Evaluation of the Supraglottic and Subglottic Activities Including Acoustic Assessment of the Opera-Chant Singers

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Summary: Opera and chant singers learn to effectively use aerodynamic components by breathing exercises during their education. Aerodynamic components, including subglottic air pressure and airflow, deteriorate in voice disorders. This study aimed to evaluate the changes in aerodynamic parameters and supraglottic structures of men and women with different vocal registers who are in an opera and chant education program. Vocal acoustic characteristics, aerodynamic components, and supraglottic structures were evaluated in 40 opera and chant art branch students. The majority of female students were sopranos, and the male students were baritone or tenor vocalists. The acoustic analyses revealed that the mean fundamental frequency was 152.33 Hz in the males and 218.77 Hz in the females. The estimated mean subglottal pressures were similar in females (14.99 cmH_2O) and in males (14.48 cmH_2O). Estimated mean airflow rates were also similar in both groups. The supraglottic structure compression analyses revealed partial anterior-posterior compressions in 2 tenors and 2 sopranos, and false vocal fold compression in 2 sopranos. Opera music is sung in high-pitched sounds. Attempts to sing high-pitched notes and frequently using register transitions overstrain the vocal structures. This intense muscular effort eventually traumatizes the vocal structures and causes supraglottic activity.

Key Words: Subglottal air pressure–Subglottal airflow–Opera-chant courses–Acoustic analysis–Compression.

INTRODUCTION

The main source of voice is the volume rate of the airflow passing through the glottis and the glottal pressure. Opera and chant singers are professionals who use their breath in the largest ranges. Their education includes breathing training for the effective use of subglottic air pressure. Subglottic air pressure is defined as the pressure measured in cmH_2O units when the vocal folds are adducted. Subglottal air pressure can be measured by direct method using a transducer, which crosses transcutaneously from the cricothyroid membrane or transnasally after the plica vocalis are anesthetized. This invasive method is rather uncomfortable for the subject. For indirect measurement, a facial mask and a transducer passing through it estimates the transglottal air pressure and glottal airflow velocity from the intraoral air pressure and airflow velocity. Aerodynamic measurements like transglottic airflow, subglottal pressure, and translaryngeal resistance, which are direct indicators of laryngeal physiology, have been used to distinguish normal and abnormal voice.[1] During singing, automatic changes in phonation modes by subglottal pressure or fundamental frequencies are not allowed because they may cause undesirable effects. In natural speech, increases in subglottal pressure also increase the vocal noise and generally the fundamental frequency.[2] But when singing, these effects are to be avoided. Eventually, perfectly controlled subglottal pressure in wide ranges during singing necessitates absolutely matched fundamental frequency and vocal noise with the pressure.[3] Opera singers perform the songs with loud sounds and in wide pitch ranges. Also, opera singing forces the singers to sing high notes and to collate registers. The effort to rise to high-pitched sounds and ranges during singing causes compensatory changes in the pharynx, one of the anatomical cavities that contribute to the resonance. In professional voice production, the intensity and the frequency of primary glottal sounds change in supraglottic area as a result of various muscle activities. For this reason, using the supraglottic structures gains importance in opera and chant training. The positions of supraglottic structures are quite different from those other singers and natural speaking.

Supraglottic activity is defined as the laryngeal movement just above the level of true plica vocalis.[4] Supraglottic activity may occur as two components during voice production.[5]

Anterior-posterior supraglottic activity occurs when the arytenoid cartilages move through epiglottal petiole, and partly or completely cover the plica vocalis (A-P compression).

Medial supraglottic activity (False Vocal Fold Compression /Medial Compression) compression occurs when the adduction of plica vestibularis closes the plica vocalis partially or completely (FVF compression). The physiology of the medial compression has not been completely understood, but it is thought to occur for increasing the immobility of plica vocalis in the epilaryngeal area through the anterior-to-posterior axis. Stager et al[4] have reported that supraglottic activity presents as different static and dynamic movements during voice production. Static component is defined as the position or configuration of the supraglottic structures during voice production. The dynamic component refers to a discrete, quick medial compression of the FVF that can occur several times or not at all during connected speech. Also, A-P compression is defined as a static component, whereas FVF compression is defined as both a static and a dynamic component.[4] Based on the previous results of Stager[6] this study was conducted to assess the "voice disorder-like

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changes" in the aerodynamic parameters and supraglottic structures of the opera and chant singers with different vocal registers.

