

CT-based Morphometric Analysis of Professional Opera Singers' Vocal Folds

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Summary: Purpose and Study Design: Our work aimed to study the relationship between the length of vocal folds and classical voice type among professional opera singers. Also, the present paper attempts to assess if individual features such as height and body mass index are associated with the vocal folds length (VFL) and the vocal range. Our research compared VFL and voice type by evaluation of neck computed tomography imaging of professional opera singers obtained between 2009 and 2015. Vocal range was measured after scanning procedure by a speech-language pathologist. The results were used to compare VFL with vocal range, voice type, and individual features of every singer.

Material and Methods: The group included 93 opera singers (female: 31 sopranos, 15 mezzos, and 5 contraltos; male: 17 tenors, 16 baritones, 6 basses, and 3 countertenors). Different values such as VFL, vocal range, and individuals' features (height, weight, body mass index) were analyzed statistically.

Results: Some significant differences and correlation were found. The VFL was diversified between classical voice types. VFL for soprano, mezzo-soprano, and bass was significantly different from every other type of voice. The vocal range has been shown to have a negative correlation with VFL value, which reflects the narrowest vocal range among bass voices. The analysis confirmed a linear correlation between VFL and individual features of the body such as height and body mass index.

Conclusion: Presented data support the hypothesis that there are significant differences of VFL, vocal range, and body morphology between professional singers of different voice classification.

Key Words: Vocal folds length—Professional singing—Voice classification—Computed tomography imaging—Opera singers.

INTRODUCTION

The phenomenon of the singing voice is a unique, very complicated process with a mechanism that is still not fully understood. One singer produces many varieties of voice with the only pair of vocal folds which generates the sound. Nevertheless, many aspects of singing production remain unanswered.

Vocal folds' dimensions highly depend on individual characteristics like gender, height, or age.¹ Because of this, the length of the vocal folds is an essential element determining the pitch range and vocal timbre.^{2,3} Knowledge of vocal folds length (VFL) has significant meaning for singers and singing teachers who want to develop the best abilities of young students. However, a simple and risk-free method that allows gathering normative reference values for laryngeal structures has not yet been created because of the limitation of available technology.

Previous studies tested various techniques. Until now, cadaveric, endoscopic, and radiographic methods with different accuracy gathered data of VFL in diverse groups. Many scientists attempted to develop robust measuring

method in a general population but dedicated less attention to analyzing the group of professional singers with a distinctive vocal characteristic. Most of the previous studies on the dimension of singers' vocal folds were measurements based on x-ray.^{4,5} These data underlaid the classification of classical voices. A large number of singers have not been tested with more modern techniques that provide more sophisticated and detail data.

Nowadays, computed tomography (CT) imaging has become the gold standard for evaluation of the larynx, giving good quality axial scanned images of true vocal folds and laryngeal cartilages. Also, it allows repeatable and accurate measurement. In the present study, authors decided to use CT imaging to obtain measurements of professional opera singers' VFL.

It should be noted that VFL was proven to increase as the fundamental frequency (F0) of phonation increased.⁶ The lengthening of vocal folds while they function to control F0 underlies two main factors: thickness (mass per unit) and tension (stiffness).⁶ Therefore, it is essential to define the measurement protocol clearly.

Clarós Clinic provides medical support for a large number of professional opera singers and Conservatory students of classical singing since the 1970s. Between 2009 and 2015, the data based on CT imaging evaluation and phoniatic's examination of 93 singers were collected regarding a variety of factors such as measurements of VFL, vocal range, body height, and weight.

Research aimed to establish whether a relationship between the length of vocal folds and classical voice type

Accepted for publication February 14, 2018.

Conflict of interest: None declared.

