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RESEARCH ARTICLE

Morphofunctional evaluation of buccopharyngeal space using three-dimensional cone-beam computed tomography (3D-CBCT)☆

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ABSTRACT

The present study aims to identify the anatomical functional changes of the buccopharyngeal space in case of singers with canto voice. The interest in this field is particularly important in view of the relation between the artistic performance level, phoniatry and functional anatomy, as the voice formation mechanism is not completely known yet. We conducted a morphometric study on three soprano voices that differ in type and training level. The anatomical soft structures from the superior vocal formant of each soprano were measured on images captured using the Cone-beam Computed Tomography (CBCT) technique. The results obtained, as well as the 3D reconstructions emphasize the particularities of the individual morphological features, especially in case of the experienced soprano soloist, which are found to be different for each anatomical soft structure, as well as for their integrity. The experimental results are encouraging and suggest further development of this study on soprano voices and also on other types of opera voices.

1. Introduction

The opera voice has always attracted the interest of researchers from both the artistic and medical field.

This paper reveals the preliminary results of the project called "*Morphofunctional Study of the Vocal Superior Formant*". The protocol for this study was endorsed by the Scientific Research Committee and Research Ethics Committee of the University of Medicine and Pharmacy "Grigore T. Popa" Iasi on 20.03.2018. In this study we aim to identify the anatomical and functional changes of the buccopharyngeal pavilion in soprano voices. The pre-existing vocal skills have been evaluated by canto specialists, for sopranos with different levels of training (Hinganu et al., 2017).

The existing literature presents the phonatory apparatus as being composed of three floors (formants), namely: infraglottic, infralaryngeal — determining the amount and pressure of the air column coming from the lungs; the glottic floor of the larynx — producing the so called fundamental frequency of the voice; the ensemble formed by the supraglottic, buccopharyngeal and nasal formants — which are modulating the voice.

☆ DPG maximum opening of the oropharyngeal isthmus in the palatoglossus muscles. DPF maximum opening of the oropharyngeal isthmus in the palatopharyngeus muscles. DEH distance between the top of the epiglottis and the body of the hyoid bone. DEL distance between the top of the epiglottis and the base of the tongue. DECV distance between the top of the epiglottis and the vertebral column. GP skeletotopic projection of glottis. ASMV maximum sagittal amplitude of valleculae. AAMV maximum axial amplitude of valleculae. PVP the position of the palatine veil. VPP skeletotopic projection of the palatine veil free edge. MLH maximum laryngeal height. mLH minimum laryngeal height. MP mimed phonation.

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The infraglottic floor of the larynx extends from the lower margin of the cricoid cartilage to the inferior arcuate line of the vocal cords (Kutta et al., 2006).

The glottic floor of the larynx extends from the arcuate line of the vocal cords to the horizontal plane through the lateral margin of the Morgagni's sinus (Mor and Blitzer, 2015). It is located between anterior and posterior commissures of the vocal cords (Paulsen and Tillmann, 1997; Tillmann and Paulsen, 1995).

The superior limit of the supraglottic floor is represented by the superior surfaces of the epiglottis and aryepiglottic folds (Mor and Blitzer, 2015). Together with the oral cavity and oropharynx, it forms the superior vocal formant (Berke and Long, 2009).

The amount and pressure of the air column on the infraglottic formant depends on the shape and dimensions of the thorax, phrenic muscles and morphological characteristics of the superior and inferior respiratory tract. The entire air column is fragmentarily released to the glottic floor of the larynx by the contraction and relaxation of the muscles attached to the true vocal folds.

The superior formant is the one that modulates the fundamental frequency, rendering the final voice. This modulation is achieved in three main ways: adding of harmonics through the vibration of fibromuscular components existing at this level; absorption of a certain amount of sound vibration; creating a returned impedance from the palatinal and pharyngeal level, which is stimulating the reflex zones of both the bulbar nuclei of the vagus and recurrent laryngeal nerves. This phenomenon allows the recurrent nerves to split their fascicles or even to divide them into 3 or 4 bundles of fibers.

Returned impedance is created by stimulating certain reflexogenic areas at the palatinal and pharyngeal level and also by guiding the main airflow towards these pressoreceptors (Husson, 1960).