METHODS

Participants

A total of 44 volunteers (21 females, 23 males) among the opera and chant students were included in the study. Participants had at least 1 year of opera training. This study was approved by the Cukurova University Faculty of Medicine Clinical Trials Ethical Committee. Participants were informed about the study, and their laryngeal examinations were performed in the Ear, Nose, and Throat Department of Cukurova University Faculty of Medicine where their vocal disturbances were evaluated. Additionally, participants completed a subject questionnaire and a professional vocal disorders form. We started with 44 people, but four smokers were excluded from the study. The final group consisted of 40 subjects. Four participants with upper airway infections were reevaluated after healing. The follow-up of these participants was done by an ENT specialist, and they had a laryngeal reevaluation and testing 15 days after healing.

Laryngostroboscopic examination

All students underwent videostrobolaryngoscopic evaluation using a 90° rigid stroboscope (EndoSTROB DH, XION, Germany) and miroVIDEO DE30 video capture cards (Microcomputer Products, Inc., CA; Pinnacle Systems). Participants were informed about the examination, and local anesthetic lidocaine 10% spray was administered on demand if a participant thought she or he could not tolerate the procedure. One of the investigators evaluated the glottal structure initially. The procedure was continued if the participants had normal structure and function. The second stage included evaluations to determine the supraglottic activity. The rigid stroboscope was passed into the oral cavity until visualization of the epiglottis was achieved, and then moved forward until complete visualization of plica vocalis and plica ventricularis was attained. When a complete image was captured, participants were requested to vocalize /i/. A-P and medial compression assessments were performed by measuring closure levels of true vocal folds between glottal stops. Then, 10 seconds of video recording were taken. To overcome the potential of medial compression at the beginning of the phonation, only qualified image frames after the first second were selected.[4] Single frames that present the minimum and maximum compression were evaluated. The structures that were screened by epiglottis were considered as a bad recording, and laryngostroboscopic images were retaken. Similar to the methods of Popolo and Titze,[7] and Su et al,[8] the images that were taken under 3 cm depth and 3× macro-magnification were standardized at the same size and perspective. Two images were selected at the position in which the plica vocalis was adducted and maximal supraglottic compression occurred. The first image included first vocalization, and the last image included last vocalization. The mid-membranous part of the adducted plica vocalis between petiole of the epiglottis and the arytenoid cartilage was measured as pixels in the Adobe System for A-P measurements. Medial compression was measured as the width between the most medial part of the ventricular cord and the opposite end when the plica vocalis were adducted. The pixel measurements were converted into centimeters.

Static and dynamic compressions were visualized by videolaryngostroboscopy during the entire phonation. The static component was scored using similar scoring as that of Stager et al where 0 = none, 1 = inadequate, 2 = adequate.[5] If A-P and FVF compression did not occur during any vocalization, then the score was "0." The compression, which did not occur during entire vocalization but at any stage of the vocalization, was scored as "1"; this score actually shows the compression with a dynamic component, which defines the image that is characterized with the rapid adduction of the plica ventricularis. The compression that occurs during entire vocalization was scored as "2." This score is defined as the static component.