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Journal of Voice, Vol. 33, No. 4, pp. 583.e1–583.e8
0892-1997

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<https://doi.org/10.1016/j.jvoice.2018.02.010>

TABLE 1.
Characteristic Features of the Study Group

	Characteristic								
	General			Men			Women		
	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N
Age (y)	37.44	12.14	93	40.78	13.26	42	34.68	10.49	51
Height (cm)	171.82	6.43		175.69	5.54		168.64	5.3	
Weight (kg)	69.78	10.88		78.83	8.33		62.33	5.97	
BMI (kg/m ²)	23.52	2.55		25.51	2.08		21.89	1.57	

Abbreviations: BMI, body mass index; N, number of participants; SD, standard deviation.

exists. Then, authors aimed to evaluate the relationship between VFL and the vocal range in professional opera singers. Lastly, the present study attempted to assess if the individual features as height and body mass index (BMI) were associated with the VFL and the vocal range.

MATERIALS AND METHODS

Participants

A total of 93 professional operatic singers and advanced singing students who underwent CT imaging of neck for various reasons were included in the study group. Patients answered questions concerning their voice, singing preferences, and medical history before the scanning procedure. The singers were divided into groups in view of tessitura (defined as most acceptable and comfortable vocal range for the given singer⁷).

The group comprised 51 women and 42 men (Table 1). Among women there were 31 soprano voices, 15 mezzos, and 5 contraltos. Among men there were 17 tenors, 16 baritone, 6 basses, and 3 countertenors.

Table 1 describes distinctive information about the study group (mean values with the standard deviation [SD] for singers' age, height, weight, and BMI).

Study design

Professional singers were offered with the possibility of measuring their vocal folds to assess the relationship between length and voice type.

Standard medical history was taken before scanning procedure. Singers answered the questions about voice disorders, vocal fatigue, history of neck trauma, congenital abnormalities in head and neck region, laryngeal surgery, the presence of chronic diseases, and current medical treatment.

Exclusion criteria were vocal complaints, laryngeal diseases, history of neck trauma, previous laryngeal surgeries, and congenital abnormalities which involved this region. Patients were free of alcohol and tobacco use. Also, singers who used medication that may alter speech emission by causing vocal fold edema were disqualified (eg, hormones, hypertension, and antipsychotic drugs). None of the participants stated episodes of vocal fatigue.

All patients signed informed consent, and they were not exposed to an increased dose of radiation because of the research. The study protocol was acknowledged by the internal ethics committee of our medical center.

Procedure

On the day of CT scanning, the radiologist asked again whether the participant is experiencing any vocal difficulties to identify potential issues like sudden infection or hoarseness.

CT imaging was performed with standard neck protocol in the supine position using Philips Brilliance ICT 256 (Medical Systems, Netherlands). Scanning started at the level of the frontal sinus and ended at the level of the aortic arch. Acquisition parameters consisted a tube current—250 mA, 120 kV, 128 × 0.625 detector collimation, 0.75-second rotation time, pitch 0.993, scan field of view of 250, standard resolution, raw slice thickness –1 mm. A set of axial reconstruction 2 × 2 angled through C4–C6 disc spaces were added for laryngeal evaluation. With scan delay of 70 seconds, patients were asked not to swallow during the scanning process and to relax the shoulders. Also, patients were asked to breathe quietly, which causes vocal folds abduction.

Image reconstruction was done with the standard method: slice thickness was 1 mm and the reconstruction interval was 0.5 mm. The intention was to create slice planes as close to parallel to the vocal folds to gain a perfect axial image of the glottis. Length of vocal folds was measured in axial view of the larynx with standard CT software. An experienced radiologist using the same protocol obtained the precise measurements of vocal folds.

First, the location of vocal folds was set, and longitudinal size of the glottis was estimated in a midsagittal plane (from anterior to a posterior boundary). Second, in the axial plane, length of vocal folds was measured between the anterior commissure and the most posterior part of vocal folds.