These three phenomena occurring at the supraglottic, supralaryngeal floor of the phonatory apparatus are the ones rendering the nature and the final quality of the voice. The ability to produce returned impedance is an individual feature that depends on an "antenna" type mechanism. This antenna transforms the radio currents of the air flow into electric currents. According to this model, the entire subjacent phonatory apparatus constitutes the emitter, while the receiver is represented by the soft palate, palatine veil with its pillars and the oropharynx. At the receptor level, there is a precise metameric arrangement of its subunits (pressoreceptors of the glossopharyngeal nerve), distributed according to the level of the sound waves to which they are sensitive. Thus, their distribution on the velopalatine mucosa is from the anterior towards the posterior, starting from a stimulation threshold of about 1000 decibels to about 3500 decibels (Sundberg, 1988; Vos et al., 2018).

The present research is an anatomo-imagistic study, which aims to highlight the morphofunctional characteristics of the "antenna apparatus", in order to establish the intrinsic factors that actively and passively participate in the formation of the soprano voice.

This type of study is highly applicable in different fields of activity, such as: medicine, music and science.

2. Materials and methods

The study was conducted on a group of subjects who have signed the agreement concerning this investigation. The study was performed in accordance with the current laws and written consent of the Scientific Ethic Committee of the Faculty of Medicine, "Grigore T. Popa" University of Medicine and Pharmacy, Iasi, Romania. It is very important to specify that this study considered adult subjects with no pre-existing pathological conditions that would influence their voice quality. This will be certified on the basis of the medical history and clinical examination.

Each person was subjected to CBCT investigations both when expressing basic vowels in phonetics, such as "I, Ə :" (called phonatory state I and phonatory state I) and in mimed phonation. When pronouncing the vowel "I" the larynx is in the highest position, while when pronouncing the vowel "Ə " the larynx goes to its lowest position.

The entire investigation took 15 min, with an exposure duration of 42 s.

The group of subjects, studied and examined for this preliminary report, consisted of three persons, with phonatory characteristics of the soprano voice assessed by canto teachers. The first subject (S1, 22 years old) has a medium vocal practice level (7 years) while the third one (S3, 48 years old) is an experienced soprano soloist having over 20 years of practice. The second subject (S2, 44 years old) has also vocal features of soprano, but with a vocal practice of over 15 years in the theater. It must be mentioned that the theater voice requires vocal exercises similarly to the opera voice, as well as vocal techniques suitable for the profession of actors.

This initial selection of the study group is based on the fundamental principle according to which function dictates the shape and vice versa. Any anatomical structure undergoes shape changes adapted to the intensity of the functional demand. In this regard, an anatomical variation owned by the subjects with special vocal abilities will be more evident in people with a long vocal practice.

The common morphometric characteristics of the studied subjects will be considered anatomical variations that empower the person concerned to master the vocal skills of canto.

Following the CBCT investigations, the mobile anatomical structures involved in the delimitation of the superior vocal formant (the palatine veil, palatine veil pillars, epiglottis, valleculae, base of the tongue and the oropharynx) were measured, marking their position in relation to the skeletal projection and determining the distances between the muscular and ligamentary structures.

2.1. Description of the imaging technique

Cone-beam Computed Tomography (CBCT) is a state-of-the-art imaging technology that allows the 3D viewing of the scanned areas.

The procedure has a short duration, and the degree of exposure to radiation in a computed tomography performed with CBCT is equivalent to a fully radiological dental status (Chan et al., 2010; Scarfe and Farman, 2008; Arai et al., 1999). The 3D conical beam technology has reached new levels and has become the reference point in maxillofacial imaging but has never been used to explore vocal training and modulation mechanisms.

According to existing literature, the spatial resolution of CBCT is higher than the one of CT (Scarfe and Farman, 2008; Al-Ekrish and Ekram, 2011; Kobayashi et al., 2004; Suomalainen et al., 2009; Loubele et al., 2009; Naitoh et al., 2009; Mah et al., 2010; Nomura et al., 2010).

The great advantages of the CBCT equipment are given by the increased flexibility (these devices having an exploration protocol that includes different sizes, as well as height and diameter, depending on the clinical utility), accessibility, easy handling and accurate information from multi-plane and three-dimensional reconstructions obtained from a single, low dose irradiation exam (Ludlow and Ivanovic, 2008; Loubele et al., 2009; Roberts et al., 2009; Hein et al., 2002; Ruivo et al., 2009; De Cock et al., 2012; Liedke et al., 2009; Lofthag-Hansen et al., 2011; Razi et al., 2014).

