Literature Review

https://doi.org/10.1590/2317-6431-2022-2725en

Audiology Communication Research
ISSN 2317-6431

Methods used in morphometric analysis of singers' vocal tracts: an integrative review

Métodos utilizados na análise morfométrica do trato vocal em cantores: revisão integrativa

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ABSTRACT

Purpose: To describe the main quantitative methods used for morphometric analysis of the vocal tract in singers, their applications and the main segments studied. **Research strategy:** This is an integrative review guided by the guiding question "What are the main quantitative methods used for morphometric analysis of the vocal tract, their applications and the main segments studied in singers?". The electronic databases PubMed, Scopus and VHL were used through the search key (Vocal tract OR Oropharynx) AND (Morphology OR Geometry) AND (Evaluation OR Diagnosis) AND (voice), without restriction of years of publication, including articles in three languages: Portuguese, English and Spanish. **Selection criteria:** The selection took place independently through reading by pairs and subsequent application of exclusion and inclusion criteria. **Results:** Of the 380 studies, 30 duplicates were excluded. After reading the abstracts, applying the selection criteria, 18 studies were selected for full reading, of which 12 were included in this review. Magnetic resonance imaging was the main instrument used and the analyzed segments ranged from the length and volume of the vocal tract to isolated segments and their morphological particularities. **Conclusion:** Vocal tract morphological quantification methods are important for the instrumental evaluation of the vocal tract and its segments, a technological update leading to better understanding of singers' voice and therapeutical intervention.

Keywords: Voice; Sing; Oropharynx; Larynx; Voice quality

RESUMO

Objetivo: descrever os principais métodos quantitativos utilizados para análise morfométrica do trato vocal em cantores, suas aplicações e os principais segmentos estudados. **Estratégia de pesquisa:** trata-se de uma revisão integrativa guiada pela pergunta condutora: "Quais os principais métodos quantitativos utilizados para análise morfométrica do trato vocal, suas aplicações e os principais segmentos estudados em cantores?". Foram utilizadas as bases eletrônicas PubMed, Scopus e BVS, por meio da chave de busca *Vocal tract OR Oropharynx AND Morphology OR Geometry AND Evaluation OR Diagnosis AND voice,* sem restrições de ano de publicação, sendo incluídos artigos em três idiomas: português, inglês e espanhol. **Critérios de seleção:** a seleção se deu de forma independente, por meio da leitura por pares e posterior aplicação dos critérios de exclusão e inclusão. **Resultados:** dos 380 estudos, foram excluídos 30 duplicados. A partir da leitura dos resumos, aplicando-se os critérios de seleção, foram selecionados 18 estudos para leitura na íntegra, dos quais, 12 foram incluídos nesta revisão. A ressonância magnética foi o principal instrumento utilizado e os segmentos analisados incluíram desde o comprimento e volume do trato vocal, como segmentos isolados e suas particularidades morfológicas. **Conclusão:** os métodos de quantificação morfológica do trato vocal integram instrumentos importantes para a avaliação instrumental do trato vocal e de seus segmentos, colaborando na atualização tecnológica em voz para melhor compreensão e intervenções fonoaudiológicas na voz cantada.

Palavras-chave: Voz; Canto; Orofaringe; Laringe; Qualidade da voz

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Conflict of interests: No.
Authors' contribution: DLSC participated in study idealization, data collection, analysis, and interpretation, and article writing; KGSCO participated in study idealization, data analysis and interpretation, and article writing; DBLAB participated in study idealization, data collection, analysis, and interpretation, and article writing; GFN participated in data analysis and interpretation; HJS participated in study idealization and data interpretation; AOCG participated in study idealization, data analysis and interpretation, and article writing.
Funding: Fundação de Amparo à Ciência e Pesquisa de Pernambuco (FACEPE) – Scientific Initiation Fellow: Edital_FACEPE_01-2020_PIBIC; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – finance code 001 and Pró-Reitoria de Pós-Graduação, Universidade Federal de Pernambuco - Edital PROPG nº 06/2022.
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Received: November 21, 2022; Accepted: January 28, 2023

INTRODUCTION

Technological advancements in laryngology and modernized voice and vocal tract (VT) assessment instruments favor studies in the field, improving and updating experts' knowledge. These instruments make it possible to demonstrate scientific evidence from speech-language-hearing (SLH) interventions to promote good voice use in individuals submitted to speech therapy[1].