Aerodynamic measurements

Mean subglottal air pressure and glottal airflow rates can be estimated by noninvasive methods during repetition of an easy syllable in the clinical evaluation of aerodynamic voice parameters. In the standard method, subglottal air pressure and glottal airflow estimations are based on the intraoral air pressure measurements during the lip closure while sounding "pa". Estimations of subglottal pressure and glottal airflow measurements were taken with AeroviewPro (Phonatory Aerodynamics System, Glottal Enterprises) set.[9] For airflow and pressure measurements, calibration signals were recorded by pressure transducer (PT-2E, PT-25, Glottal Enterprises) and USB interface providing analog to digital conversion (MS-100, Glottal Enterprises). Pneumotach calibration was done before each test, and individualized facial masks were used for each participant. Air pressure calibration was applied once for each recording. While transforming the graphs into numerical data, measurements were recorded by standardizing to 20 cmH_2O pressure and 2.56 seconds on the time scale. Syllable index repetition was adjusted to 2.5–4.0 seconds. Oral airflow and subglottal pressure were measured by a two-chamber Rothenberg mask using a thin plastic tube with a pressure transducer from Glottal Enterprises (Glottal Enterprises, Syracuse, NY). The end of the thin plastic catheter was placed just behind the teeth, and the other end was connected to a pressure transducer with a linear frequency separator that responds to 30 Hz.

Data collection and analyses

The stop consonant with vowel "pa" was used to determine the subglottal air pressure levels in aerodynamic measurements.[10] Five repetitions of the syllable were recommended for the measurements. Accordingly, participants were told to say "pa" syllable 5 times consecutively following a deep breath and with a gradually decreased pitch at repetition. Because participants continuously decreased vocal sound tone at each repetition of the "pa" syllable, subglottal pressure decreased at each vocalization of the syllable. Sound pressure level for the participants was determined during recordings to ensure pitch differences did not to occur. Participants were told to perform their vocal tasks at a "comfortable" and "natural" vocal pitch.