2.2. CBCT examination protocol

The CBCT equipment used was Planmeca Promax 3D Mid (Planmeca OY, Helsinki, Finland). Scanning was performed by selecting a 20 × 17 mm FOV with the following exposure parameters: 65 kV,

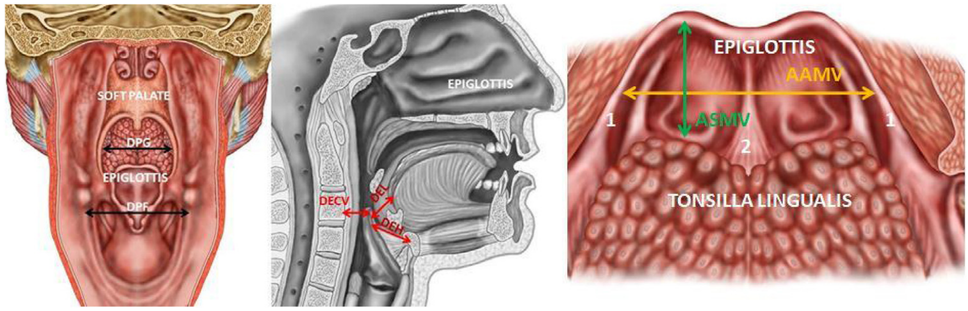

Fig. 1. Measurements of the buccopharyngeal pavilion. 1 = plica glossoepiglottica lateralis, 2 = plica glossoepiglottica medialis.

8 mA, 13.9 s and 0.4 × 0.4 × 0.4 mm voxel size. Data was processed using Romexis 4.4.2 software. Scanning is done by exposing the seated patient to the equipment. Both the x-ray source and sensor will make a complete cycle of rotation around the cranial-cervical region, resulting in a volume acquisition that is further used for the required reconstructions. Each patient signed an informed consent explaining the purpose of the study.

All the research team has been involved in establishing the appropriate protocol. After repeated previews, a pre-set exploration protocol for 10.2 cm section was selected. The selection of the protocol is justified by the possibility of obtaining images of the buccopharyngeal pavilion from glottis to hard palate, as well as anterior-posterior images from the dental arches to the vertebral column. The inclusion of vertebral landmarks in the CBCT sections is essential because it represents the main fixed reference for the skeletal projection or from where linear measurements begin.

The data processing software enabled the 3D reconstruction of this space and to compare the features of the new model with the results of the linear measurements made in the 2D sections.

The acquired data were interpreted starting from the measured values of the CBCT exploration of the subjects in mimed phonation. Practically, the following measurements were considered (Fig. 1):

- the maximum opening of the oropharyngeal isthmus between the palatoglossus (DPG) and between palatopharyngeus muscles (the height of Passavant ridge — DPF);
- the distance between the top of the epiglottis and the body of the hyoid bone (DEH), the base of the tongue (DEL) and the vertebral column (DECV);
- the skeletotopic projection of the glottis (GP);
- the maximum sagittal (ASMV) and axial amplitude (AAMV) of valleculae;
- the position of the palatine veil (PVP) and the skeletotopic projection of its free edge (VPP).

DPG and DPF values characterize the last sphincterlike mechanism of the phonatory apparatus. They are related to the functional state of the palatoglossus and palatopharyngeus muscles. The contraction of these muscles is changing and permanently adapting the oropharyngeal isthmus to the singer's needs.

The position of the epiglottis related to the base of the tongue characterizes its orientation.

Together with glottic projection, the skeletotopic projection of the epiglottis is a mark of the laryngeal elevation during phonation.

The position of the epiglottis in relation to the hyoid bone describes the complex activity of its muscular apparatus during phonation.

By measuring the vallecular spaces in different phonatory states, we highlight their possible contribution to voice formation.

Table 1
DPG values in mm.

Subject	MLH	mLH	MP
S1	34.80 mm	48.01 mm	42.00 mm
S2	39.25 mm	37.22 mm	45.61 mm
S3	23.42 mm	40.80 mm	42.82 mm

Table 2
DPF values in mm.

