Literature Review

https://doi.org/10.1590/2317-6431-2021-2498

Audiology Communication Research
ISSN 2317-6431

Instruments for acoustic capture and analysis of cervical auscultation signals in speech-language pathology clinic practice: an integrative literature review

Instrumentos para captação e análise acústica dos sinais de ausculta cervical na prática clínica fonoaudiológica: uma revisão integrativa de literatura

Valdani Dias[1], *Geovana de Paula Bolzan*[2]

ABSTRACT

Purpose: Describe the instruments used to capture and analyze the acoustic signals obtained from cervical auscultation, and identify those with the greatest potential for application in the speech pathology clinic. **Research strategy:** This is an integrative literature review. Searches were performed in the MEDLINE/PubMed, Scopus and Web of Science databases in November 2020, using relevant keywords combined with Boolean operators. **Selection criteria:** Scientific articles published in Portuguese, Spanish or English in the last five years (2016-2020) and that presented a study of cervical auscultation. **Results:** Ninety-eight articles were found. After the application of selection criteria, 26 articles were selected for this review. Microphones were the most common instruments used to perform cervical auscultation, followed by high-resolution cervical auscultation techniques, which combine acoustic and vibrational signals recorded by a microphone and an accelerometer, respectively. Acoustic analysis was performed using different software packages and/or algorithms depending on the goals of each study. **Conclusion:** The combination of high-resolution cervical auscultation and machine learning for acoustic analysis has great potential for utilization in the clinical assessment and monitoring of swallowing in speech pathology.

Keywords: Deglutition; Auscultation; Critical pathways; Acoustics; Software; Review

RESUMO

Objetivo: Descrever os instrumentos utilizados para captação e análise acústica dos sinais de ausculta cervical e identificar aqueles com maior potencial para aplicação na clínica fonoaudiológica. **Estratégia de pesquisa:** Trata-se de uma revisão integrativa de literatura. As buscas foram realizadas nas bases de dados MEDLINE/PubMed, Scopus e Web of Science, a partir da combinação de termos de relevância e operadores booleanos, durante o mês de novembro de 2020. **Critérios de seleção**: Artigos científicos publicados nos idiomas português, espanhol ou inglês, nos últimos cinco anos (2016-2020) e que apresentassem estudo da ausculta cervical. **Resultados:** Foram encontrados 98 artigos. Após a aplicação dos critérios de seleção, 26 artigos foram selecionados para esta revisão. Para captação dos sinais de ausculta cervical, o microfone foi o instrumento mais utilizado, seguido pela técnica de ausculta cervical de alta resolução, que combina sinais acústicos e vibratórios registrados por um microfone e um acelerômetro, respectivamente. *Softwares* e/ou algoritmos foram selecionados para análise acústica dos sinais, de acordo com o objetivo de cada estudo. **Conclusão:** O método de ausculta cervical de alta resolução e a análise acústica por meio de algoritmos de aprendizado de máquina apresentaram grande potencial para utilização na prática clínica fonoaudiológica para avaliação e monitoramento da deglutição.

Palavras-chave: Deglutição; Auscultação; Procedimentos clínicos; Acústica; Software; Revisão

Study carried out at Curso de Fonoaudiologia da Universidade Federal de Santa Maria – UFSM – Santa Maria (RS), Brasil.
[1]Curso de Fonoaudiologia, Universidade Federal de Santa Maria – UFSM – Santa Maria (RS), Brasil.
[2]Departamento de Fonoaudiologia, Universidade Federal de Santa Maria – UFSM – Santa Maria (RS), Brasil.
Conflict of interests: No.
Authors' contribution: VD participated in the idealization of the study, collection, analysis and interpretation of data and writing of the article; GPB participated in the idealization and methodological design of the study, analysis and interpretation of data, guidance and writing of the article.
Funding: None.
Corresponding author: Valdani Dias. E-mail: valdanidias@gmail.com
Received: March 31, 2021; **Accepted:** May 05, 2021

INTRODUCTION

Normal swallowing is a complex and dynamic neuromuscular activity that depends on a set of physiological behaviors, controlled by the central and peripheral nervous system. The integrity of these behaviors results in the transport of solid, liquid and saliva substances, efficiently and safely, from the mouth to the stomach(1-4).

The biomechanical movements of the different structures involved before, during and after the passage of the food bolus through the pharynx produce the sounds of swallowing(5).

These sounds are generally described as two or three distinct clicks, with two audible clicks, accompanied by an expiratory blow, which occurs immediately after swallowing apnea(6,7). For other authors, there are three components that comprise the sounds of normal swallowing: [1] a weak signal associated with laryngeal lifting and passage of the bolus through the pharynx; [2] a loud sound associated with cricopharyngeal opening and [3] a weak signal associated with laryngeal descent(8,9).

When coordination of movements is lost, causing changes in the dynamics of swallowing in one or more of its phases, there may be a picture of dysphagia(10). Dysphagia is not classified as a disease, but as a symptom of some underlying disease that has high morbidity and mortality, and can lead to numerous clinical complications, such as dehydration, malnutrition, pneumonia, among other problems(4,11).

Currently, there are many resources and technological methods available for the assessment, monitoring and biofeedback of swallowing(12), which provide consistent assistance in the treatment of individuals(13). For an accurate diagnosis, effective therapeutic planning and better definition of the prognosis, the swallowing clinical assessment associated with complementary instrumental tests, when necessary, is considered essential(14).

The swallowing clinical assessment consists of anamnesis, evaluation of the oral sensorimotor system, evaluation of masticatory function, swallowing function and speech articulation(15). The instrumental tests most used to complement swallowing clinical assessment are videofluoroscopic swallowing study (VFSS)(10) and swallowing videoendoscopy (FEES® - fiberoptic endoscopic evaluation of swallowing)(16). Still, other available methods can be used as complementary resources for the evaluation of swallowing, such as surface electromyography (SEMG)(17), swallowing ultrasound (US)(18), pulse oximetry and cervical auscultation(14).

Despite all the advantages of an instrumental assessment, the main methods currently used may be difficult to access for some patients, due to their high operational cost. Furthermore, they may involve exposure to radiation and invasive procedures(2,19).

A low-cost, easy-access, reproducible and non-invasive option highlighted in the clinical practice of speech therapists for evaluation and monitoring of dysphagic patients is cervical auscultation. This method consists of listening to the swallowing sounds through a sound amplification instrument placed on the patient's neck(20). However, the accuracy of auscultation is debatable, as the interpretation of the signals is subjective, considering the risk of suffering interference, both from the characteristics of the instrument used, and from the experience of the evaluator(14,21).

The ability to digitize and record the signal offers numerous possibilities for processing and analyzing the acoustic characteristics of swallowing sounds. For this reason, the use of an additional device to the assessment, although not common in the clinical setting, has clear advantages compared to the subjective assessment based on cervical auscultation performed with a conventional stethoscope(22).

Different methods of digital cervical auscultation, which involve instruments such as accelerometer(23), electronic stethoscope(24), microphone(25), acoustic emission sensor(26), piezoelectric sensor(27) and Doppler sensor(28), have been studied in the last years. These methods allow the digitalization of the signal, enabling the analysis of swallowing sounds in a more objective way, based on parameters such as duration, signal frequency and wave amplitude, among other aspects(12,22,29).