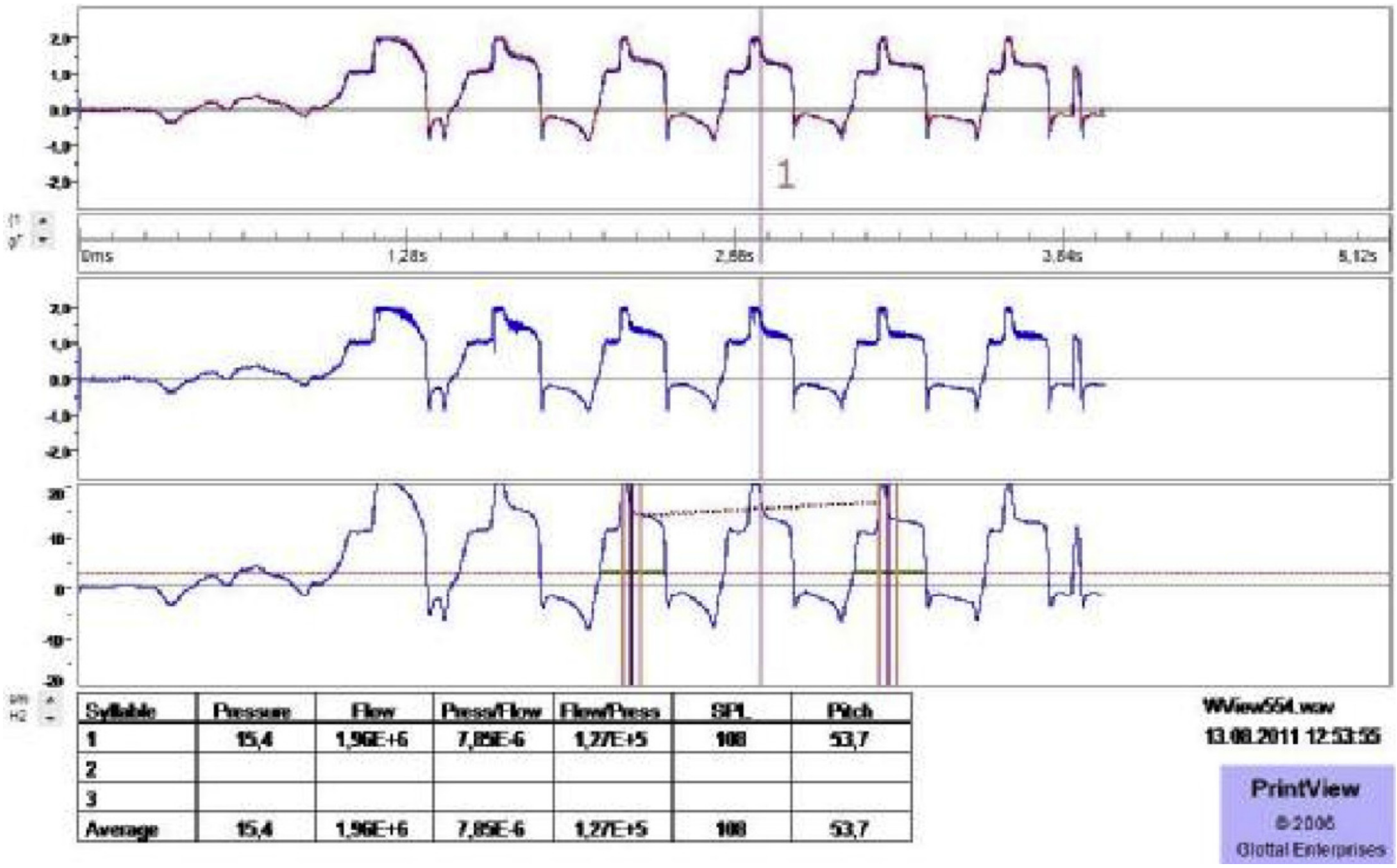

FIGURE 1. Illustrating the measurement of subglottal airflow and air pressure method (L/s-cmH_2O).

The syllable index frequency was set to 2.5–4.0 seconds in monitored graph recordings, and the data with best graph curve was recorded. Subglottal airflow and air pressure values were recorded as numerical data. Calculations were made at the midpoint of the vocal segment. The midpoint of each pressure curve was regarded as the reference of fluctuations corresponding to "pa" consonant in pressure and flow graphs, and at least three segments (from the five recommended curves) were selected and converted to numerical data (Figure 1). The intraoral airflow and air pressure are measured at two slightly different time points; however, the subglottic air pressure is assumed to be constant and this is essential for the validity of the indirect assessment method.[10] The software provided mean air pressure values from the range produced.

Acoustic analysis vocal data measurement method

Sound recordings for acoustic vocal analyses were obtained in anechoic chamber where the environmental noise was minimal. Participants were told to vocalize at a "comfortable" and "natural" pitch and loudness. Initially, they were told to produce the /a/ phoneme for 3 seconds at prolonged normal loudness,[11] and then they were told to read a passage entitled "Diyet" by Omer Seyfettin at their own pitch three times in a row with a 15-second pause between each reading. The best of three samples was considered for assessment. Recordings were obtained under the supervision of one of the investigators and by using an M-Audio Fast Tracker USB II sound-card connected Shure SM58S microphone (Shure Inc., Mexico), and *GoldWave* software (GoldWave Inc., St. John's, NL, Canada). Recordings were transferred as "wav" files to *Doctor Speech Real Analysis* (Tiger Electronics, Neu-Anspach, Germany) software. Mean fundamental frequency, jitter, shimmer, harmonic-to-noise ratio (HNR), and normalized noise energy values were determined for each sound sample.

STATISTICAL ANALYSES

The mean values and distributions of aerodynamic and acoustic parameters for each group were compared with parametric one-way analysis of variance, and the alternative nonparametric method Kruskal-Wallis statistical tests between groups. Results were presented as means and standard deviations.

RESULTS

The age range of the participants was 19–32 years with a mean of age of 23.37 ± 2.66. There were 15 sopranos (83.3%), 3 mezzo-sopranos (16.7%), 11 baritones (50%), 4 basses (18.2%), and 7 tenors (31.8%). Aerodynamic and acoustic data were categorized and assessed according to vocal types.