Subject	MLH	mLH	MP
S1	35.21 mm	35.60 mm	30.04 mm
S2	33.61 mm	33.65 mm	33.82 mm
S3	36.51 mm	47.18 mm	39.40 mm

Table 3
DEH values.

Subject	MLH	mLH	MP
S1	21.20 mm	19.33 mm	17.26 mm
S2	15.01 mm	19.97 mm	25.74 mm
S3	26.08 mm	18.12 mm	20.74 mm

Table 4
DEL values.

Subject	MLH	mLH	MP
S1	15.21 mm	8.41 mm	6.80 mm
S2	9.21 mm	6.40 mm	5.61 mm
S3	7.20 mm	10.00 mm	6.01 mm

Table 5
DECV values.

Subject	MLH	mLH	MP
S1	22.00 mm	15.81 mm	18.00 mm
S2	27.58 mm	21.60 mm	15.20 mm
S3	19.62 mm	16.40 mm	10.00 mm

The skeletotopic projection and position of the palatine veil mark the direction of the airflow towards the anterior opening of the oral cavity and/or the nasal and paranasal cavities.

3. Results

The results of the measurements are indicated separately for the three subjects in each of the three states listed above (MLH — maximum Laryngeal height — or mLH — minimum laryngeal height — and in mimed phonation — MP).

All linear measurements are presented in Tables 1–9.

The data are used for comparison purposes between all three subjects and the existing differences are presented below relative to control values.

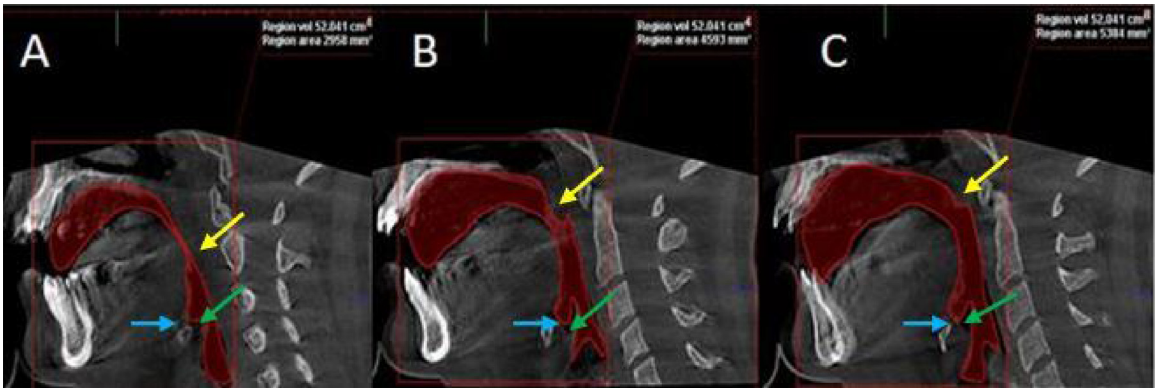

Fig. 2. 3D reconstruction of the buccopharyngeal pavilion of subject S1; A — phonation with larynx in uppermost position, B — phonation with larynx in lowermost position and C — miming phonation. All 3D reconstructions are represented in sagittal view. Yellow arrows mark the free edges of the palatine veil; green arrows mark the top of the epiglottic cartilage; light blue arrows mark the valleculae. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