The possibility of adding objective data in the analysis of swallowing sounds presents a potential that can increase the accuracy of assessments and favor the early detection of risks, before major complications arise, which can also provide significant savings to the healthcare sector, due to the low operating cost(22).

OBJECTIVE

To conduct a literature review in order to describe the instruments used to capture and analyze the acoustic signals of cervical auscultation and identify those with the greatest potential for application in speech-language pathology clinic.

RESEARCH STRATEGY

This study is characterized as an integrative literature review, which consists in the construction of a broad analysis of relevant research and synthesis of the state of knowledge of a given subject, enabling the discussion of research methods and results, support for the taking of decisions and advances in clinical practice, in addition to reflections on knowledge gaps and the performance of future studies(30).

In order to ensure the methodological accuracy of the study and the validation of its results, the six stages of construction of an integrative literature review(31) were followed, namely: identification of the topic and selection of the research question; establishment of inclusion and exclusion criteria; identification of pre-selected and selected studies; categorization of selected studies; analysis and interpretation of results and, finally, presentation of the review/synthesis of knowledge.

To guide the bibliographical research, the following research question was elaborated for this study: *"Which instrument for capturing and analyzing acoustic signals from cervical auscultation has the greatest potential for implementation in speech-language pathology clinic practice?"*

The search took place in November 2020. The MEDLINE/PubMed, Scopus and Web of Science virtual databases were consulted (via Capes journal). The combination of relevance terms and Boolean operators used as a search strategy was: *"deglutition"* OR *"deglutitions"* OR *"swallow ing"* OR *"swallowings"* OR '*'swallow"* OR *"swallows"* AND *"acoustic analysis"* OR *"acoustic analysis"* " OR *"auscultation"* OR *"cervical auscultation"* OR *"swallowing sounds"* OR *"swallow sounds"* OR *"signal processing"* OR *"acoustics"* OR *"acoustic*" OR *"software"* AND *"accelerometry"* OR *"swallowing accelerometry signals"* OR *"stethoscope"* OR *"digital stethoscope"* OR *"electronic stethoscope"* OR *"doppler effect"* OR *"sonar doppler"* OR *"microphone"*. The search strategy was chosen and adapted according to the coding and coherence of each database to be consulted (Appendix A).

SELECTION CRITERIA

To refine the research, only scientific articles published in Portuguese, Spanish or English in the last five years (2016-2020) and that presented a study of cervical auscultation were included. The decision to cover only articles published in the last five years aimed to draw a more up-to-date profile on the subject, enabling a reflection on future studies.

Publications that had content incompatible with the theme of this review, duplicated or presented in books and book chapters, letters, ordinances, editorials, news, conference abstracts, dissertations and theses were considered as exclusion criteria.

Initially, the titles, abstracts and keywords of all publications found through the search strategy were carefully read. The adequacy of the works with the inclusion and exclusion criteria was verified, as well as the correspondence with the guiding question of the study. When the reading of titles, abstracts and keywords were not enough to define the selection of a work, publication in full was sought.

Data analysis

The systematization of the articles selected for this review was based on the extraction and analysis of the following variables: authors and year of publication, research objective, sample characteristics, evaluation and procedures performed, acoustic analysis methods, and main results and conclusions presented. This information was structured in a synthesis matrix (Chart 1) elaborated in the *Microsoft Office – Excel® software*, subdivided into nine analytical categories according to the assessment instruments used to capture cervical auscultation signals during swallowing: accelerometer; electronic stethoscope; microphone; microphone and accelerometer; microphone and acoustic emission sensor; microphone, Doppler sensor and stethoscope; Doppler sensor and microphone; Doppler sensor; and piezoelectric sensor.

The steps of search, selection and initial systematization of articles were carried out by one of the authors. When this author had doubts about the adequacy of pre-selected articles to the study's inclusion and exclusion criteria, they were reread in full by both researchers, who evaluated and established a consensus on the selection.

RESULTS

98 articles were found through search strategies in the databases, 22 in MEDLINE/PubMed, 34 in Scopus and 42 in Web of Science. After analyzing and applying the inclusion and exclusion criteria, 26 articles were selected for the study (Figure 1).

From the selected articles, substantial information was extracted to highlight the aspects analyzed in this study (Chart 1).