Aerodynamic

The subglottal air pressure was found to be significantly different between genders ($P = 0.030$). Women had significantly higher subglottal air pressure values than men (Table 1). When the mean subglottal air pressure values were evaluated according to vocal

TABLE 1.
The Mean Values Subglottal Air Pressure According to Gender (cmH_2O)

	Mean	SD	Minimum	Maximum
$P = 0.002$*				
Female	15.31	2.16	9.79	18.70
Male	12.87	2.37	8.83	16.80

* $P < 0.05$.
Abbreviation: SD, Standard deviation.

groups, mean subglottal air pressure values of soprano and mezzo-soprano women were found to be significantly higher than the bass and baritone men (Tables 2–3) ($P > 0.01$). The airflow values were not found to be significantly different between male and female opera and chant students ($P > 0.05$). The mean subglottal airflow velocity value was 1.62 ± 0.41 L/s (Table 4). The mean subglottal airflow values were not significantly different between vocal groups.

The correlation analyses between subglottal air pressure, subglottal airflow, and acoustic data revealed a significant positive correlation between subglottal air pressure and fundamental frequency ($P = 0.040$) (Figure 2). No significant correlation was found with subglottal airflow. There was a 62% positive correlation between airflow and air pressure. Subglottal air pressure was found to be increased as the airflow increased ($P = 0.001$) (Figure 3).

Acoustic data

The mean fundamental frequency for males was 142.38 ± 37.76 Hz and 232.53 ± 23.76 Hz for females (Table 5). The distribution of fundamental frequencies in each vocal category is also presented in the table (Table 6). Mean jitter value was 0.29 ± 0.13%, mean shimmer value was 1.91 ± 0.89%, mean HNR was 26.32 ± 2.87 dB, and mean normalized noise energy was −12.77 ± 5.15 dB. Mean values according to gender are presented in Table 6. Our results confirmed the fact that increased subglottal pressure also resulted in increased fundamental frequency (2) ($P = 0.001$) (Figure 2).

TABLE 2.
Average Values of the Subglottal Air Pressure According to Vocal Groups (cmH_2O)

	Mean	SD	Minimum	Maximum
Soprano	14.99	2.13	9.79	17.80
Mezzo-soprano	17.06	1.60	15.50	18.70
Bass	12.35	3.92	8.96	14.90
Baritone	12.29	2.34	8.83	15.70
Tenor	14.48	1.68	13.10	16.80

TABLE 4.
The Mean Values of Subglottal Airflow Velocity According to Gender (L/s)

	Mean	SD	Minimum	Maximum
Female	1.66	0.32	1.03	2.16
Male	1.56	0.36	1.03	2.13
Mean	1.62	0.41	1.03	2.90

Supraglottic activity

Partial A-P compression and medial compression were observed in two female sopranos. Only A-P compression was observed in two men. Medial compression was not observed during any vocalization. Moreover, no complete compression was observed in any vocal group or gender. The compression level monitoring method is shown in Figure 4 and Figure 5.

DISCUSSION

The importance of subglottal pressure in voice disorders has been shown in several studies. Increased or decreased subglottal pressure is characterized with vocal hyperfunction or laryngeal pathologies.[2] Netsell and Hixon[12] compared the groups with and without voice disorders in aerodynamic and perceptual measurements, and found that subglottal pressure was higher in individuals with tense and rough voice quality, and voice disorder. In chant phonation, a regular voice intensity is needed, and this intensity is adjusted with the subglottal air pressure coming from the lungs below the plica vocalis. Keeping this air pressure is only feasible by coordinating the muscles responsible for inspiration and expiration. In this way, a regular sound intensity is maintained by the stable subglottal air pressure under plica vocalis that is provided by the diaphragm. Increased subglottal air pressure and subsequent voice intensity enlarges the laryngeal lumen, decreases the vibration, and increases the voice frequency. Iwarsson et al[13] reported that untrained subjects tended to increase the sound intensity using glottal adduction to increase the decreasing lung volume occurring at the end of the "pa" sequences. This causes constriction in airways and increases supraglottic pressure, which eventually increases intraglottic pressure.[14] Thomasson and Sundberg[15] reported that

TABLE 3.
The Comparison of Subglottal Air Pressure Between Vocal Groups (cmH_2O)

	Bass-Baritone	Soprano-Mezzo-soprano	Tenor	
Air pressure	Mean ± SD	Mean ± SD	Mean ± SD	*P*
	12.84 ± 3.45	15.46 ± 2.30	14.10 ± 4.46	0.028*

* $P < 0.05$ one-way ANOVA.