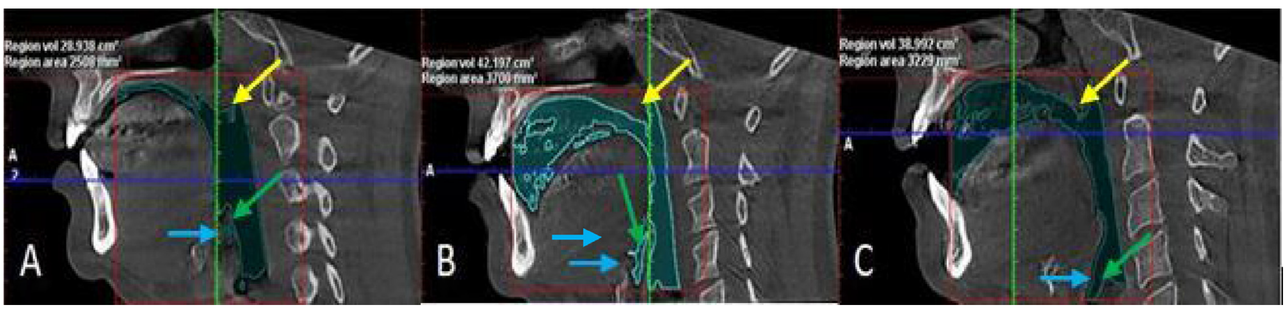

Fig. 3. 3D reconstruction of the buccopharyngeal pavilion of subject S2; A — phonation with larynx in uppermost position, B — phonation with larynx in lowermost position and C — miming phonation. All 3D reconstructions are represented in sagittal view. Yellow arrows mark the free edges of the palatine veil; green arrows mark the top of the epiglottic cartilage; light blue arrows mark the valleculae. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

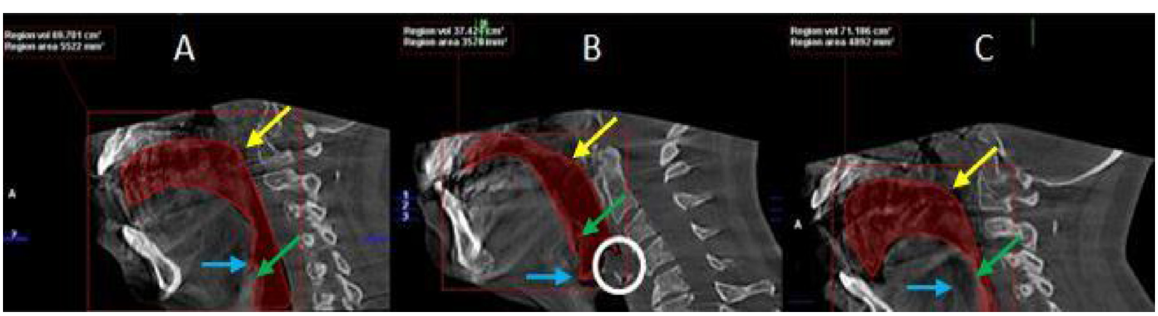

Fig. 4. 3D reconstruction of the buccopharyngeal pavilion for subject S3; A — phonation with larynx in lowermost position, B — phonation with larynx in uppermost position and C — miming phonation; the white circle marks the anterior protrusion of the posterior pharyngeal wall due to the contraction of palatopharyngeus muscles (Passavant's ridge). All 3D reconstructions are represented in sagital view. Yellow arrows mark the free edges of the palatine veil; green arrows mark the top of the epiglottic cartilage; light blue arrows mark the valleculae. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The 3D reconstructions performed on the three subjects show significant differences in axial and coronal diameters for the same phonatory state, but also individual differences of these diameters for the measurements made in different phonatory states for the same subject (Figs. 2–4).The axial sections at the interest region level can also be colored so that the color of each region depends on its size.

The visualization of the 3D reconstructions shows the influence of the buccopharyngeal muscles (palatoglossus, palatopharyngeus, hyoglossus, genioglossus and longus capitis muscles) on the volume and especially on the shape of the buccopharyngeal pavilion in sustained phonation (Fig. 5).

Table 6
GP values (corresponding vertebra).

Subject	MLH	mLH	MP
S1	C6	C7 lower 1/3	C7 upper 1/3
S2	C6–C7 intervertebral disc	C6	C5–C6 intervertebral disc
S3	C5–C6	T1	C7-T1 intervertebral disc

Table 7
ASMV values.

Subject	MLH	mLH	MP
S1	18.39	13.40	12.39
S2	21.20	14.80	12.01
S3	21.97	23.61	19.62