On the day after the CT scanning procedure, vocal range was measured in the office by a speech-language pathologist. The vocal recording was performed in a silent room, with a microphone placed in the lower part of the neck, below the larynx. To measure the top of the range, the

singer was asked to sing the highest note that he or she could sing comfortably without straining. For the lowest limit, the singer was asked to produce the lowest note in which he or she felt comfortable singing.

All voice recordings were obtained in equal conditions. For that purpose the speech-language pathologist used the microphone from Bruel & Kjaer Rhino-larynx Stroboscope—Type 4914 (Brüel & Kjør Sound & Vibration, Denmark). Results were acquired in hertz.

Lastly, a video laryngoscopy with conventional equipment was performed to examine the vocal folds (Hopkins II lateral telescope 70 degrees, Karl Storz, Germany) by the same senior and most experienced ENT consultant. The aim of this examination was an assessment of the anatomy of the vocal folds. The senior consultant looked for vocal nodules, edema, signs of phonotrauma, and any disturbances of vocal folds appearance and structure.

After the results were obtained, the group was divided depending on the type of voice patient had. Seven groups of voices were created: soprano, mezzo, contra alto, tenor, baritone, bass, and countertenor. Mean values of VFL for each type of voice were calculated.

Statistical analysis

Data were collected in *Excel* sheet and implemented to *Statistica 13.1* (Statsoft Poland, Cracow) software for statistical analysis. Statistical significance was reported at the alpha level of 0.05 ($\alpha = 0.05$). A *P* value below 0.05 was considered significant ($P < 0.05$).

The Student *t* test was used to determine statistical relevance for the difference in VFL between genders.

Likewise, the analysis of variance was used to establish the statistical distinction in VFL value between different type of singers' voice (TESS—tessitura: soprano, mezzo-soprano, contralto, tenor, baritone, bass, and countertenor).

Moreover, the model of multiple regression was used to establish the correlation between VFL value and variables (gender, height, and BMI).

Lastly, the correlation between vocal range and VFL was tested using Spearman rank correlations coefficient.

It needs to be highlighted that some types of voice are very infrequent, which influence the precision of statistical

analysis. In this study, the contraltos, basses, and countertenors occurred in the minority.

RESULTS

The research results section is divided into two parts: presentation of the descriptive data (Tables 2 and 3) and summary of the statistical analysis (Table 4, Figures 1, 2, and 3A and B).

The average values with an SD of all the measurements for the entire group (general), men, and women are shown in Tables 2 and 3.

Statistical analysis—summary

Strong gender-related differences in VFL were identified (Student *t* test, $P = 0.00$). Values were significantly larger for all male types of voice (tenor, baritone, bass, and countertenor, $P < 0.05$) in comparison to female voices.

Analysis of variance demonstrated that some types of singers have significantly different VFL values (analysis of variance, $P = 0.00$; Figure 2). Afterward, the post hoc test was used to determine the contrast between male voices (Tukey honest significant difference test; Figure 1).

Therefore, VFL values for soprano was significantly lower in comparison to other voice types. The difference was also demonstrated for mezzo-soprano and bass.

Post hoc test revealed the lack of notable distinctions in values of VFL between contralto and tenor, and tenor and countertenor ($P > 0.05$). These types of singers, despite the difference in tessitura, have similar VFL (Figure 2).

Furthermore, analysis of variance was used to compare singers' height. Significant discrepancies between genders were found (analysis of variance, $P = 0.00$). However, among singers of the same gender, differences in the height of various types of singers were only present in the male group. The tenors had significantly lower values in comparison to baritones and basses, but not to countertenors ($P = 0.008$, $P = 0.04$). In the female singers' group, the distinction of height for sopranos, mezzo-sopranos, and contraltos were not observed.

Model of multiple regression was proved to be statistically significant between VFL and variables: gender, height, BMI ($R = 0.87$, $R^2 = 0.76$, $P = 0.00$; Table 4.). Dependent variable (VFL) was highly influenced by gender, height, and

TABLE 2.