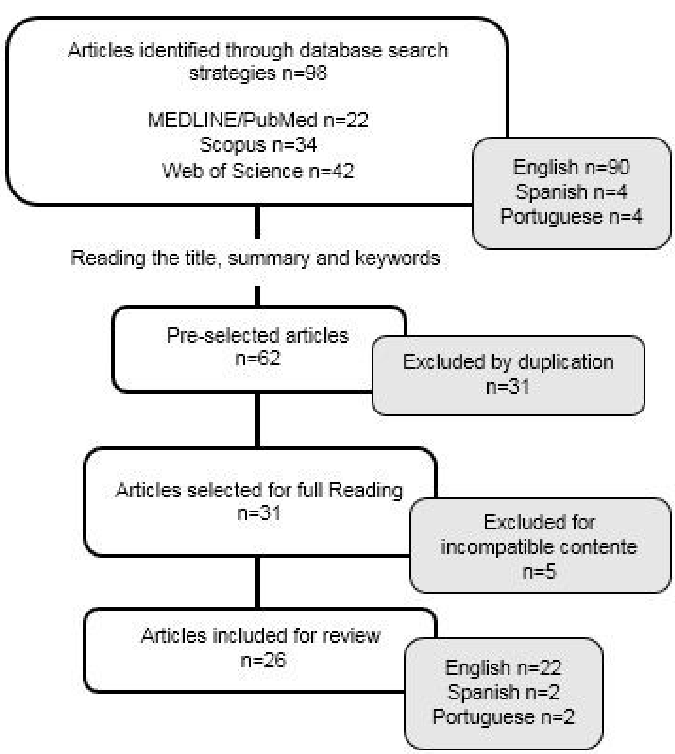

Figure 1. Flowchart of article selection
Subtitle: n = number of studies

Chart 1. Systematization of selected articles in the review

Authors	Objective	Sample	Assessment/ procedures	Acoustic analysis	Main results and conclusions
			Accelerometer		
Steele et al.[23]	To develop algorithms to detect swallowing problems using a system based on Accelerometer.	305 individuals with stroke, other brain damage or at risk for dysphagia.	Cervical auscultation with a dual-axis accelerometer. VFSS Exam.	Algorithms developed by the authors.	The system created allowed the identification of alterations in the swallowing of thin liquids with high precision (sensitivity 90.4%; specificity 60.0%). Algorithms represent a first step in the development of a device based on accelerometry for screening of deglutition.
			Electronic stethoscope		
Sánchez-Cardona et al.[21]	To characterize and classify the cervical auscultation signals and discriminate the swallowing sounds from those associated with the noise.	10 individuals healthy (6 men; mean age 27.3 years old).	Cervical auscultation with an electronic stethoscope (E- scope® Cardionics).	Selected and Machine Learning Algorithms.	The proposed method allowed the classification of swallowing sounds using a stethoscope. It was 97.7% accurate for detecting acoustic events and 91.7% for swallowing sounds by glottic closure, in the presence of noise sources.
García[24]	To support the evaluation processes of cervical auscultation from the structuring of the spectrographic profile of the pharyngeal phase.	93 healthy individuals, over 18 years old.	Cervical auscultation with an electronic stethoscope (Littman® 3200).	StethAssist software.	The spectrographic profile of the pharyngeal phase represented four swallowing events that can be analyzed from the times obtained in the digital analysis of the acoustic wave. Thus, it provided parameters for the functional interpretation of swallowing.
			Microphone		
Bi et al.[32]	Accurately and conveniently monitor daily food intake through the AutoDietary system developed.	12 individuals.	Cervical Auscultation with a throat microphone.	Smartphone application.	The mean accuracy of food type recognition by AutoDietary was 84.9%, and up to 97.6% for classifying liquid and 99.7% solid food intake. AutoDietary presented itself as a promising device for the recognition of food intake in daily life.
Honda et al.[33]	To Characterize and identify the sound generation process during swallowing in healthy young adults.	33 young and healthy, subdivided into three experimental groups: 1) 10 men and 10 women, with a mean age of 25.8 years old; 2) 5 men and 5 women, with a mean age of 28.0 years old; 3 men, mean age 27.6 years old.	Cervical auscultation with a condenser microphone. Simultaneous recording of VFSS in experiment 3.	DADiSP software.	The sound of swallowing can be divided into three periods: Oral phase: posterior movement of the tongue and hyoid bone; Pharyngeal phase: laryngeal movement, elevation of the hyoid bone, closure of the epiglottis and passage of the bolus into the esophagus; - Hyoid bone and laryngeal repositioning phase and epiglottis reopening.
Frakking et al.[25]	To establish acoustic and perceptual profiles of swallowing sounds with and without aspiration, in children with dysphagia, and determine if there is a difference between these two types of swallowing	47 children (57% male).	Cervical Auscultation with an omnidirectional condenser microphone. VFSS Exam.	Adobe Audition Software. Matlab Software.	The presence of a glottic release sound together with normal breath sounds after swallowing are possible indicators of non-aspiration swallowing. On the other hand, the presence of noisy breathing and one or more of the sounds of coughing, wheezing, rales, hawking and stridor are indicative of swallowing aspiration, when compared to VFSS.
Kamiyanagi et al.[34]	To assess swallowing ability in patients Maxilectomized with and without the obturator prosthesis placed.	27 patients with maxillectomy (15 men; mean age 66 years old); 30 healthy controls (14 men; mean age 44.9 years old).	Cervical auscultation with an electret condenser microphone.	Speech Lab Computerized Software.	Significant differences were observed, mainly in the measure of duration of the intensity peak of the analyzed variables inter and intra-groups. The swallowing ability in patients with maxillectomy can be improved with the use of an obturator prosthesis.

Subtitle: VFSS = videofluoroscopic swallowing study; Q-Q plots = quantile-quantile plots of probability distribution

Chart 1. Continued...

Authors	Objective	Sample	Assessment/ procedures	Acoustic analysis	Main results and conclusions
Li et al.[35]	To characterize the temporal pattern of the tongue, hyoid and supra- and infra-hyoid muscles and determine how they are related and coordinated.	15 healthy men (mean age 27.7 years old).	Detection system consisting of a pressure sensor, a curvature sensor, surface electrodes and a microphone.	No method described.	Significant correlations were confirmed among muscles related to swallowing, tongue pressure and hyoid. The non-invasive detection system has the potential to be a good contributor to monitor and assess the oropharyngeal phase of swallowing.
Frakking et al.[36]	To obtain normative data on the acoustic parameters of swallowing and determine if they are age-related. To obtain perceptual clinical signs of breath and swallowing sounds before, during and after swallowing.	74 healthy children, between 4 and 36 months (35 men; mean age 17.1 months).	Cervical auscultation with an omnidirectional condenser microphone. A digital video recorder to visualize laryngeal movement associated with swallowing.	Adobe Audition Software. Matlab Software.	Swallowing sounds become louder as children get older, and with chewable solids they become shorter. Most children have normal breath sounds before and after swallowing. A very small number present an occasional single cough with thin fluids, said to be normal in the process of learning and controlling the flow and volume of food.
Almeida et al.[37]	To characterize the acoustic signal of silent tracheal aspiration in children with oropharyngeal dysphagia.	18 children (56% girls, median age 6 years old). Groups: 8 that aspire and 10 do not aspire.	Cervical auscultation with an electret condenser microphone. VFSS Exam.	Raven software.	The spectral power density curve of swallows with aspiration showed an ascending pattern, while the curve for normal swallows was flat. The non-invasive technique identified the aspiration by an increase in the of spectral power density curve in aspirated sounds.
Kurihara et al.[38]	To develop a swallowing motion detection device and a swallowing state estimation system.	7 healthy men (mean age 22 years old; height: 175.1 cm; weight: 61.6 kg).	Device comprises a bidirectional electret condenser microphone and air tube. The experiment included f1 (swallowing nothing), f2 (tea), f3 (thickened tea) and f 4(rice cake).	Matlab software.	As viscosity increased, the larynx exhibited complex movements to swallow food. These movements were reflected in the signal. The proposed method was validated based on the estimate of f1 -f4, and accuracies of 0.99, 0.81, 0.84 and 0.91, respectively, were achieved.
Miyagi et al.[39]	To investigate the use of machine learning to classify swallowing sounds as: normal, or mild, moderate and severe dysphagia.	17 healthy men and 10 healthy women (mean age 22.4); 78 men and 65 women with dysphagia (mean age 83.3).	Cervical Auscultation with a throat microphone.	Audacity software and machine learning algorithm.	In normal and dysphagic individuals, the maximum F measure was 78.9%. For normal and dysphagic subjects of mild, moderate and severe degrees, the values of measure F were 65.6%, 53.1%, 51.1% and 37.1%, respectively, insufficient to use the classifier as an independent method for diagnosis.
Microphone and Accelerometer - High Resolution Cervical Auscultation					
Dudik et al.[40]	To characterize the signs of cervical auscultation in individuals with dysphagia that aspire.	76 adults (50 men; mean age 62 Years old), 17 with a diagnosis of stroke, 59 with other medical conditions.	Cervical auscultation with a triaxial accelerometer and a contact microphone. VFSS Exam.	LabView software and selected algorithms.	Few differences were presented between safe and unsafe swallows based on the chosen characteristics. Several statistical resources should be used simultaneously when aspiration is chosen as a variable in future work.
Movahedi et al.[41]	To investigate whether the swallowing signals recorded by a microphone and a triaxial accelerometer differ from each other or carry unique information about function of swallowing.	72 participants (42 men; mean age 63, years old), of these, 20 with a history of stroke.	Cervical auscultation with a triaxial accelerometer and a contact microphone. VFSS Exam.	LabView software and selected algorithms.	Although the sounds and vibrations of swallowing may have the same physiological sources, the signs of swallowing recorded by the microphone and by the accelerometer differed from each other in the domains of time and frequency. The information provided by the sounds and vibrations of swallowing are not interchangeable.

Subtitle: VFSS = videofluoroscopic swallowing study; Q-Q plots = quantile-quantile plots of probability distribution

Chart 1. Continued...