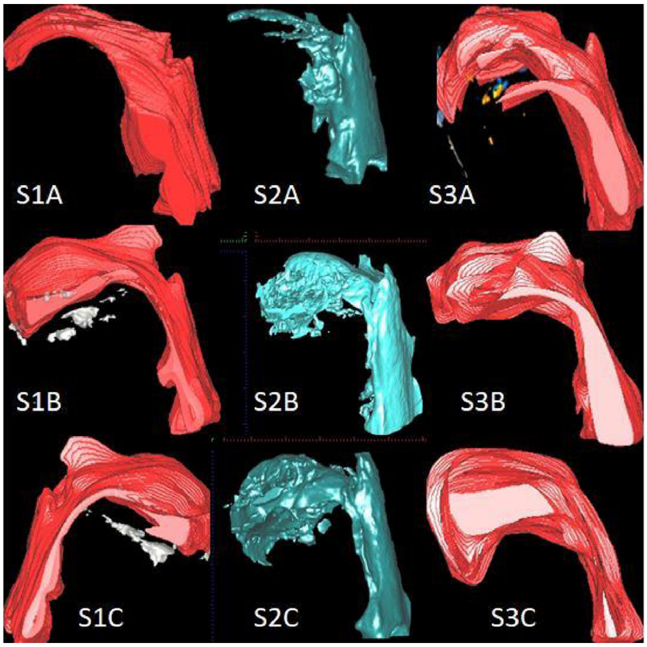

Fig. 5. 3D reconstruction posterior lateral view; S1A, S1B and S1C — 3D reconstruction of S1 subject while phonating letters "I:", "Ə " and miming phonation; S2A, S2B and S2C — 3D reconstruction of S2 subject while phonating letters "I:", "Ə " and miming phonation; S3A, S3B and S3C — 3D reconstruction of S3 subject while phonating letters "I:", "Ə " and miming phonation.

Table 8
AAMV values.

Subject	MLH	mLH	MP
S1	34.40 mm	37.09 mm	28.99 mm
S2	30.92 mm	30.82 mm	32.84 mm
S3	32.80 mm	44.09 mm	37.31 mm

Table 9
PVP and VPP values.

Subject	MLH	mLH	MP
S1	C2 — horizontally	C3 — obliquely	C1–C2 — horizontally
S2	C1–C2 horizontally	C2–C3 obliquely	C2 — obliquely
S3	C2 — horizontally	C1 — horizontally	C1 — horizontally

3.1. DPG value

For subject S1, in comparison to the value measured in the mimed phonation, this distance decreases in phonation with the larynx in state I and increases in state II, between −17.14% and +14.3%. This does not happen in the case of the other two subjects, where the DPG value decreases in both states (13.9% and 18.4% for subject S2, respectively 45.3% and 4.7% for subject S3) (Table 1).

3.2. DPF value

The values of this measurement are very different from the previous ones, so that in the case of subject S2 they are smaller in both phonatory situations than in mimed phonation but the differences are slightly insignificant (−0.62% and −2.9%) (Table 2).

3.3. DEH value

This measurement was performed in order to evaluate the position of the epiglottis to the hyoid bone (mobile point), which indirectly reveals the interaction of the hyoidian suspensory muscular apparatus in the act of phonation.

Subject S1 presents DEH values higher than the reference value corresponding to the mimed phonation by 22.83% in the phonatory state I and 12% in the phonatory state II.

For subject S2, the values are lower than the control value (mimed phonation) in both phonatory states: 41.69% and 22.43%, respectively.

In comparison to the control value, subject S3 presents in phonatory state II a decreased DEF value with 25.75% and in the phonatory state I a value increased with 12.63% (Figs. 2–4, Table 3).

3.4. DEL value

In phonatory state I and II, all three subjects present increased DEL values in reference to the control value, as follows: S1 with 123.68% and 23.6%, S2 with 64.17% and 14.08% and S3 with 19.80% and 66.39% (Figs. 2–4, Table 4).

3.5. DECV value

This measurement reveals that subject S1 has an increase of 22.22% compared to the reference value in phonatory state I and a decrease of 12.17% in phonatory state II. For subjects S2 and S3, these values increase in both phonatory states by 81.45% and 42.11% respectively by 96.20% and 64.00% (Figs. 2–4, Table 5).

3.6. GP value

The skeletotopic projection of the glottis for subject S1 reveals it to be more elevated in the phonatory state II and more lowered in phonatory state I.

Subject S2 presents the same glottic projection in the phonatory state II as in the mimed phonation and a lower one in phonatory state I.

Subject S3 presents a glottic projection somewhat similar to subject S1 (elevated in the phonatory state I and lowered in phonatory state II), but the glottic elevation in phonatory states is projected with an extra vertebra above (Figs. 2–4, Table 6).

3.7. ASMV value

For this measurement, we recorded higher values for all subjects in both phonatory states.

Subjects S1 and S2 show a significant increase of the ASMV value in phonatory state I and significant decrease in phonatory state II (48.43% and 8.15% for S1, 76.53% and 23.23% for S2).