Results: Presentation of the Mean Values for the Length of Vocal Folds (VFL) and Vocal Range (VR) between Participants

Results	General			Men			Women		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
VFL (mm)	20.01	2.71	93	22.28	1.85	42	18.13	1.67	51
VRmin (Hz)	178.53	69.66		114.54	31.61		231.23	42.87	
VRmax (Hz)	740.48	303.01		432.92	76.2		993.76	138.9	

Notes: Values of each parameter are given as means \pm SD for men, women, and the entire group (general).

Abbreviations: BMI, body mass index; N, number of participants; SD, standard deviation; VFL, vocal folds length; VRmax, maximal vocal range; VRmin, minimal vocal range.

TABLE 3.
Results: Vocal Folds Length in a Different Group of Voices (Tessitura)

	Voice Characteristic																				
	Soprano			Mezzosoprano			Contralto			Tenor			Baritone			Bass			Countertenor		
	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N	Mean	±SD	N
VFL (mm)	17.03	0.83	31	19.33	±0.49	15	21.4	0.89	5	20.47	0.71	17	23.19	0.83	16	25.17	0.75	6	22.0	0	3
VRmin (Hz)	264.71	6.38		173.93	4.57		195.6	3.36		138.23	23.4		109.56	23.03		67.5	2.74		177.0	1.0	
VRmax (Hz)	1027.9	8.07		1038.7	11.93		647.4	271.3		519.0	8.54		392.81	1.91		318.0	4.86		389.0	2.0	
Height (cm)	166.74	4.5		171	5.38		173.4	4.5		171.82	6.17		177.88	3.03		180.17	3.25		177.0	1.0	
BMI (kg/m ²)	21.66	1.83		22.19	0.98		22.45	1.09		24.6	1.75		25.98	2.08		27.75	1.03		23.73	0.78	

Notes: Values of each parameter are given as means ± SD for specific types of voice. Values of each parameter are given as means ± SD for specific types of voice.

Abbreviations: BMI, body mass index; N, number of participants; SD, standard deviation; VF, vocal folds length; VRmax, maximal vocal range; VRmin, minimal vocal range.

BMI. Pearson R coefficients value over 0.85 represented the strong correlation between variables. The model's match was reflected R² coefficient of determination. R coefficient value for VFL versus height proved strong dependence, and R-coefficient for VFL versus BMI showed moderate dependence. Table 4 shows B-values with SD for every independent variable (gender, height, BMI) used in the model. Accordingly, gender was shown to have the highest partial influence on VFL value. Subsequently, the increase in the value of BMI rather than in height would have more influence on changes in VFL values. The prognostic potential for regression model is limited by the range of variables used to build it.

In summary, VFL increases with height and BMI within these data series. Moreover, in the model of multiple regression, the gender was shown to have the highest partial influence on VFL value.

Furthermore, owing to the nonparametric nature of variables, Spearman correlation was employed to assess the relationship between vocal range (VR) and VFL and showed inversely proportional correlation ($P = 0.00$, VRmin $R = -0.88$, VRmax $R = -0.77$).

Owing to these results, it can be presumed that with the increase of VFL value, vocal range became narrower. Accordingly, bass voices had the largest VFL values and the narrowest vocal range.

DISCUSSION

Our research aimed to determine the differences in VFL between groups with specific voice types. Also, the dependence between the VFL and factors such as height, BMI, and vocal range were determined.

The method to obtain results based on CT imaging had the highest accuracy among other methods available for authors. Issues which could be the result of inter-rater reliability were minimalized because data were collected by the same, experienced senior consultant of radiology who used the strict protocol to assure repeatability of the measurement. However, the limitation of the current study is the fact that measurements were collected only once, and there was no available data to compare for intra-rater reliability. Such parameters such as Cohen kappa and intraclass correlation coefficient which represent repeatability of measurement of a given variable by the same researcher were not possible to estimate.