Authors	Objective	Sample	Assessment/ procedures	Acoustic analysis	Main results and conclusions
Dudik et al.[42]	To develop a method for investigating swallowing disorders, and characterize and compare the swallowing of healthy and unhealthy patients.	Control group: 55 healthy individuals (28 men; mean age 39 years old). Study group: 53 patients with suspected dysphagia: 13 (10 men; mean age 66 years old) with current diagnosis of stroke and 40 (24 men; mean age 62 years old) with other medical conditions.	Cervical auscultation with a triaxial accelerometer and a contact microphone. Study group: VFSS exam.	LabView software and selected algorithms.	Almost all the resources chosen for vibrations and sounds showed significant differences between healthy and unhealthy swallows, despite the absence of aspiration. The findings should collaborate with the field of cervical auscultation and serve as a reference for future investigations into more specialized characterization methods.
Rebrion et al.[43]	To compare hyoid bone displacement from VFSS images with characteristics of the auscultation signal.	25 patients (12 men; mean age 60 years old).	Cervical auscultation with a triaxial accelerometer and a contact microphone. VFSS Exam.	LabView software and selected algorithms.	The sounds and vibrations of swallowing are related to the horizontal and vertical movements of the anterior and posterior parts of the hyoid bone.
Kurosu et al.[44]	To examine whether there is an association between acoustic signals of high-resolution cervical auscultation and the kinematic events of swallowing.	35 patients with stroke and suspected dysphagia (26 men; mean age 65.8 years old).	Cervical auscultation with a triaxial accelerometer and a contact microphone. VFSS Exam.	LabView software and selected algorithms.	There is a strong relationship between high-resolution cervical auscultation signals and various kinematic events of swallowing (opening of the upper esophageal sphincter; closing of the laryngeal vestibule; reopening of the laryngeal vestibule; onset, maximum displacement and rest of the hyoid). There is potential for this method of cervical auscultation to be developed for clinical diagnosis and treatment of dysphagia rehabilitation.
Donohue et al.[45]	To investigate the ability of high-resolution cervical auscultation to track displacement of the hyoid bone during swallowing.	114 patients (65 men; ages between 19 and 94 years old) with suspicion /confirmation of dysphagia; 16 healthy adults.	Cervical auscultation with a triaxial accelerometer and a contact microphone. VFSS Exam.	LabView Software and Machine Learning Algorithms.	Machine learning algorithms were able to locate approximately half (51% of the patient dataset, 49.9% of the healthy dataset) of the hyoid body in each frame of the swallow segments. Accurate and automated tracking of hyoid bone displacement is possible from high-resolution cervical auscultation signals without the use of VFSS images.
Donohue et al.[46]	To Know whether high-resolution cervical auscultation signals can differentiate between swallows from healthy people and people with neurodegenerative diseases.	20 patients with neurodegenerative diseases (10 men; mean age 61.25 years old); 51 healthy adults (22 men; mean age 67.21 years old).	Cervical auscultation with a triaxial accelerometer and a contact microphone. VFSS Exam.	LabView Software and Machine Learning Algorithms.	High-resolution cervical auscultation signal characteristics combined with statistical methods and machine learning techniques can effectively differentiate swallows from healthy people from people with neurodegenerative diseases, with a high degree of accuracy (99%), sensitivity (100%) and specificity (99%).
Microphone and Acoustic Emission Sensor					
Kamiyanagi et al.[47]	To establish a swallow assessment method that can be used for screening reliability.	6 healthy men (mean age 40.2 years old) and 6 men with a palatal augmentation prosthesis (mean age 72.1 years old).	Cervical auscultation with a throat condenser microphone and an acoustic emission sensor.	Sound it! Premium software and selected algorithms.	The duration of the swallowing sound measured by the microphone was significantly higher in patients with palatal augmentation prosthesis. The acoustic emission sensor allowed the measurement of high frequency ranges that could not be measured with the microphone. The findings suggested the validation of the swallowing sound analysis based on the probability distributions through Q- Q graphs.

Subtitle: VFSS = videofluoroscopic swallowing study; Q-Q plots = quantile-quantile plots of probability distribution

Chart 1. Continued...

Authors	Objective	Sample	Assessment/ procedures	Acoustic analysis	Main results and conclusions
Chikai et al[26].	To propose a swallowing sound measurement system that employs a sensor capable of acquiring acoustic information in a wide range frequency range.	1 healthy male individual (age: 29 years old).	Cervical auscultation with a throat condenser microphone and an acoustic emission sensor.	Adobe Audition software and selected algorithms.	The acoustic emission sensor exhibited acoustic signals above 3 KHz, which was not possible with the microphone. The data measured with the acoustic emission sensor reflected more sensitively and, combined with the Q-Q plots, showed the potential to distinguish the difference in sample viscosity.
Microphone, Doppler Sensor and Stethoscope					
Taveira et al.[48]	To analyze the diagnostic validity of different methods for assessing swallowing sounds, when compared to the VFSS exam.	3 articles: - United Kingdom (2004): stethoscope; - Brazil (2013): Doppler sonar; - Japan (2015): microphone The sample ranged from 10 to 30 individuals healthy and 14 to 70 dysphagic.	Articles in which the main objective was to assess the accuracy of swallowing sounds were searched in five electronic databases without language or publication time limitations.	United Kingdom (2004): not applicable. Brazil (2013): VoxMetria software. Japan (2015): Audio Director Software; Audacity and selected algorithms.	Accuracy values were 0.94 for microphone, 0.80 for Doppler and 0.60 for stethoscope. Doppler showed excellent diagnostic accuracy in discriminating swallowing sounds. The microphone reported good sensitivity for discrimination of swallowing sounds in dysphagic patients. The stethoscope presented the best screening test in the discrimination of swallowing sounds.
Doppler sensor and microphone					
Choi et al.[49]	To develop a non-invasive and quantitative swallowing monitoring and evaluation system.	24 healthy individuals (14 men; Mean age 30.5 years old).	System: an array of ultrasonic Doppler sensors, an omnidirectional electret condenser microphone, an inertial measurement unit and a Bluetooth module.	Signal processing program developed by the authors.	Peak amplitudes and energy significantly decreased with viscosity and peak-to-peak time interval and duration increased with volume. The system developed can be used effectively for tracking, monitoring and quantifying the swallowing function, through further research.
Doppler sensor					
Soria et al.[13]	To compare the acoustic parameters of oropharyngeal swallowing among different age groups.	Group I: 75 healthy elderly (Mean age 71 years old). Group II: 72 healthy adults (mean age 42 years old).	Audible signal captured by Doppler sonar.	VoxMetria Software.	There was a change in the acoustic pattern of swallowing, both in terms of consistency and volume of the food bolus, when comparing elderly and adults. The main characteristic found in the elderly was a curve with smaller amplitude and longer time than in adults.
Lee[28]	To detect food intake using ultrasonic Doppler sonar.	10 individuals healthy (7 men; ages between 17 and 50 years old).	Detection of chewing and swallowing events with acoustic Doppler sonar.	33250A function generator, selected algorithms and machine learning.	The method of detection of food intake based on acoustic Doppler sonar produced promising results with maximum recognition rates of 91.4% for chewing and 78.4% for swallowing. In addition to the high recognition performance, it proved to be convenient and safe and did not cause any skin problems related to the contact sensor.
Piezoelectric sensor					
Yagi et al.[27]	To evaluate the efficiency and effectiveness of a swallowing monitoring system that uses respiratory flow, swallowing sound and laryngeal movement.	11 healthy individuals (9 men; mean age 40.1 years old); 10 patients with dysphagia (4 men; mean age, 75.6 years old).	The system comprises a nasal cannula-type flow sensor and a piezoelectric sensor. VFSS Exam.	Matlab software and selected algorithms.	Elevation delay time and laryngeal elevation time were significantly prolonged in patients with dysphagia, especially in food with higher viscosity. The occurrence rate of the inspiration-swallowing pattern increased significantly in the group of patients. The device can facilitate the assessment of some aspects of swallowing dysfunction, especially the coordination between swallowing and breathing.