VT is delimited by the supraglottal region and configured according to the movement of the structures that make up the stomatognathic system, working as a filter and favoring voice resonance. Thus, different harmonics are amplified, originating the formants, and characterizing voice quality. The vocal folds (VF) are identified as the sound source and the supraglottal region (resonating system), as the filter[2-5].

SLH voice assessments count on elements that consider the multidimensionality of the voice, including auditory-perceptual assessment and computerized acoustic analysis – which is complementary to clinical SLH assessment[6-9]. Over the decades, voice assessment has been constantly improved in SLH therapy, otorhinolaryngology, and head and neck surgery[6].

Singers can explore the interactions between VT and the glottal source to improve their efficiency[10]. Applying instruments that quantitatively assess VT morphology helps understand the conformation of this system and makes it possible to assess the effect of using vocal techniques and their relationship with VT morphology[11].

The instrumental methods that measure the different VT structures include radiography (X-ray), magnetic resonance imaging (MRI), computed tomography scan (CT scan) (TC), cone beam CT scan (CBCT), and acoustic pharyngometry (AP). All these methods measure the various VT structure dimensions[12-17].

X-Ray and MRI assess inner anatomical structures through a sagittal projection of the upper airways and detailed visualization of the laryngeal, pharyngeal, and oral cavities, and VT articulators[12-13]. CBCT identifies anatomical and functional changes in the oropharyngeal space, VT soft tissue structures, and oropharyngeal measurements[18]. AP is a technique that measures the area, volume, and length of the oral and oropharyngeal cavities to the glottal region through acoustic signals[16].

This study included VF morphometric analyses as well, attentive to the fact that some instrumental VT assessment methods (e.g., AP, X-ray, and CT scan) include and make it possible to measure the glottal area[11, 19-21].

Studies with instrumental methods often explore singing voices, as this population needs to regulate the VT shape to produce a superior voice in terms of harmonic sources. Moreover, specific VT and VF dimensions and formant frequencies are associated with different singing voice classifications[10-12, 22].

Such quantitative measures obtained with instrumental methods can be quite useful in SLH clinical practice. Morphometric analyses in combination with instruments that assess the acoustic signal provide precise and reliable results related to the effects of applied vocal techniques. They are also useful to classify singers' ideal voices, define the most adequate VT adjustment to the individual, and select vocal techniques that better explore certain VT areas related to singing and therapy goals[11-13, 22].

The importance of instrumental methods must be highlighted. Their quantitative data favor comparative SLH diagnostic and intervention studies, minimizing subjective aspects in voice assessment[12-13, 22].

Given the above and the awareness that voice assessment methods are mostly qualitative, it can be inferred that a review study on this topic will help researchers and therapists understand the state-of-the-art use of instrumental methods in singers. Hence, it may broaden their knowledge and posterior application in studies, with great scientific evidence, in individuals with vocal pathologies or other occupational voice users, to standardize the measures of VT structures in each study population. Understanding how instruments are used to assess VT morphometry helps choose the assessment method, considering, for instance, their cost, details, and invasiveness to the detriment of the intended results.

Thus, this review contributes not only to expanding SLH knowledge of voice but also understanding the VT dynamics in singing. It also helps health professionals and singing teachers to understand vocal strategies and indicate adequate exercises according to these dynamics, such as articulating vocal techniques that better explore certain VT areas related to the goals of singing.

OBJECTIVE

To describe the main quantitative methods used in the morphometric analysis, their applications, and the main VT segments studied in singers.

RESEARCH STRATEGY

This integrative review was constructed based on the following question: "What are the main quantitative methods used in morphometric VT analysis, their applications, and the main segments studies in singers?".

The PVO strategy was conducted as follows: population (P): adolescent and/or adult singers; study variable (V): VT; outcomes (O): quantitative methods used, applications, and main segments studied. This study searched the main databases available in October and November 2021, namely: PubMed, Scopus, and Virtual Health Library (VHL). There were technical limitations to the number of databases, as there was no institutional access to the CAPES journal platform for approximately 30 days, restricting the search to only three databases.

There was no restriction on the year of publication, and articles in three languages (Portuguese, English, and Spanish) were included. To retrieve as many articles as possible, a search key was used in association with the Boolean operators "AND" and "OR", as follows: Vocal tract OR Oropharynx AND Morphology OR Geometry AND Evaluation OR Diagnosis AND voice. All descriptors used in the search keys were obtained from the Medical Subject Headings (MeSH) and/or Free Terms databases.