Influence of audiation during scanning procedure was not taken into consideration. Notational audiation is a process involving kinesthetic-like covert excitation of the vocal folds linked to phonatory resources and theoretically could affect the results.⁸ Researchers did not examine that aspect.

Principal elements of vocal characteristics like pitch range and timbre are highly correlated with VFL.² Thus, this information is particularly interesting because it can be presumed to be one of the crucial factors in vocal classification. So, understandably, young singers in particular want to determine the length of their vocal folds.

TABLE 4.
Results of Multiple Regression Model ($R = 0.87$, $R^2 = 0.76$, $P = 0.00$): B-partial Regression Coefficient Value for Independent Variable and P Values for Gender, Height, and BMI

	Model of Multiple Regression								
	Gender			Height			BMI		
	B	\pm SD	PValue	B	\pm SD	PValue	B	\pm SD	PValue
VFL	1.64	0.5	0.000	0.16	6.43	0.003	0.38	2.56	0.000

Notes: All three independent variables were shown to be statistically significant in the regression model ($P < \alpha$). B-partial regression coefficient reflects how a given independent variable influence change in a dependent variable. In the model of multiple regression, the gender was shown to have the highest partial influence on VFL value.

Abbreviations: VFL, vocal folds length; B, partial regression coefficient value for independent variable.

Researchers, through many years, have endeavored to develop a quick and reliable method to achieve accurate measurements of laryngeal structures. However, the variability of those reported values due to methodological limitations and the absence of unity for referential values of vocal folds in different methods result in lack of a universal way to estimate VFL.

Early attempts to measure vocal folds dimension in cadavers made by Hirano or Kahane were questioned because of the argument that with loss of muscular tension (which happens around 4 hours after death⁹), exact length of vocal folds increases.¹⁰ Studies conducted on fresh frozen cadavers provided results in which average length of the membranous part of vocal folds in male was 13.2 mm and in female was 10.6 mm, and showed a significant difference between genders.¹¹ Later, the most intuitive methods turned out to be insufficient in the case of a living subject because of the lack of dynamic and fixation of tissue.¹²

Likewise, direct measuring method during laryngoscopy, under neuroleptic or general anesthesia, confirmed the meaningful difference of VFL between men and women. However, it is not possible to apply that type of measuring protocol in everyday practice.¹³

Advances in technology led to the expansion of endoscopic examination. This method revolutionized the diagnostic and treatment of almost every laryngeal disease. Unfortunately, it turned out to be useless in achieving the correct measures of anatomical structures in the larynx. Primary arguments were an insufficient field of view and lack of standardized quantitative data due to change of lens-to-field distance.¹²

Radiography-based measuring methods are relatively new in comparison to the others, which started with lateral x-ray and continued with CT and magnetic resonance imaging. In the literature available to authors, one of the largest groups of measurements gathered from professional singers was presented by Neng Run and Siao Chung.⁹ VFL in