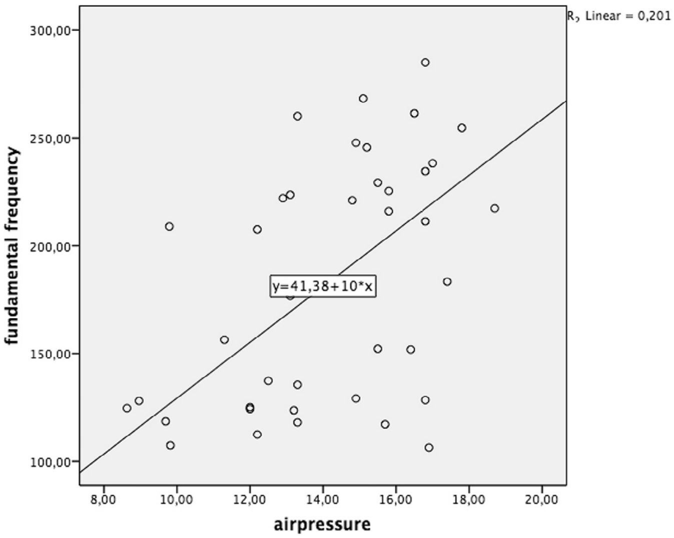

FIGURE 2. Relationship between fundamental frequency and subglottal air pressure (Hz/cmH_2O).

this effect is not observed in trained singers. Based on those findings, trained participants were included in our study to eliminate the factors that may cause increased subglottal air pressure. Giovanni et al[11] found that subglottal air pressure was 23 ± 12.5 cmH_2O in patients and 6.2 ± 1.3 cmH_2O in normal individuals. In our study, the subglottal air pressure was found to be 14.50 ± 2.21 cmH_2O in opera and chant students. There are two factors associated with the increased subglottal air pressure in individuals with voice pathologies. First is the compensation mechanism of glottal leakage, which aims to achieve the required air pressure to initiate the mucosal vibration. The second factor is the poor vibration quality of the residual mucosa, which requires a much higher pressure than the normal mucosa to initiate the vibration.[10]

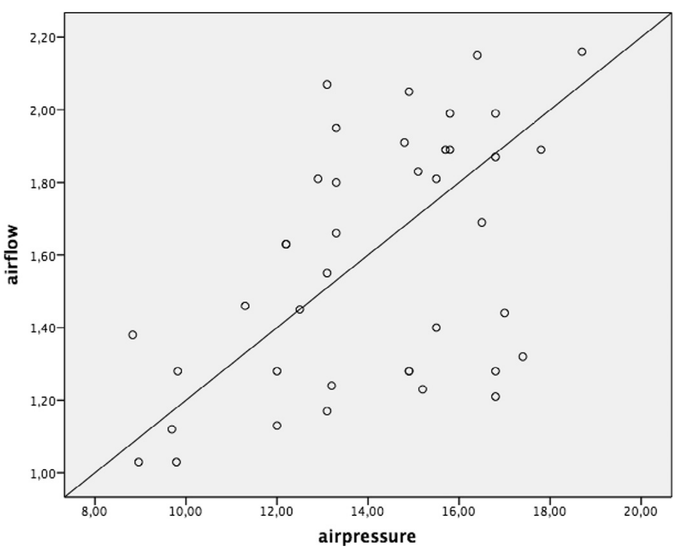

FIGURE 3. Relationship between subglottal airflow rate and air pressure (L/s-cmH_2O).

Lundy et al have measured the mean airflow velocity as 172.90 mL/s (0.172 L/s) in music department students.[16] Giovanni et al[11] have measured this value as 170 ± 129 mL/s (0.17 L/s) in normal nonsingers. We have found that the airflow velocity was 162 ± 0.41 L/s. Those studies used Escala Visual-Analógica (EVA) system, which has a similar measurement style of the Aeroview Phonatory Aerodynamic System. The differences between the results were considered to be associated with the different equipment used in the studies, or with the different skill levels gained through training.

