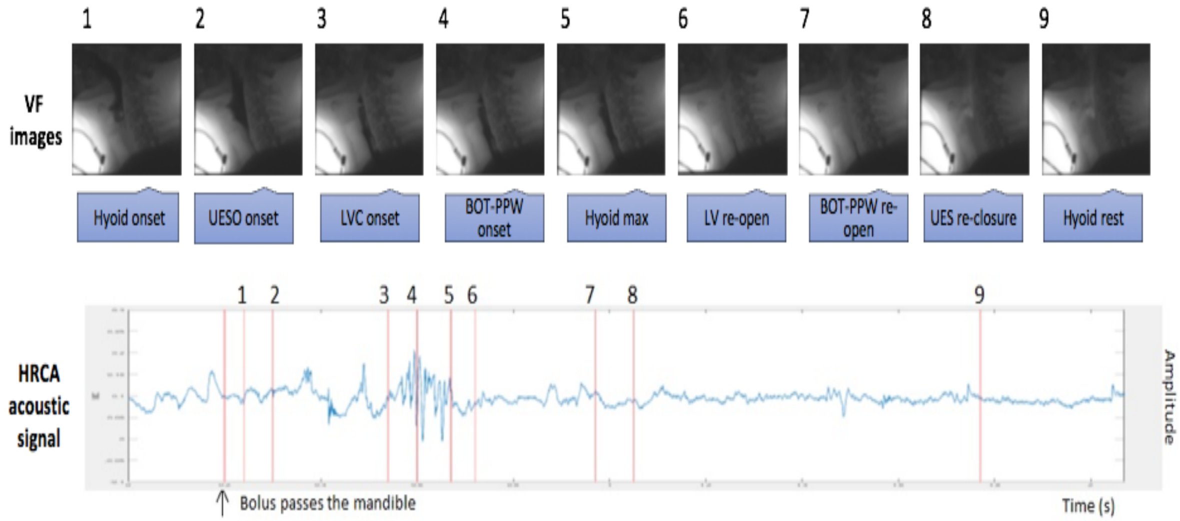
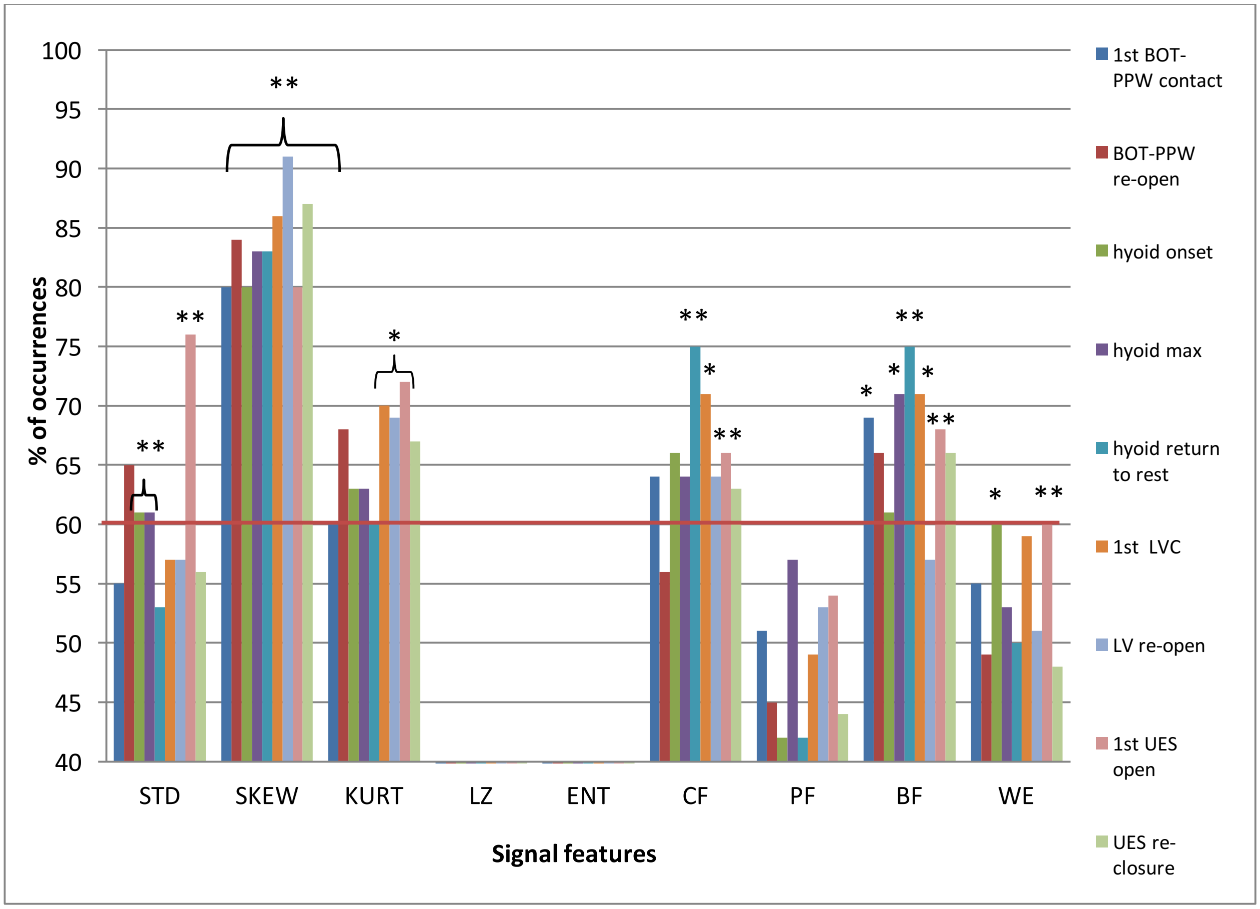


Figure 3. Illustration of the concurrent acoustic signal and VFSS images from a single swallow.