SELECTION CRITERIA

Three independent reviewers participated in the study. Firstly, two evaluators selected the articles, beginning by reading their titles and abstracts and then their full texts, following the preestablished inclusion and exclusion criteria. Divergences regarding data selection and extraction were discussed between the reviewers at the end of each stage to reach a consensus. If they still did not agree, a third evaluator was consulted.

The initial paper selection stage, in which article titles and abstracts were assessed, was conducted on the Rayyan platform. After selecting studies by abstract reading, those previously selected were read in full text. Then, the research included original articles that approached professional and/or amateur adolescent and adult singers of both sexes, using quantitative methods, their applications, and segments studied in singers' VT morphometric analysis.

There was no restriction on study design, as long as they described adolescent and/or adult human singers that had been submitted to quantitative morphometric VT analysis methods. The exclusion criteria were as follows: literature reviews; editorials; book chapters; studies in occupational voice users other than singers or in singers with VT pathologies; and any other factor that did not meet the eligibility criteria.

DATA ANALYSIS

The reviewers independently extracted the following data from the selected articles in digital format: article title, authors' names, year of publication, country, study type and objective, method, sample size, the age range of the study group, VT assessment method, segments assessed, method applications, main conclusions of the studies, and level of evidence.

Data extracted from the studies were descriptively compiled in a previously developed Excel table to synthesize article information and identify and reformulate topic categorization.

Lastly, the levels of evidence were analyzed through a hierarchy pyramid of medical evidence. The analysis was based on a meta-analysis and systematic review to assess the level of evidence, reconfiguring the pyramids according to study type and/or applicability to a model, with randomized case-control studies at the top of the pyramid, and then cohort studies, case-control studies, and case series or reviews at the base[23].

RESULTS

Altogether, 380 studies were identified in the initial search. Of these, 48 articles were selected after reading their titles and abstracts. After removing the duplicates, 18 articles were read in full text. Lastly, 12 articles were selected after excluding the ones that did not meet the methodological eligibility criteria (Figure 1).

After analyzing all studies included in the integrative review, it was verified that one of them was a nonrandomized experimental study (level of evidence 3)[11], six were observational studies (level of evidence 4)[19-21, 24-26], and five were case studies and/or series (level of evidence 5)[12, 22, 26-28], according to the classification used by Murad et al. [23].