Subtitle: VFSS = videofluoroscopic swallowing study; Q-Q plots = quantile-quantile plots of probability distribution

As noted, the microphone was the most used instrument for capturing cervical auscultation signals, followed by its combination with the accelerometer. On the other hand, for the acoustic analysis of these signals, a variety of available resources, such as softwares and/or algorithms, were selected according to the objective of each study.

DISCUSSION

Instruments for capturing cervical auscultation signals

Cervical auscultation with a stethoscope is one of the non-invasive instrumental techniques most used by speech therapists to assess the pharyngeal phase of swallowing. Due to the subjective interpretation of this technique, digital cervical auscultation methods with different capturing instruments that enable an objective and/or automatic analysis of the signals are presented in the literature(21). However, for a new technique to obtain clinical acceptability, must meet criteria, such as being well researched, so that it provides information about its reliability; be easily applied in the clinical situation and present, preferably, low cost. Furthermore, the equipment used and its application must be standardized, so that the information is comparable among dysphagia clinics(50).

It was observed, in the selected studies, that the main instruments used to capture the swallowing signals were the microphone and its combination with the accelerometer, a technique defined as high-resolution cervical auscultation, which records sounds and vibrations of the swallowing function. As well as these methods, other instruments for recording cervical auscultation signals also presented important results in this area. This information will be described below, organized according to the main contributions they offer to speech-language pathology clinic practice.

The kinematic sources of the acoustic signs of swallowing have not been fully elucidated, despite all the possibilities involving digital cervical auscultation(44) and the importance of this interpretation. In view of this, some research based on different methodologies had this theme as the object of study.

The spectrographic profile of the pharyngeal phase of normal swallowing, for liquid and pureed consistencies, in healthy individuals, older than 18 years old, was structured by means of cervical auscultation signals obtained with an electronic stethoscope(24). The total time of the pharyngeal phase was less than 1 second and represented four swallowing events that can be analyzed from the times obtained in the digital analysis of the acoustic wave:

- the pharyngeal transit time, which had an average of 0.409 seconds and, for the analysis of normal swallows, should last approximately half of the swallowing apnea time and be positioned in the center of the graph in the spectrographic study;
- the swallowing apnea time, which had an average of 0.78 seconds and low intensity acoustic factors, and should be at the beginning (laryngeal protection activation) and at the end (opening of the glottic region) of the spectrographic representation and, therefore, its position on the graph will be higher;
- temporal relationship between the activation of the protection mechanisms of the lower airways and the beginning of the passage of the food bolus through the pharyngeal phase, which averaged 0.134 seconds and will be represented at the beginning of the spectrography graph, right after the activation of laryngeal protection;
- the time it took the larynx to return to its respiratory function after the complete passage of the food, which presented an approximate interval of 0.20 to 0.26 seconds and its position in the graph will be at the end.

A study that used cervical auscultation signals captured by a condenser microphone and images from the videofluoroscopy exam presented the division of the swallowing sound into three periods, associated with each phase of its movements: oral phase, which comprises the posterior movement of the tongue and the hyoid bone; pharyngeal phase, associated with laryngeal movement, elevation of the hyoid bone, closure of the epiglottis and passage of the bolus into the esophagus; phase of repositioning of the hyoid bone and larynx, with the reopening of the epiglottis(33).

Another study analyzed the association between high-resolution cervical auscultation signals, recorded by a contact microphone and a triaxial accelerometer, and the kinematic events of swallowing during the pharyngeal phase, assessed by images from the videofluoroscopy exam. Time and frequency domain characteristics were calculated and the maximum values of each variable, such as standard deviation, asymmetry, kurtosis, centroid frequency, bandwidth and wave entropy, were associated with hyoid elevation, laryngeal vestibule closure, opening of the superior esophageal sphincter, tongue base contact and pharyngeal posterior wall(44). Furthermore, other researchers have shown that the horizontal and vertical movements of the anterior and posterior part of the hyoid bone are also related to the sounds and vibrations of swallowing(43).

In the investigation of normal and altered swallowing in children, cervical auscultation signals were obtained by an electret condenser microphone and compared to videofluoroscopy. A first study highlighted acoustic and perceptual signs, indicative of aspiration in the presence of noisy breathing and of one or more of the following sounds after swallowing: coughing, wheezing, rales, hawking and stridor. Health professionals were encouraged to refer the patient for an additional instrumental assessment, when these signs were present on auscultation. The authors describe as a pattern indicative of normality the presence of a glottic release sound together with normal respiratory sounds after swallowing(25) Another study presented the possibility of identifying aspiration through the spectral density curve, which is a parameter capable of verifying changes in respiratory sound signals immediately after swallowing. The curve for swallowing with aspiration showed an ascending pattern, while the curve for normal swallowing was flat[37].

In a study developed with high-resolution cervical auscultation signals, the authors observed that, in order to differentiate normal from altered swallowing, a series of statistical resources should be used to analyze the characteristics of the acoustic signal[42]. When the characteristics of the high-resolution cervical auscultation signal were combined with statistical methods and machine learning techniques, they could predict whether the swallows were from healthy people or from patients with neurodegenerative diseases and suspected dysphagia, with a high degree of accuracy (99%), sensitivity (100%) and specificity (99%)[46].

Finally, when using a piezoelectric sensor to record the swallowing sounds and images from the videofluoroscopy exam, a study highlighted that the elevation delay time and the laryngeal elevation time were significantly prolonged in patients with dysphagia, especially in food with higher viscosity. In addition, the occurrence rate of the inspiration-swallowing pattern increased significantly in the group of these patients[27].

When analyzing the variations in the results obtained in relation to the characteristics of the food ingested, it could be verified, in the studies, that the larynx performs complex movements for swallowing food bolus with higher viscosity[38]; the combined use of an acoustic emission sensor and probability distribution plots (Q-Q plots) allows distinguishing viscosity differences[26]; peak amplitude measurements and energy significantly decrease with the viscosity of the food bolus, the time interval, peak to peak, and duration increase with the volume of the bolus[49]; the acoustic pattern of swallowing changes in relation to the consistency and volume of the food bolus over the years, and, in the elderly, it presents a curve with smaller amplitude and longer time than in adults[13].

To analyze the characteristics of the food, the following instruments were used: bidirectional electret condenser microphone[38]; throat condenser microphone and acoustic emission sensor[26]; Doppler sensor and omnidirectional electret condenser microphone[49]; Doppler sensor[13]. A great methodological diversity was observed in the analyzed studies. Although other devices such as electronic stethoscope, acoustic emission sensor, Doppler sensor and piezoelectric sensor have also shown important clinical results, the microphone and its combination with the accelerometer stood out. However, even when selecting these two instruments, there is a variety of models available for each one, which allow for different signal recordings.