Subject S3 shows a slight increase in the sagittal diameter of the glottis (11.98% and 20.37%), inversely proportional to the other 2 subjects: the ASMV growth values in the phonatory state II are approximately double in reference to the state I (Figs. 2–4, Table 7).

3.8. AAMV value

The measurement of the transversal diameter of the valleculae has a completely different presentation in all three subjects.

Subject S1 presents an increase in this diameter in both phonatory states by 18.66%, respectively 27.94%.

Subject S2 presents a decrease of this value in both phonatory states by 5.85%, respectively 6.15%.

Subject S3 presents a decrease of the AAMV value by 12.09% in phonatory state I and an increase by 18.17% in phonatory state II (Figs. 2–4, Table 8).

3.9. PVP and VPP values

The analysis of the position of the palatine veil and the skeletotopic projection of its free edge reveals that in the case of subject S1, it is almost horizontal in phonatory state I and in mimed phonation and obliquely descended in phonatory state II.

Subject S2 presents a horizontal palatine veil in phonatory state I and an oblique one in the other two situations. In phonatory state II, its position is lower than in mimed phonation.

Subject S3 presents a horizontal position of the palatine veil in all three situations, slightly lowered in phonatory state I (Figs. 2–4, Table 9).

4. Discussions

Existing literature (data bases sources as Clarivate, PubMed, Scopus, Index Copernicus or specialty books) refers to radiologic explorations of the vocal tract, especially MRI.

None of the explored subjects were related to aging phenomena, which could influence the quality of voice production (Claassen et al., 2009).

In sustained phonation, superior vocal formant acts as a resonator, modifies the signal spectrum and defines both the vocal quality and the characteristics of the voice timber. These aspects are important mainly for opera voices. The semi-automatic segmentation algorithm that works with reoriented images has been used for the 3D reconstruction of the superior vocal formant (Mainka et al., 2017). These data can be used to deepen the understanding of the physiology of the superior vocal formant.

Other related MRI studies describe inaccurate 3D reconstructions possibilities due to supine position of the subject in the MRI scanner, which limits the movements of the hypopharynx (Clément et al., 2007; Kitamura et al., 2005).

Studies that used three-dimensional computed tomography have been conducted on cricothyroid space, during sustained phonation. Authors showed there are two important movements of the cricothyroid joint during high-pitch phonation which occur simultaneously: rotational and anterior gliding movement. Because of these movements, the vocal cords elongate (Hiramatsu et al., 2012). In this study, the authors state that the anterior horizontal gliding is the main movement, leading to the efficient elongation of the vocal cords.

To our knowledge, no studies derived from 3D-CBCT data on the morphology of the superior vocal formant during phonation have been reported so far. We conducted this study in order to reveal the morphometry of this space under different phonatory states. We did the interpretation of the obtained data for each subject in part, as well as comparatively in the same phonatory states.

Regarding the DPG and DPF values, for subject S3 there is a significantly increased variation of 40.6% of DPG in the two phonatory states, close to the 31.44% value found for subject S1. However, in the case of experienced soprano (S3) this variation is totally negative.

Subject S2 has a variation of only 4.5% between the two phonatory situations.

Both values are higher in phonation for subject S1: +4.12% and +18.51%.

For subject S3, the values in phonation are diametrically opposed to the control value (mimed phonation): − 7.34% and +19.75%.

When comparing the DPG and DPF values for subject S1, it results that the oropharyngeal isthmus narrows from the posterior to the anterior in phonatory state I and opens anteriorly in phonatory state II.

In the same way, in the case of subject S3, the opening of the isthmus will be backwards, similar to subject S1: the posterior diameter decreases by 37.96% in reference to the anterior one in phonatory state I. In phonatory state II happens the same situation but the values are higher.

For the anterior opening of the isthmus, subject S2 has negative relative values of 13.28% and 15.5% in the two phonatory states.

The three subjects are totally different in the two phonatory states. The greatest differences are in the case of the experienced soprano, where the morphology and the phonatory role of the oropharyngeal isthmus are different (wider openning in phonatory state II).

The DPG value characterizes the implication of the palatoglossus muscle into the voice formation. Studies about these muscles show they may receive branches from the trigeminal nerve, which explains its participation in the formation of the velopharyngeal impedance (resistance) during phonation (Abd-EL-Malek, 1938; Fehrenbach, 1998; Moore et al., 2014).