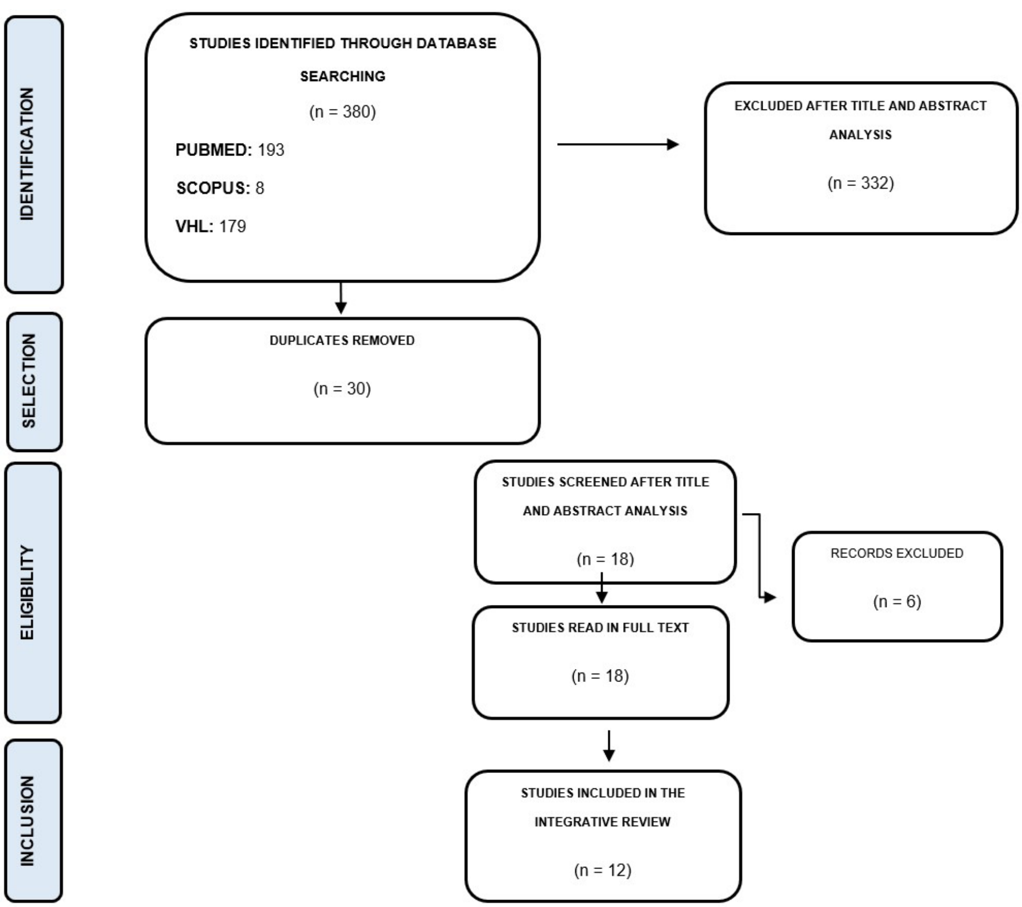

Figure 1. Flowchart of article screening
Subtitle: n = number of articles

Studies included in the review were produced between 2009 and 2020. The participants in all studies were singers of both sexes, aged 16 to 69 years.

The articles approached in this study are from Europe[12, 19-22, 25-29], America[11], and Eurasia[24].

As for quantitative morphometric analysis methods, six studies used MRI RMN[12, 24, 28-30], two used CT scan[19, 21], one used AP[11], one used X-ray[14], one used ultrasound (USG) associated with MRI[27], and one used electroglottography (EGG) – which does not directly measure the VT and its segments but, using mathematical and physical calculations, establishes VT length[25] to quantify its assessment.

The studies had various applications of the quantitative methods: assessment of vocal techniques used on VT[11], the study of morphological VF changes[19], measurement of thyrohyoid ligaments[24], measurement of mandible drop in a singing maneuver[27], measurement of VF length, VT assessment in singing when emitting German vowels[26], assessment of volume and area of VT segments[29], analysis of the influence of vocal conditions on VT[30], the relationship between VF length and classical voice types[21], observation of VT morphological differences to the detriment of supine and erect positions[12], analysis of VT area in tenors[28], and implications of the *passagio* (transition notes) to VT morphology[25].

Concerning segments, the studies analyzed different areas: oral cavity length and volume, pharyngeal cavity length and volume, VT length and volume, oropharyngeal junction area, glottal area[11], subglottal-tracheal anteroposterior distance, VF anterior end distance[20], laryngeal height, endolaryngeal area and volume, hypopharyngeal area and volume[26], oral cavity volume and area, oropharyngeal volume and area[29], lip opening, tongue dorsum, mandible opening and protrusion, pharyngeal width, uvula length, laryngeal position and angle[30], VF length[21], the distance between the tip of the tongue and the hard palate, oropharyngeal width, uvula elevation, laryngeal vertical position and tilt angle[12], VT length[25], VT area[28], VF angle[19], thyrohyoid ligaments[24], and extent of mandible drop[27].

Thus, summarizing the VT segments analyzed, the main ones reported in studies in singers were the oral cavity, oropharynx, hypopharynx, and articulators, whose measures – e.g., length, volume, area, distance, height, elevation, lip opening, VF angle, and structure position – were analyzed in the said information (Chart 1).