Although the acoustic signals obtained with the microphone and the accelerometer have the same physiological sources, differences in the domains of time and frequency are observed, demonstrating that the data provided by these instruments are not interchangeable[41]. Both the sounds and vibrations of swallowing provide useful information about the function. In view of this, the combined use of the microphone and the accelerometer to obtain cervical auscultation signals may be promising for researchers in the field. They believe that the high-resolution cervical auscultation system can be a valuable contributor to dysphagia screening and, in the future, a non-invasive and adjuvant method in the diagnosis of swallowing disorders[45].

Based on the analyzed studies, it is highlighted that the selection of the most adequate instrument for capturing digital cervical auscultation signals is an essential step to be standardized for the use of this technique in speech-language pathology clinic practice. However, for these signs to provide substantial information for swallowing assessment, the analysis methodology must be carefully selected. Therefore, it is worth considering that an analysis using objective parameters also depends on the examiner's prior knowledge to interpret them, and that the greatest contribution would be if this analysis could be done automatically.

Acoustic analysis methods

Acoustic analysis of cervical auscultation signals can be performed with a variety of available resources. In the studies included in this research, LabView, Matlab, Adobe Audition, VoxMetria and Audacity softwares were identified as the most used, in addition to selected algorithms and machine learning, algorithms and signal processing program developed by authors, smartphone application and role generator. The selection of the best method is guided by the objective of each study, that is, by the characteristics to be extracted and analyzed. In addition, the possibility of creating new analysis methods has been motivating some researchers not only in the health area, but also in engineering and information technology.

Among the analysis methods, a study developed and evaluated three algorithms to detect disorder and three to detect swallowing efficiency[23]. Other researchers sought to monitor daily food intake through a smartphone application, developed and programmed with specific algorithms, to recognize and classify different food[32]. In a third study, a signal processing program was created to monitor and quantitatively assess swallowing[49]. The results of this research characterized such analysis methods developed with potential for screening and monitoring of swallowing through further research.

When combined the use of statistical resources with the acoustic analysis of cervical auscultation signals, many parameters can be obtained. However, no single statistical resource is able to differentiate safe from unsafe swallowing[40] Accordingly, researchers carried out a new study, using a wide selection of statistical parameters to characterize healthy and disturbed swallows. They observed that normal swallows in a healthy control group and in patients with dysphagia have different patterns, despite the absence of aspiration[42].

In order to collaborate with the analysis methods, machine learning algorithms, defined as an iterative process to determine accuracy from a gold standard, presented important results in the research area discussed. This resource is cited in the literature as useful for detection, recognition and classification of swallowing events. When applied in one study, the method showed a global accuracy of 97.7% for detecting acoustic events and 91.7% for swallowing sounds by glottic closure, in the presence of other noise sources (pronunciation of a phoneme and hawking sound)[21]. In another study, it produced results with maximum recognition rates of 78.4% for swallowing[28].

Machine learning use of high-resolution cervical auscultation signal resources demonstrated feasibility of accurate and automated tracking of hyoid bone displacement, without the use of videofluoroscopy exam of swallowing, with an accuracy level of 50.75%. Although this level does not seem significant, the structure of the hyoid bone is very small and, in view of this, the possibility of detecting its position in more than 50% of the swallowing segments without the use of images was considered quite remarkable[45].

As noted, machine learning algorithms proved to be a promising resource for the analysis of cervical auscultation signals in speech-language pathology clinic practice, through evidence of their high accuracy. Thus, they enabled the use of non-invasive methods of capture and automatic analysis for screening, assessment and monitoring of swallowing. However, further research is needed to standardize and validate these algorithms regarding the method used to capture the cervical auscultation signals and regarding variables such as normal swallowing and swallowing altered by different medical conditions, silent aspiration, age, gender, body mass index, food volume and consistency.

In general, different methods for capturing and analyzing signals from cervical auscultation were presented and described as to their potential for implementation in clinical practice. These methods evidenced the advances in research in partnerships between the areas of health, engineering and information technology, in search of resources that enable the recording and objective and/or automatic analysis of the signs of swallowing, with good accuracy and easy clinical applicability. In addition, the studies presented allow speech therapists to reflect on the use of technological resources in the clinic and their potential for improving the clinical assessment of oropharyngeal dysphagia.

CONCLUSION

This review revealed a current and potently growing research scenario on cervical auscultation and analysis of signs of swallowing.

The high-resolution cervical auscultation method, combined with machine learning algorithms, has shown great potential for use in speech-language pathology clinic practice for swallowing assessment and monitoring. New studies must be carried out in order to standardize and validate these methods.

REFERENCES

1. Dray TG, Hillel AD, Miller RM. Dysphagia caused by neurologic deficits. Otolaryngol Clin North Am. 1998 Jun;31(3):507-24. http://dx.doi.org/10.1016/S0030-6665(05)70067-0. PMid:9628947.
2. Macedo ED Fo, Gomes GF, Furkim AM. Manual de cuidados do paciente com disfagia. São Paulo: Lovise; 2000. 122 p.
3. Marchesan IQ. O que se considera normal na deglutição. In: Jacobi, JS, Levy DS, Silva LMC, organizadores. Disfagia: avaliação e tratamento. Rio de Janeiro: Revinter; 2003. p. 3-17.
4. Cámpora H, Falduti A. Evaluación y tratamiento de las alteraciones de la deglución. Rev Am Med Respir. [Internet]. 2012 [citado em 2020 Nov 15];12(3):98-107. Disponível em: http://www.redalyc.org/articulo.oa?id=382138394004
5. Ferrucci JL, Mangilli LD, Sassi FC, Limongi SCO, Andrade CRF. Sons da deglutição na prática fonoaudiológica: análise crítica da literatura. Einstein. 2013;11(4):535-9. http://dx.doi.org/10.1590/S1679-45082013000400024. PMid:24488399.
6. Padovani AR, Moraes DP, Mangili LD, Andrade CRF. Protocolo fonoaudiológico de avaliação do risco para disfagia (PARD). Rev Soc Bras Fonoaudiol. 2007;12(3):199-205. http://dx.doi.org/10.1590/S1516-80342007000300007.
7. Patatas OHG, Gonçalves MIR, Chiari BM, Gielow I. Parâmetros de duração dos sinais acústicos da deglutição de indivíduos sem queixa. Rev Soc Bras Fonoaudiol. 2011;16(3):282-90. http://dx.doi.org/10.1590/S1516-80342011000300008.
8. Hamlet SL, Patterson RL, Fleming SM, Jones LA. Sounds of swallowing following total laryngectomy. Dysphagia. 1992;7(3):160-5. http://dx.doi.org/10.1007/BF02493450. PMid:1499359.
9. Morinière S, Boiron M, Alison D, Makris P, Beutter P. Origin of the sound components during pharyngeal swallowing in normal subjects. Dysphagia. 2008 Set;23(3):267-73. http://dx.doi.org/10.1007/s00455-007-9134-z. PMid:18071792.
10. Spadotto AA, Gatto AR, Cola PC, Montagnoli AN, Schelp AO, Silva RG, et al. Software para análise quantitativa da deglutição. Radiol Bras. 2008;41(1):25-8. http://dx.doi.org/10.1590/S0100-39842008000100008.
11. Santini CS. Disfagia neurogênica. In: Furkim AM, Santini CS, organizadores. Disfagias orofaríngeas. São Paulo: Pró Fono; 2001. p. 19-34.
12. Santos RS, Macedo-Filho E. D. Sonar Doppler como instrumento de avaliação da deglutição. Arq Int Otorrinolaringol. 2006;10(3):82-91.
13. Soria FS, Silva RG, Furkim AM. Acoustic analysis of oropharyngeal swallowing using Sonar Doppler. Rev Bras Otorrinolaringol. 2016 Jan-Fev;82(1):39-46. http://dx.doi.org/10.1016/j.bjorl.2015.12.001. PMid:26718958.
14. Montoni NPC. Métodos instrumentais complementares. In: Dedivitis RA, Santoro PP, Arakawa-Sugueno L, organizadores. Manual prático de disfagia: diagnóstico e tratamento. Rio de Janeiro: Revinter; 2017.
15. Vale-Prodomo LP, Carrara-de-Angelis E, Barros APB. Avaliação clínica fonoaudiológia das disfagias. In: Jotz GP, Carrara-de-Angelis E, Barros APB, organizadores. Tratado de deglutição e disfagia: no adulto e na criança. Rio de Janeiro: Revinter; 2009. p. 61-7.
16. Castro E, Fonseca L, Matos JP, Bernardo T, Silva AP. Videoendoscopia da deglutição: protocolo de avaliação. Port J ORL. 2012;50(3):197-204. http://dx.doi.org/10.34631/sporl.112.