BOT-PPW: base of the tongue contacts to the posterior pharyngeal wall; LV: laryngeal vestibule; LVC: laryngeal vestibule closure; UES: upper esophageal sphincter; UESO: upper esophageal sphincter opening; VF: videofluoroscopic

Figure 4. Percent of the signal feature maxima occurring within 0.1 seconds of each swallow kinematic event.



BW: bandwidth; BOT: posterior pharyngeal wall; CF: centroid frequency; ENT: entropy rate; KURT: kurtosis; SKEW: skewness; STD: standard deviation; LV: laryngeal vestibule; LVC: laryngeal vestibule closure; LZ: Lempel-Ziv Complexity; PF: peak frequency; PPW: posterior pharyngeal wall; UES: upper esophageal sphincter; UESO: upper esophageal sphincter opening; WE: wavelet entropy; * p<.05; ** p< .0001

Table legends

Table 1. Summary of the patient demographic information.

Table 2. Definitions of swallow kinematic measures.

Table 3. Summary of signal features and equations for calculation for each feature.

Tables

Table 1. Summary of the patient demographic information.

Variable		
Age	Mean ± SD	65.8 ± 11.2
	Range	41 - 84
Sex	Male	26
	Female	9
Race/Ethnicity	Asian	2
	African American	2
	Caucasian	31
Lesion	Left	14
	Right	8
	Bilateral	4
	Brainstem	4
	Multiple	1
	Unknown	4

Table 2. Definitions of swallow kinematic measures.

	Definitions
Onset of hyoid elevation (Hyoid onset)	The first superior movement of the hyoid leading to maximal hyoid elevation during swallowing
Maximum hyoid elevation (Hyoid max)	The point that the hyoid is at its maximally displaced position during swallowing
Hyoid return to the resting position (Hyoid rest)	The point that the hyoid is motionless after returns to its resting position
Onset of laryngeal vestibule closure (LVC onset)	The first point of the closure within the laryngeal vestibule between the arytenoid and base of the epiglottis
Laryngeal vestibule re-opening (LV re-open)	The point immediately preceding airspace re-appearance within the vestibule
Onset of upper esophageal sphincter opening (UESO onset)	The first separation of tracheal and esophageal walls
Upper esophageal sphincter re-opening (UES re-closure)	The point at which bolus clears between the tracheal and esophageal walls
Onset of the base of the tongue contacts to the posterior pharyngeal wall (BOT-PPW onset)	The first point of the closure within the pharynx between the base of the tongue and the posterior pharyngeal wall
Base of the tongue and the posterior pharyngeal wall re-opening (BOT-PPW re-open)	The first separation of the tongue and the posterior pharyngeal wall

Table 3. Summary of signal features and equations for calculation for each feature.

Features	Definitions	Equations
Time domain features		
Standard deviation (σ)	Reflects how a signal fluctuates around the mean value of a signal.	$\alpha_X = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu_X)^2}$
Skewness (ξ):	Describes the asymmetry of the amplitude distribution.	$\varepsilon_X = \frac{\frac{1}{n}\sum_{i-1}^{n}(x_i - \mu_X)^3}{\left\{\frac{1}{n}\sum_{i-1}^{n}(x_i - \mu_X)^2\right\}^{\frac{3}{2}}}$
Kurtosis (γ):	Describes peaked/flat amplitude distribution.	$\left\{\frac{1}{n}\sum_{i-1}^{n}(x_i - \mu_X)^2\right\}$
Lempel-Ziv Complexity	Evaluate the randomness of a signal.	$LZC = \frac{K\ log_{100} n}{n}$
Entropy rate (ρ)	Evaluates the degree of regularity of the signal distribution.	$u_i = 10^{H-1}\hat{x_i} + H - 1 + 10^{H-2}\hat{x_i} + H - 2 + ... + 10^{0}\hat{x_i}$
Frequency domain features		
Peak frequency (f)	Describes the frequency corresponding to the maximum spectral power.	$fp = \text{arg}_{f\in[0,f_{max}]}\ max\lvert FX(f)\rvert$
Centroid frequency ($\hat{f}$)	Indicates the "center of mass" of the frequency spectrum of a signal.	$\hat{f} = \sqrt{\frac{\int_0^{f_{max}} f\lvert F_X(f)\rvert^2 df}{\int_0^{f_{max}}\lvert F_X(f)\rvert^2 df}}$
Bandwidth	Difference between the upper-most and lowermost frequencies in a signal.	$BW = \sqrt{\frac{\int_0^{f_{max}}(f-\hat{f})^2\lvert F_X(f)\rvert^2 df}{\int_0^{f_{max}}\lvert F_X(f)\rvert^2 df}}$
Wavelet entropy (ΘX)	Evaluates the disorderly behavior in time-frequency domain	$WE = -\frac{Er_{a10}}{100}log_2\frac{Er_{a10}}{100} - \sum_{k=1}^{10}\frac{Er_{a10}}{100}\ log_2\frac{Er_{a10}}{100}$