Chart 1. Method(s), application, and segment(s) analyzed

AUTHOR(S) AND YEAR	METHOD(S)	APPLICATION	SEGMENT(S)	MAIN RESULT(S)
Oliveira et al.[11] (2020)	AP	Assessment of the effect of vocal techniques on VT.	Oral cavity length and volume, pharyngeal cavity length and volume, VT length and volume, oropharyngeal junction area, and glottal area.	VT length was greater in the group that used FRT than in those who performed VLVT. Also, GNE improved, and noise decreased, only in the group of singers submitted to VLVT.
Unteregger et al.[19] (2020)	CT scan	Study of VF morphological changes.	VF angle.	Results suggest that TA has greater action during emission in f0 than in 2f0, as the VF angle is greater in f0. The CT muscle contracts and VF is thinner in 2f0; however, CT contraction is maintained, and the VF angle increases in 4f0, which suggests TA action to maintain subglottal pressure at higher frequencies.
Berdan et al.[24] (2019)	MRI	LTL measurement	LTL	LTL length was greater in men. This finding confirms specific laryngeal structure differences between the sexes. Vocal training time did not make a difference in LTL in the groups; the acoustic voice analysis improved in the group with vocal training.
Nair et al.[27] (2016)	MRI and ultrasound	Measurement of the extent of mandible drop in a singing maneuver.	The extent of mandible drop.	The extent of mandible drop in MLM ranged from 0.7 to 3.1 cm, which increased the first harmonics and improved the singer's formant.
Roers et al.[14] (2009)	X-ray	VF length measurement.	Subglottal-tracheal anteroposterior distance and VF anterior end distance.	Morphological measures in the X-ray of TS (between the thyroid cartilage and the anterior contour of the nearest cervical vertebra) and STAP distances (anteroposterior diameter of the subglottal and tracheal contour) are correlated with VF length. There was a covariation between VF length measured in X-ray and vocal classifications.

Subtitle: AP = acoustic pharyngometry; MRI = magnetic resonance imaging; CT scan = computed tomography scan; EGG = electroglottography; FRT = flexible resonance tube; VF = vocal folds; VT = vocal tract; LTL = lateral thyrohyoid ligament; CT = cricothyroid; TA = Thyroarytenoid; F1 = first formant; MLM = mandible lowering maneuver; VLVT = voiced lip vibration technique; f0 = fundamental frequency; GNE = glottal-to-noise excitation ratio; TS = segment between the thyroid cartilage and the anterior contour of the nearest cervical vertebra; STAP = anteroposterior diameter of the subglottal and tracheal contour.

Chart 1. Continued...

AUTHOR(S) AND YEAR	METHOD(S)	APPLICATION	SEGMENT(S)	MAIN RESULT(S)
Mainka et al.[26] (2015)	MRI	VT assessment in German vowel emission in singing.	Laryngeal height, endolaryngeal area and volume, hypopharyngeal area and volume.	Singing vowels, in contrast with speech vowels, were produced with lowered larynx, greater cross-sectional area and lower hypopharyngeal volume, and smaller proportion of the laryngeal-hypopharyngeal area and volume. There was a significant variance of all lower VT measures with vowel quality. Combined lowered larynx and widened hypopharynx were found in vowels /o/ and /u/ emitted in singing. Acoustically, there was an increase in high-frequency energy when singing above 2 kHz, correlated with a broader hypopharyngeal area. There was also evidence that the fourth formant displaced down with lower VT structures in the singing configuration.
Mainka et al.[29] (2017)	MRI	Assessment of volume and area of VT segments.	Oral cavity volume and area, oropharyngeal volume and area, hypopharyngeal volume and area, and endolaryngeal volume and area.	Morphological data based on multiple images with the segmentation model were highly reproducible, with an overall variation of around 8%. 3D data on VT morphology based on various MRI images during phonation can be generated with high precision in experienced singers.
Echternach et al.[30] (2014)	MRI	Analysis of the influence of vocal conditions on VT.	Lip opening, tongue dorsum, mandible opening and protrusion, pharyngeal width, uvula length, and laryngeal position and angle.	Falsetto after the passage note was performed with similar VT shapes in the various vowels emitted. However, some articulators, such as pharyngeal width, changes along with the vowels.
Clarós et al.[21] (2019)	CT scan	Relationship between VF length and classical voice types.	VF length	The analysis confirmed a linear correlation between VF length and individual body characteristics, such as height and body mass index.
Traser et al.[12] (2014)	MRI	Observation of VT morphological differences in relation to body supine and erect positions.	Lip opening, mandible opening and protrusion, the distance between the tip of the tongue and the hard palate, oropharyngeal width, uvula elevation, and laryngeal vertical position and tilt angle.	There are few VT configuration differences between the positions analyzed. VT changes associated with register and tuning are not much affected by the position.
Echternach et al.[28] (2011)	MRI	Analysis of VT area in tenors.	VT area.	VT shapes in vowel /a/ differ between the modal register and falsetto. The oral cavity was wider in the modal register. Moreover, F1 was greater in the modal register than in the falsetto.
Andrade[25] (2012)	EGG	Implications of the *passagio* to VT morphology.	VT length.	Western classical singers tend to lower the larynx in the neck after the passage, thickening the VF, reducing central formant frequencies, and thus increasing supraglottal cavities.