17. Coriolano MGWS, Lins OG, Belo LR, Menezes DC, Moraes SRA, Asano AG, et al. Monitorando a deglutição através da eletromiografia de superfície. Rev CEFAC. 2020;12(3):434-40. http://dx.doi.org/10.1590/S1516-18462010005000015.

18. Honda T, Baba T, Fujimoto K, Nagao K, Takahashi A, Ichikawa T. Swallowing sound waveform and its clinical significance: evaluation using ultrasonography. J. Oral Health Biosci. 2015;28(1):21-7.

19. Gonçalves MIR, Oliveira IC No. Diagnóstico instrumental na deglutição normal e patológica. In: Fernandes FDM, Mendes BCA, Navas ALPGP, organizadores. Tratado de Fonoaudiologia. 2. ed. São Paulo: Roca; 2009. p. 468-70.

20. Youmans SR, Stierwalt JA. Normal swallowing acoustics across age, gender, bolus viscosity, and bolus volume. Dysphagia. 2011;26(4):374-84. http://dx.doi.org/10.1007/s00455-010-9323-z. PMid:21225287.

21. Sánchez-Cardona Y, Orozco-Duque A, Roldán-Vasco S. Caracterización y clasificación de señales de auscultación cervical adquiridas con estetoscopio para detección automática de sonidos deglutorios. Rev Mex Ing Biomed. 2018;39(2):205-16. http://dx.doi.org/10.17488/RMIB.39.2.6.

22. Dudik JM, Coyle JL, Sejdić E. Dysphagia screening: contributions of cervical auscultation signals and modern signal-processing techniques. IEEE Trans Hum Mach Syst. 2015;45(4):465-77. http://dx.doi.org/10.1109/THMS.2015.2408615. PMid:26213659.

23. Steele CM, Mukherjee R, Kortelainen JM, Pölönen H, Jedwab M, Brady SL, et al. Development of a non-invasive device for swallow screening in patients at risk of oropharyngeal dysphagia: results from a prospective exploratory study. Dysphagia. 2019;34(5):698-707. http://dx.doi.org/10.1007/s00455-018-09974-5. PMid:30612234.

24. Vargas García M. Perfil espectrográfico de la deglución normal en el adulto. Nutr Hosp. 2019;36(2):412-9. http://dx.doi.org/10.20960/nh.2173. PMid:30836762.

25. Frakking T, Chang A, O'Grady K, David M, Weir K. Aspirating and nonaspirating swallow sounds in children: a pilot study. Ann Otol Rhinol Laryngol. 2016;125(12):1001-9. http://dx.doi.org/10.1177/0003489416669953. PMid:27683588.

26. Chikai M, Kamiyanagi A, Kimura K, Seki Y, Endo H, Sumita Y, et al. Pilot study on an acoustic measurements system of the swallowing function using an acoustic-emissions microphone. J Adv Comput Intell Intell Informar. 2017;21(2):293-300. http://dx.doi.org/10.20965/jaciii.2017.p0293.

27. Yagi N, Nagami S, Lin MK, Yabe T, Itoda M, Imai T, et al. A noninvasive swallowing measurement system using a combination of respiratory flow, swallowing sound, and laryngeal motion. Med Biol Eng Comput. 2017;55(6):1001-17. http://dx.doi.org/10.1007/s11517-016-1561-2. PMid:27665103.

28. Lee KS. Food intake detection using ultrasonic doppler sonar. IEEE Sens J. 2017;17(18):6056-68. http://dx.doi.org/10.1109/JSEN.2017.2734688.

29. Cagliari CF, Jurkiewicz AL, Santos RS, Marques JM. Análise por sonar Doppler dos sons da deglutição em indivíduos pediátricos normais. Rev Bras Otorrinolaringol. 2009;75(5):706-15. http://dx.doi.org/10.1590/S1808-86942009000500016.

30. Mendes KDS, Silveira RCCP, Galvão CM. Revisão integrativa: método de pesquisa para a incorporação de evidências na saúde e na enfermagem. Texto Contexto Enferm. 2008;17(4):758-64. http://dx.doi.org/10.1590/S0104-07072008000400018.

31. Botelho LLR, Cunha CCA, Macedo M. O método da revisão integrativa nos estudos organizacionais. GeS. 2011;5(11):121-36. http://dx.doi.org/10.21171/ges.v5i11.1220.

32. Bi Y, Lv M, Song C, Xu W, Guan N, Yi W. AutoDietary: a wearable acoustic sensor system for food intake recognition in daily life. IEEE Sens J. 2016;16(3):806-16. http://dx.doi.org/10.1109/JSEN.2015.2469095.

33. Honda T, Baba T, Fujimoto K, Goto T, Nagao K, Harada M, et al. Characterization of swallowing sound: preliminary investigation of normal subjects. PLoS One. 2016;11(12):e0168187. http://dx.doi.org/10.1371/journal.pone.0168187. PMid:27959902.

34. Kamiyanagi A, Sumita Y, Ino S, Chikai M, Nakane A, Tohara H, et al. Evaluation of swallowing ability using swallowing sounds in maxillectomy patients. J Oral Rehabil. 2018;45(2):126-31. http://dx.doi.org/10.1111/joor.12593. PMid:29197111.

35. Li Q, Minagi Y, Ono T, Chen Y, Hori K, Fujiwara S, et al. The biomechanical coordination during oropharyngeal swallowing: an evaluation with a non-invasive sensing system. Sci Rep. 2017;7(1):15165. http://dx.doi.org/10.1038/s41598-017-15243-6. PMid:29123186.

36. Frakking TT, Chang AB, O'Grady KF, Yang J, David M, Weir KA. Acoustic and perceptual profiles of swallowing sounds in children: normative data for 4–36 months from a cross-sectional study cohort. Dysphagia. 2017;32(2):261-70. http://dx.doi.org/10.1007/s00455-016-9755-1. PMid:27830392.