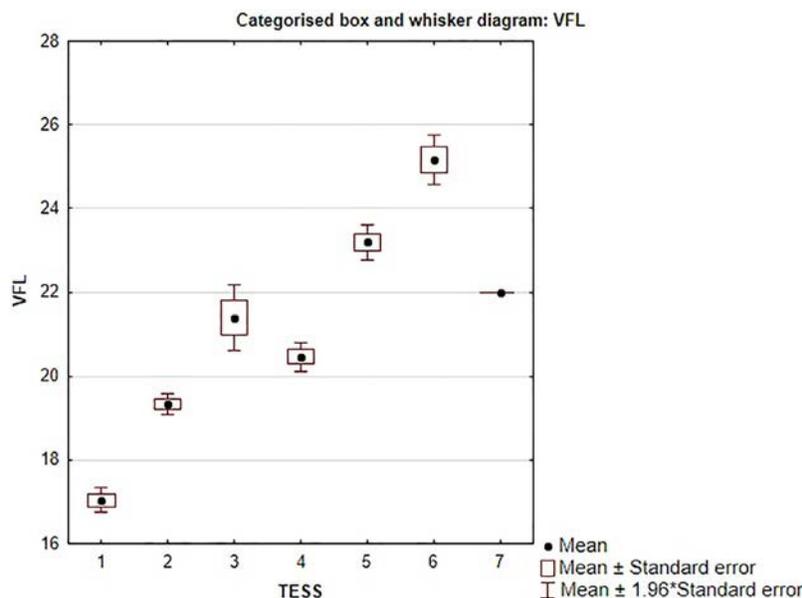


FIGURE 1. Categorized box and whisker diagram with results of ANOVA. The graph is showing the mean values with standard deviation (SD) for the length of vocal folds for a different type of singers' voice (TESS—tessitura: 1, soprano; 2, mezzosoprano; 3, contralto; 4, tenor; 5, baritone; 6, bass; 7, countertenor). ANOVA, analysis of variance.

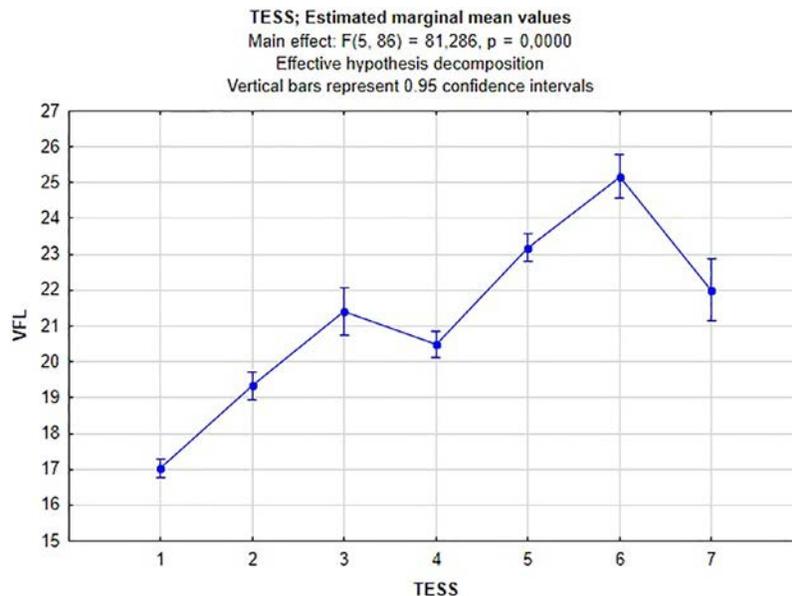


FIGURE 2. The graph of the main effect for ANOVA presenting the mean values with 95% confidence intervals (CIs) for vocal folds length (VFL) and different types of singers' voices (TESS—tessitura: 1, soprano; 2, mezzosoprano; 3, contralto; 4, tenor; 5, baritone; 6, bass; and 7, countertenor). ANOVA, analysis of variance.

opera singers was obtained under specified conditions and landmarks were established in detail.⁹ This study helped to underlie the classification of particular types of voice. Length of soprano's vocal folds was established to be between 13 and 22 mm measured by that method. For mezzo-soprano, the length was between 14 and 18 mm. For male voices, tenors' vocal folds were between 20 and 22 mm and baritones' were between 17 and 27 mm.⁹

Direct comparison of our results with the ones mentioned above was not possible because of different methodology. Our study confirmed the meaningful dependence between VFL and the voice type. Significant differences in VFL were present nearly between every voice type. Statistical analysis showed that along with the increasing length of vocal folds, the vocal range becomes narrower. Therefore, soprano voice has the broadest vocal range and bass the narrowest.

An interesting phenomenon is the singing skills of a countertenor whose VFL value is between that of a tenor and a baritone, but whose voice range is more characteristic for mezzo-soprano or other female voices. The countertenor is an artificial type of voice and majority of countertenors are baritones who underwent specific voice training. Our study confirmed lack of differences in length of vocal folds between countertenor and tenor. However, a limitation of our analysis was the small number of countertenor singers, owing to the rare incidence of this voice.