Subtitle: AP = acoustic pharyngometry; MRI = magnetic resonance imaging; CT scan = computed tomography scan; EGG = electroglottography; FRT = flexible resonance tube; VF = vocal folds; VT = vocal tract; LTL = lateral thyrohyoid ligament; CT = cricothyroid; TA = Thyroarytenoid; F1 = first formant; MLM = mandible lowering maneuver; VLVT = voiced lip vibration technique; f0 = fundamental frequency; GNE = glottal-to-noise excitation ratio; TS = segment between the thyroid cartilage and the anterior contour of the nearest cervical vertebra; STAP = anteroposterior diameter of the subglottal and tracheal contour.

DISCUSSION

The results show that MRI was the most used method[12, 24, 26-30], presented as the most up-to-date technique in VT functional visualization. It acquires images during phonation and makes it possible to better understand VT physiology.

MRI can be dynamic (using a single image), analyzing the dimension of only one VT cross-section, and thus inferring conclusions on the whole VT behavior. It can also be static (using various images) to cover the whole 3D anatomy of the VT; in this case, the vocal state must be constant, without variations in tone, timbre, or volume[29].

MRI presents satisfactory volume and area assessment results of VT segments[12, 24, 26-30]. However, it is high-cost equipment, which may hinder its use in studies[31].

Instructing singers about the mechanism of voice production physiology stimulates sensory-motor self-awareness of their VT[32]. MRI provides such knowledge, and its clinical application may benefit vocal adjustment control, according to the requirements of each musical piece and style.

Adjustments in non-phonating VT shapes can facilitate voice production. In subjects who had learned to individually adjust VT shape, it was demonstrated that non-phonating VT adjustment is maintained during voice production and affects voice efficiency[33].

High-resolution MRI revealed differences in lower VT geometry in speech and singing during sustained vowels. The combination of the lowered larynx and widened hypopharynx was found in vowels /o/ and /u/ emitted in singing. Moreover, the fourth formant was displaced down in singing in subjects with a smaller VT[26]. Taking such quantitative measurements makes it possible to standardize VT structure measures in different populations.

After MRI, CT scan was the second most used method[19, 21], ahead of the X-ray[14], EGG[25], AP[11], and combined MRI and ultrasound[27].

CT scan is considered the gold standard to assess laryngeal structures, providing high-quality axial images of true VF and laryngeal cartilages. Moreover, its measurements have high precision and reproducibility[19, 21]. This review found that the CT scan made it possible to assess VF length[21] in singers of different voice classifications. This analysis confirmed a linear correlation between VF length and individual body characteristics, such as height and body mass index, helping elucidate the various laryngeal and VT structures found in different singing voice classifications[14, 34].

CT scan also assessed the VF angle in different octaves. This angle is associated with thyroarytenoid (TA) muscle action during emissions, making it possible to understand that TA is more active during fundamental frequency emission than in its octave. However, in the following octave, the VF angle increases again, which suggests a TA action to maintain subglottal pressure at higher frequencies[19].

The X-ray provided morphological measures between the thyroid cartilage and anterior contour of the nearest cervical vertebra and the distance of the anteroposterior diameter of the subglottal and tracheal contour – which are measures correlated with VF length. Previous studies have used X-rays to measure VF length[14,19]. Although AP was used in only one South American study[11], it is a quick, noninvasive, easily applied method[15-16]. It does not provide VT images for analysis, but on the other hand, it effectively measures volume, length, and area, corroborating oropharyngeal geometry studies[11,15-16]. However, it does not enable VT functional assessments, and its application to study specific VT segments is limited due to the lack of images.

Ultrasound was used along with MRI, which is justified because it produces videos of the phonation moment, resourcefully enriching study data with stop action[27]. EGG, although it does not directly measure VT and its segments, quantified VT length when used in combination with mathematical and physical calculations. This tool showed that Western classical singers tend to lower the larynx in the neck after the passage, slightly thickening VF, reducing central formant frequencies, and thus increasing supraglottal cavities[25].