The mean acoustic values were 142.380 ± 37.76 Hz for men and 232.53 ± 23.76 Hz for women. Plica vocalis had length differences because of gender, and men had longer and looser plica vocalis, which causes men's voice to have lower fundamental frequency. The acoustic analyses of the students who were in the soprano category and men in baritone and tenor categories revealed that the fundamental frequency was 149.471 Hz in tenors, and 233.92 Hz in sopranos, which suggests that having such high-pitched voices makes these people suitable to sing opera.

Using *Dr. Speech* software, Zhang et al[17] have found that jitter was 0.18 ± 0.07%, shimmer was 1.6 ± 0.74%, HNR was 25.34 ± 3.12 dB, and normalized noise energy was –16.95 ± 3.57 dB in the acoustic analyzes of 153 participants who were randomly selected from a population. Standard acoustic measurements are important parameters for distinguishing normal and abnormal voice characteristics. Individuals who took voice training have particularly lower shimmer and HNR values. These values, which are considered as indicators of good vocal quality, were found to be in normal range for the opera and chant students in our study.

Supraglottic activity either occurs as a compensatory action in case of an incomplete closure of the plica vocalis, or occurs as an action against vocal use with muscle overstraining.[5] The presence of supraglottic activity is frequently associated with and thought to indicate disordered voice production.[5,18] Examples of voice disorders that have frequently been associated with observations of supraglottic activity include glottal incompetence, muscle tension dysphonia, conversion aphonia, habituated hoarseness, inappropriate falsetto, vocal fold nodules, and polypoid

TABLE 5.
Average Values of Acoustic Analysis Results According to Gender

	FO (Hz) Mean ± SD	Jitter (%) Mean ± SD	Shimmer (%) Mean ± SD	HNR (dB) Mean ± SD	NNE (dB) Mean ± SD
Female	232.53 ± 23.76	0.24 ± 0.11	2.28 ± 0.77	26.71 ± 2.76	–13.74 ± 2.34
Male	142.38 ± 37.76	0.33 ± 0.14	1.61 ± 0.88	26 ± 2.98	–11.97 ± 2.59
Mean	182.95 ± 55.46	0.29 ± 0.13	1.91 ± 0.89	26.32 ± 2.87	–12.77 ± 5.15

TABLE 6.
Average Values of Fundamental Frequency According to Vocal Groups (Hz)

	Mean	SD	Minimum	Maximum
Soprano	218.77	40.14	126	268
Mezzo-soprano	228	10.53	217	238
Bass	117.75	10.47	106	128
Baritone	125.33	15.60	107	156
Tenor	152.33	21.60	123	177

degeneration.[5] The presence and incidence of supraglottic activity has been noted in recent studies of individuals with normal laryngeal structure and function and normal vocal cord mucosa, but there is no clear information to explain the presence of supraglottic activity in voice production. Observations about the presence of supraglottic activity in normal individuals have led investigators to conduct similar studies on nonprofessional singers who have normal vocal characteristics.[5,19] These studies have evaluated whether supraglottic activity is the result of increased muscle strain because of vocal hyperfunctioning, or a static or dynamic position of the larynx during forced voice production. However, little is known about the contributions of the physiological changes in vocal effort. Investigators reported that medial compression of the ventricular folds is rather a dynamic articulatory characteristic; however, A-P compression can represent a dysfunction as a static posture in all tasks. Previous categorical and qualitative assessment studies showed that A-P compression is not dependent on any speech content, but medial compression of the ventricular folds presented significant differences in speech tasks between groups.[19] Stager et al[4] reported that static activity is best represented by A-P compression, and compression of plica ventricularis shows both static and dynamic activities. Stager et al did not find any differences between groups in their study that evaluated medial compression of the ventricular vocal folds in healthy individuals with voice fatigue of non-nodular and non-organic origin. But, there was a difference between dysphonic and normal individuals regarding A-P compression level.[4] Behrman et al[19] found in their study that A-P compression level was significantly higher in dysphonic individuals than in normal individuals. They also reported that medial over-compression will make the vibration of the vocal folds impossible. Additionally, a small adduction will also increase the glottal resistance and subglottic pressure during closed phase of the glottal cycle, which eventually increases the fundamental frequency.[19]