In our research, data showed diversity in terms of height in the studied groups. The most significant differences were noticeable between genders. Male groups differed from each other. Several previous studies proposed a relationship between height, age, and gender on VFL and confirmed significantly higher values for men.^{12,14}

Interesting results were presented in the analysis of multiple regression which showed that VFL values differ in

adjusting for gender, height, and BMI. As men were significantly taller and had higher BMI, the larger VFL value in male singers could be explained by height and BMI effect. Among variables, a gender effect was regarded as the highest. The difference between men and women in laryngeal anatomy was proposed in many previous studies and was confirmed by almost every measuring method. The anatomical gender-related changes are believed to account for the differences in vocal pitch between male and female singers.¹²

Although VFL was demonstrated to vary systematically between different types of voice, it would be difficult to use it as an only criterion of such classification. Nonetheless, singing range and formant frequency depend not only on VFL but also on the size of the resonant cavity.^{15,16} For instance, formant frequencies were also proved to have a systematic distinction between tenors, baritones, and basses.¹⁵ In a research conclusion, Cleveland suggested that differences were due to various dimension of the oral and pharyngeal cavity.¹⁵

Furthermore, a research conducted by Sundberg on operatic singers' formant frequency suggested systematic differences in voice classification.¹⁷ Studies of vocal tract shape contributed significantly to better understanding distinctions of voice classification.

Research based on x-ray evaluation has identified the length intervals for every type of voice. Development and availability of modern diagnostic techniques (CT, magnetic resonance imaging) created new possibilities of assessing the anatomy of living subjects. Equally, both techniques opened a new chapter in anatomy detail research.

The 3-dimensional (3D) models of larynx achieved in high-resolution CT scanning are helpful in providing a better understanding of the complex movements of laryngeal