The contraction of palatopharyngeus muscles could produce a mucosae fold called Passavant's ridge and participates to the anterior movement of the posterior wall of the oropharynx (Calnan, 1958; Yamawaki et al., 1994; Yamawaki et al., 1996).

The interpretation of DEH, DEL and DECV results reveals that subject S1 produces an anterior protrusion of the oral floor in both phonatory states, subject S2 a retropulsion, and S3 produces a retropulsion in state I and a protrusion in state II. It was possible to correlate the movements of the oral cavity floor with the elevation of the base of the tongue. Acute sounds involve higher elevations of the oral floor.

The values of this measurement present specific particularities for the experienced soprano, for which the increases are in inverse relation to the other two subjects — the DEL value increases much more in the phonatory state II than in state I. This means that the first two subjects produce a greater anterior protrusion of the tongue in the phonatory state I than in II while subject S3 behaves diametrically opposed.

We emphasize that this measurement shows that subject S3 has the highest increase of these values in both phonatory states.

By comparing the GP values for all three subjects, it can be concluded that the experienced soprano has the maximum laryngeal height in phonatory state I (acute vowels). The elevation of the larynx contributes to the elongation of the vocal cords which stimulates vocal muscles contractions. The particular arrangement of the vocal muscle insertions allows them to accelerate their contraction rate by two mechanisms: individual characteristics of the recurrent laryngeal nerves which can split their fascicle in two, three or even four bundles and tension receptors of the vocal ligaments (Kutta et al., 2007).

Measurements of the ASMV and AAMV values show that, in opposition to the other two subjects, the experienced soprano soloist achieves a larger amplification of the length of valleculae in the phonatory state II than in the first one.

Analysis of the ASMV and AAMV measurements indirectly indicates volumetric changes occurring at the valleculae level in the singing voice. In relation to this situation, subject S1 presents an increase of the sagittal and transversal diameters in both phonatory states. Subject S2 has increased sagittal diameters in both phonatory states, but partially compensates by decreases in the transversal ones.

In the case of the experienced soprano, the increase of the sagittal diameter in phonatory state I is compensated almost entirely by the decrease of the transversal diameter. In the phonatory state II, both diameters increase.

Thus, we can conclude that subjects S1 and S2 present apertures of vallecular spaces in both phonatory states, while for subject S3 this happens only in phonatory state II.

Related literature describes epiglottic vallecula as “spit traps” which prevent the initiation of the swallowing reflex (Briche et al., 1991) but no data are available about its possible function in phonation.

After analyzing the PVP and VPP values, we can conclude that subjects S1 and S2 are nasal in the phonatory state II while the experienced soprano is nasal in none of the states.

All these values are characterizing and directly influencing the velopharyngeal space. The velopharynx (VP) is a complex muscular sphincter, influencing acoustic and aerodynamic energy through oral and nasal cavities. The movements of its muscular walls alter the size of this sphincter and give it the special functional adaptability (Barlow and Stumm, 2009).

5. Conclusions

Using CBCT in anatomical exploration of the superior vocal formant is a new and complex method. Choosing the right imaging protocol that considers the entire explored area and fixed marks is the key to this functional radiological investigation. The ability to accurately measure soft structures and the spaces between them with minimal exposure to X-rays make CBCT a highly performing and useful exploration. Making the 3D reconstructions brings for the first time information about the changes that take place during phonation at the buccopharyngeal pavilion. Our pilot study demonstrates the usefulness of CBCT in the study of superior phonatory formant, opening the way for future studies on statistically significant number of subjects. The practical applicability of this research is especially in the study of functional and clinical anatomy of morphology and volumetry of buccopharyngeal space.

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Author contributions

Hînganu Marius Valeriu and Hînganu Delia performed the experiments, analyzed the data, and wrote the paper. Haba Danisia performed data aquisition and interpretation. Cozma Sebastian Romică performed the clinical evaluation of the phonatory apparatus of the subjects. Asimionoaiei-Simionescu Cristina and Scutariu Irina Andreea conducted the assessment of the subject’s voice type. Ionesi Dorin Savin contributed to the design of the work and 3D reconstructions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.aanat.2018.06.008.

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