Concerning the segments analyzed, VF were addressed in four studies[11,14,19,21]. They assessed their length[11,21], glottal area[11], the angle of each VF[19], subglottal-tracheal anteroposterior distance, and VF anterior end distance[14]. VF length was widely analyzed by the studies, as different sizes can predispose vocal frequency and timbre characteristics and singing voice classifications[14, 19].

Adjustments according to vocal frequency and intensity variations are also important to speech and singing voice production. These variations are necessary for singing and are also associated with changes throughout the VT, as singers can explore the interactions between VT and the glottal source to improve their efficiency[10].

The oral cavity was assessed in two studies[11,29], which measured its length[11], area[29], and volume[11,29]. Adjacent structures correlated with the oral cavity that participate in associated functions were also analyzed, namely: lip opening, tongue dorsum, mandible opening and protrusion, uvula length, the distance between the tip of the tongue and the hard palate, uvula elevation, and extent of mandible drop[12,27,30].

Pharyngeal segments were also studied, measuring hypopharyngeal area and volume[26,29], oropharyngeal volume and area[29], oropharyngeal width[12], and oropharyngeal junction area[11].

Laryngeal assessments involved the analysis of laryngeal height[26], endolaryngeal area and volume[26,29], laryngeal position and angle[30], and laryngeal vertical position and tilt angle[12]. Given the importance of glottal and supraglottal structures to singing voice production and singer's formants, these studies encompassed broader VT structure assessments in this population, indicating the importance of increasingly precise and detailed methods to understand VT anatomy and functioning[35].

Studies took both total and segmented VT measures, as previously described, approaching its articulators and resonance cavities, and analyzing their length[11,25], volume[1], and area[28].

The volume and length of VT regions were related to the singer's formants[25, 28], which are fundamental frequency harmonics – i.e., fundamental frequency integral multiples standing out throughout the VT.

The third, fourth, and fifth formants are considered superior ones, as they do not interfere with vowel identification and intelligibility (unlike the first and second formants), though they are influenced by the VT and are found in the voice of singer and well-trained actors[31]. Harmonics are also related to the study of the extent of mandible drop, which increases in the first harmonics and well-trained singer's formant; hence, it is ascribed to greater mandible lowering[27] and VT geometry values in relation to the *passagio*. This demonstrates that western classical singers tend to lower the larynx after the passage, slightly thickening VF, reducing central formant frequencies, and thus increasing supraglottal cavities[25]. VT shapes differed between the modal register and falsetto – the oral cavity was wider in the modal register. Furthermore, the first formant was larger in the modal register than in the falsetto[28].

It was demonstrated that VT length was greater in the group that performed exercises with flexible resonance tubes than in those submitted to the voiced lip vibration technique. This helps to understand that VT differs according to the vocal exercise used, though using the same vocal technique[11].

The thyrohyoid ligament length was analyzed and found to be longer in men, corroborating laryngeal structure differences between the sexes[24]. Since various laryngeal structures change with voice training, and intrinsic laryngeal elements contribute to movements and voice production, the ligament connection between the larynx and the hyoid bone may change according to voice production. However, vocal training time did not make a difference in lateral thyrohyoid ligament (LTL) in the study groups[24].

Therefore, it can be inferred that there is great variability in VT segments and different ways of assessing it as a whole to study singers' voices and understand VT morphology and functioning in singing. Moreover, MRI proved to be the currently most used method to visualize VT functioning, while the CT scan is the gold-standard method in laryngeal structure assessment.

CONCLUSION

MRI was the most used VT morphological quantification method, followed by CT scan, X-ray, EGG, AP, and combined MRI and ultrasound. As for applications, it is possible to obtain high-precision 3D data on experienced singers' VT morphology; perform post-training voice assessments; analyze differences in VT segments and variations in these segments in supine and erect positions; observe VT length variations when changing vocal register and VT area in modal register and falsetto; characterize laryngeal and subglottal structures according to individual characteristics and the singer's vocal classification; understand VF muscle action according to frequency variations and relate the findings to acoustic and perceptual voice assessments.

This study helped understand the use of instrumental VT and laryngeal assessment methods and their applications in singers. Thus, it helped update voice-related technology and understanding for research and SLH interventions in singing voices.

ACKNOWLEDGMENTS

Fundação de Amparo à Ciência e a Pesquisa de Pernambuco – Brazil (FACEPE). *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* - Brazil (CAPES). Dean's office for research of the Federal University of Pernambuco – (PROPG-UFPE).

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