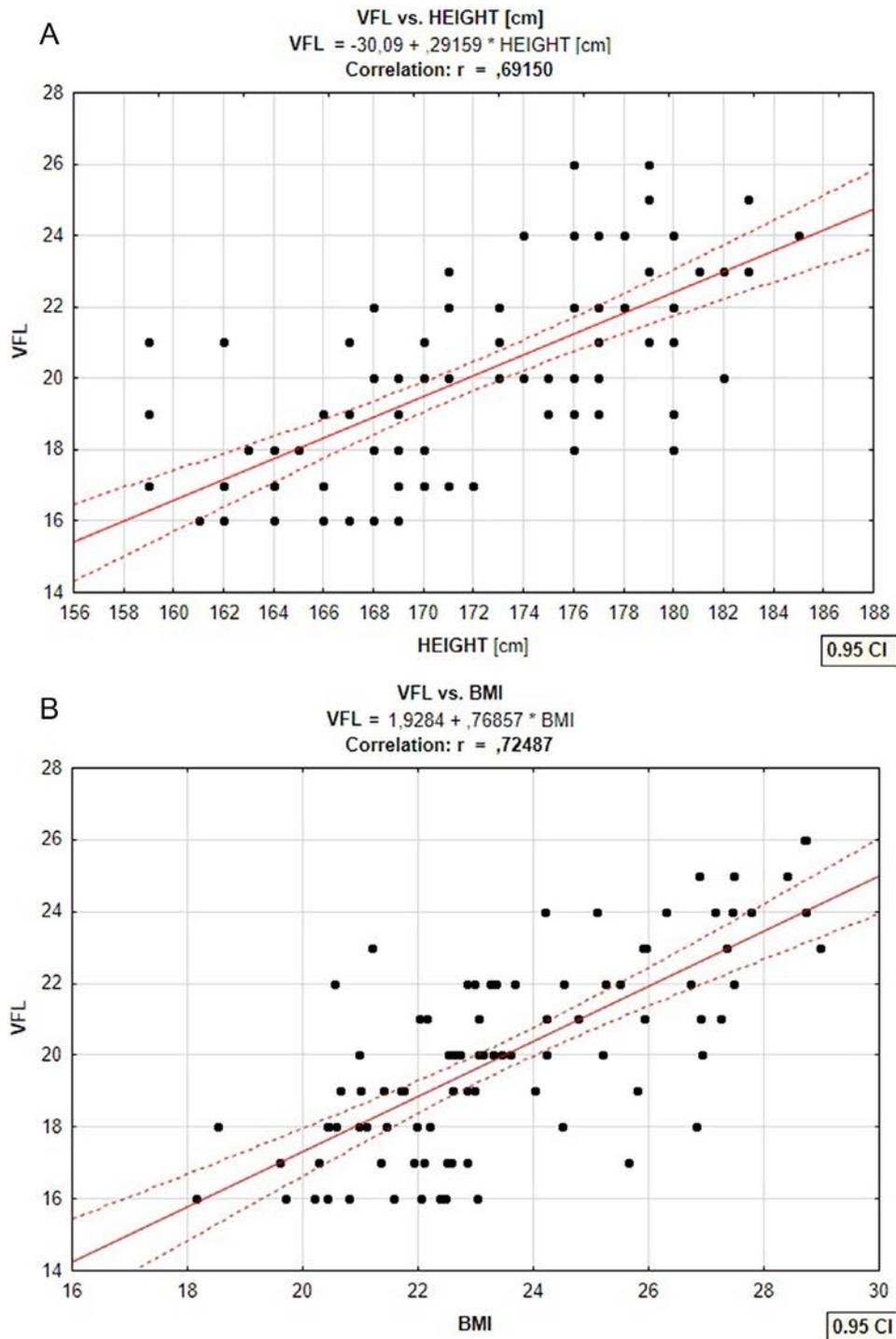


FIGURE 3. Scatter plots for vocal folds length (VFL) by height (A) and body mass index (BMI) (B). Scatter plots show all the VFL values by height and BMI. The fitted regression line represents the relationship between the VFL and height or BMI. In that data series, as the value of height or BMI increases, the length of vocal folds also increases. Pearson correlation R coefficient is the measure of linear correlation between two variables: VFL versus height and VFL versus BMI. $R_{BMI} = 0.72$ demonstrates very strong dependence between variables and $R_{Height} = 0.69$ stands for moderate dependence. The positive value of Pearson R-coefficient represents positive correlation.

structures during singing.^{18,19} Such pilot study conducted by Vorik proved the usefulness of high-resolution scanning as a noninvasive method of visualization of living subjects' singing and provided analysis of laryngeal structures during singing.¹⁸ The 3D reconstruction of these scans allowed

observation of the vocal folds' elongation during pitch changes and modification of VF tension and stiffness.¹⁹ Moreover, high-resolution computed tomography imaging of the neck region is associated with a relatively small dose of radiation, which makes this type of scanning technique safe.¹⁹

Furthermore, cone beam CT scanning is a simple, more office-based method to acquire measurements of a singer's airway. The method allows obtaining reasonably high-quality images that enable 3D reconstruction and measurements of airway tract with a significantly lower dose of radiation.²⁰ In several studies, cone beam scanning was demonstrated to provide accurate images that make possible the measurement of soft tissue structures.²¹ The cost is not expensive and a cone beam CT scanner is relatively easy to manage without the need for a specialized radiologist. We believe that progressive advances in cone beam CT imaging may be the future of outpatient management because of the possibility of fast and low-dose assessment of the head and neck region.

CONCLUSIONS

Our research showed that among professional opera singers from the studied group, the VFL varies among different types of classical voices. Moreover, the VFL was inversely related to the vocal range and strongly influenced by gender, height, and BMI.

Acknowledgments

We would like to thank both of our anonymous reviewers for their insightful comments on the manuscript, as their suggestions led us to improve our work.

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