37. Almeida ST, Ferlin EL, Maciel AC, Fagondes SC, Callegari-Jacques SM, Fornari F, et al. Acoustic signal of silent tracheal aspiration in children with oropharyngeal dysphagia. Logoped Phoniatr Vocol. 2018;43(4):169-74. http://dx.doi.org/10.1080/14015439.2018.1487993. PMid:30111199.

38. Kurihara T, Kaburagi T, Kumagai S, Matsumoto T. Development of swallowing-movement-sensing device and swallowing-state-estimation system. IEEE Sens J. 2019;19(9):3532-42. http://dx.doi.org/10.1109/JSEN.2019.2894744.

39. Miyagi S, Sugiyama S, Kozawa K, Moritani S, Sakamoto SI, Sakai O. Classifying dysphagic swallowing sounds with support vector machines. Healthcare . 2020;8(2):103. http://dx.doi.org/10.3390/healthcare8020103. PMid:32326267.

40. Dudik JM, Kurosu A, Coyle JL, Sejdić E. A statistical analysis of cervical auscultation signals from adults with unsafe airway protection. J Neuroeng Rehabil. 2016;13(1):7. http://dx.doi.org/10.1186/s12984-015-0110-9. PMid:26801236.

41. Movahedi F, Kurosu A, Coyle JL, Perera S, Sejdić E. A comparison between swallowing sounds and vibrations in patients with dysphagia. Comput Methods Programs Biomed. 2017;144:179-87. http://dx.doi.org/10.1016/j.cmpb.2017.03.009. PMid:28495001.

42. Dudik JM, Kurosu A, Coyle JL, Sejdić E. Dysphagia and its effects on swallowing sounds and vibrations in adults. Biomed Eng Online. 2018;17(1):69. http://dx.doi.org/10.1186/s12938-018-0501-9. PMid:29855309.

43. Rebrion C, Zhang Z, Khalifa Y, Ramadan M, Kurosu A, Coyle JL, et al. High-resolution cervical auscultation signal features reflect vertical and horizontal displacements of the hyoid bone during swallowing. IEEE J Transl Eng Health Med. 2018;7:1800109. http://dx.doi.org/10.1109/jtehm.2018.2881468. PMid:30701145.

44. Kurosu A, Coyle JL, Dudik JM, Sejdic E. Detection of swallow kinematic events from acoustic high-resolution cervical auscultation signals in patients with stroke. Arch Phys Med Rehabil. 2019;100(3):501-8. http://dx.doi.org/10.1016/j.apmr.2018.05.038. PMid:30071198.

45. Donohue C, Mao S, Sejdić E, Coyle JL. Tracking hyoid bone displacement during swallowing without videofluoroscopy using machine learning of vibratory signals. Dysphagia. 2021 Abr;36(2):259-69. http://dx.doi.org/10.1007/s00455-020-10124-z. PMid:32419103.

46. Donohue C, Khalifa Y, Perera S, Sejdić E, Coyle JL. A preliminary investigation of whether hrca signals can differentiate between swallows from healthy people and swallows from people with neurodegenerative diseases. Dysphagia. 2021 Ago;36(4):635-43. http://dx.doi.org/10.1007/s00455-020-10177-0. PMid:32889627.

47. Kamiyanagi A, Sumita Y, Chikai M, Kimura K, Seki Y, Ino S, et al. Evaluation of swallowing sound using a throat microphone with an AE sensor in patients wearing palatal augmentation prosthesis. J Adv Comput Intell Intell Informar. 2017;21(3):573-80. http://dx.doi.org/10.20965/jaciii.2017.p0573.

48. Taveira KVM, Santos RS, Leão BLC, Stechman J No, Pernambuco L, Silva LKD, et al. Diagnostic validity of methods for assessment of swallowing sounds: a systematic review. Rev Bras Otorrinolaringol. 2018;84(5):638-52. http://dx.doi.org/10.1016/j.bjorl.2017.12.008. PMid:29456200.

49. Choi Y, Kim M, Lee B, Yang X, Kim J, Kwon D, et al. Development of an ultrasonic doppler sensor-based swallowing monitoring and assessment system. Sensors. 2020;20(16):4529. http://dx.doi.org/10.3390/s20164529. PMid:32823533.

50. Cichero JA, Murdoch BE. Detection of swallowing sounds: methodology revisited. Dysphagia. 2002;17(1):40-9. http://dx.doi.org/10.1007/s00455-001-0100-x. PMid:11824392.

Appendix A. Database search strategy

Scopus	(TITLE-ABS-KEY (deglutition) OR TITLE-ABS-KEY (deglutitions) OR TITLE-ABS-KEY (swallowing) OR TITLE-ABS-KEY (swallowings) OR TITLE-ABS-KEY (swallow) OR TITLE-ABS-KEY (swallows) AND TITLE-ABS-KEY ("acoustic analysis") OR TITLE-ABS-KEY ("acoustical analysis") OR TITLE-ABS-KEY (auscultation) OR TITLE-ABS-KEY ("cervical auscultation") OR TITLE-ABS-KEY ("swallowing sounds") OR TITLE-ABS-KEY ("swallow sounds") OR TITLE-ABS-KEY ("signal processing") OR TITLE-ABS-KEY (acoustics) OR TITLE-ABS-KEY (acoustic) OR TITLE-ABS-KEY (software) AND TITLE-ABS-KEY (accelerometry) OR TITLE-ABS-KEY ("swallowing accelerometry signals") OR TITLE-ABS-KEY (stethoscope) OR TITLE-ABS-KEY ("digital stethoscope") OR TITLE-ABS-KEY ("electronic stethoscope") OR TITLE-ABS-KEY ("doppler effect") OR TITLE-ABS-KEY ("sonar doppler") OR TITLE-ABS-KEY (microphone))
MEDLINE/ Pubmed	(("deglutition"[Title/Abstract] OR "deglutitions"[Title/Abstract] OR "swallowing"[Title/Abstract] OR "swallowings"[Title/Abstract] OR "swallow"[Title/Abstract] OR "swallows"[Title/Abstract]) AND ("acoustic analysis"[Title/Abstract] OR "acoustical analysis"[Title/Abstract] OR "auscultation"[Title/Abstract] OR "cervical auscultation"[Title/Abstract] OR "swallowing sounds"[Title/Abstract] OR "swallow sounds"[Title/Abstract] OR "signal processing"[Title/Abstract] OR "acoustics"[Title/Abstract] OR "acoustic"[Title/Abstract] OR "software"[Title/Abstract])) AND ("accelerometry"[Title/Abstract] OR "swallowing accelerometry signals"[Title/Abstract] OR "stethoscope"[Title/Abstract] OR "digital stethoscope"[Title/Abstract] OR "electronic stethoscope"[Title/Abstract] OR "doppler effect"[Title/Abstract] OR "sonar doppler"[Title/Abstract] OR "microphone"[Title/Abstract])
Web of Science	TS=(deglutition OR deglutitions OR swallowing OR swallowings OR swallow OR swallows) AND TS=(acoustic analysis OR acoustical analysis OR auscultation OR cervical auscultation OR swallowing sounds OR swallow sounds OR signal processing OR acoustics OR acoustic OR software) AND TS=(accelerometry OR swallowing accelerometry signals OR stethoscope OR digital stethoscope OR electronic stethoscope OR doppler effect OR sonar doppler OR microphone)