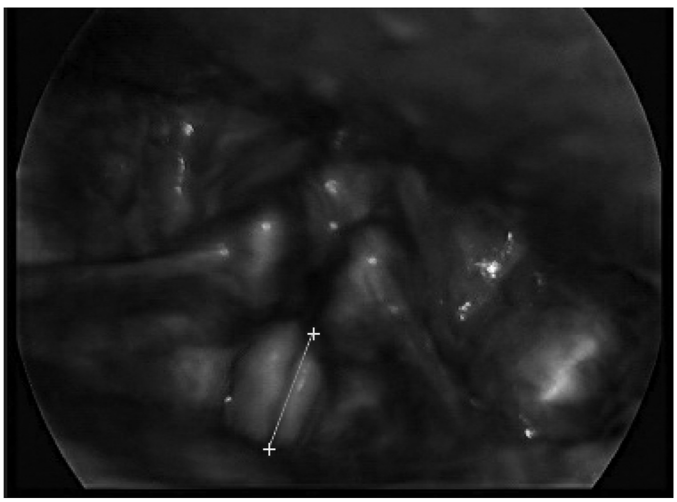

FIGURE 4. A-P compression. Measurement in pixels of the anterior-posterior distance between arytenoid cartilage and petiole (partial compression).

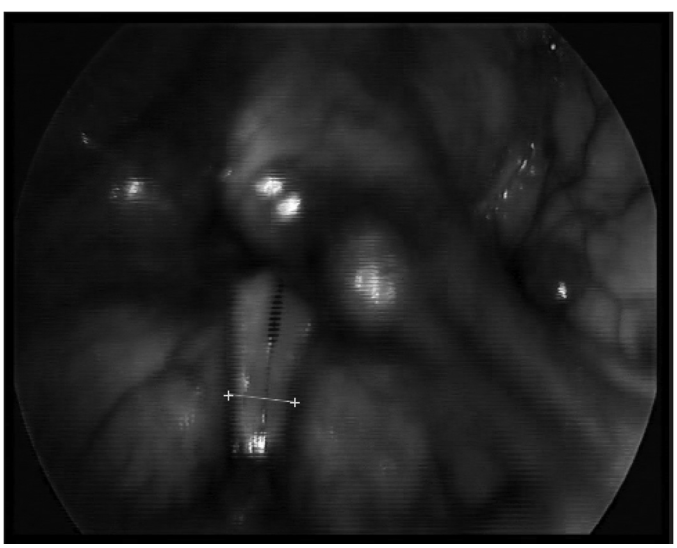

FIGURE 5. FVF compression. Measurement of pixel of the width distance of true folds during phonation (partial compression).

Stager et al[1] reported that formation of the dynamic supraglottic activity is related to the special linguistic content, and gender factor does not affect supraglottic activity. But, they also showed that static FVF and A-P compression were significantly higher in men than in women. On the other hand, FVF compression for initiating the voice was observed more often in women than in men.[6] In our study, we have identified partial A-P compression in two sopranos, and FVF compression in two other sopranos among women, and A-P compression and supraglottic activity in two tenors. FVF compression was not observed among men. Additionally, complete compression was not observed in any gender or within any vocal register. A statistically significant correlation between groups was not found. As Pemberton et al[20] and Stager[6] stated, supraglottic activity may occur in normal individuals, even in people with highly qualified musical training. In accordance with the fact that it may differ according to gender, FVF compression was not observed in our male singers. We have only observed the supraglottic activity in tenors and sopranos, which indicates that A-P compression is not a static state. Also, it was confirmed to occur with the muscle strain, because tenors and sopranos have high-pitched voice and they force themselves to incline to higher pitched sounds, which causes forced vocal use. We thought as did Stager[6] that supraglottic compression may be present before sound quality changes and that might be an indication of a voice disorder. This theory could be confirmed by reexamining in our subjects the supraglottic activity and voice disorders in their later professional singing careers. Further studies with larger samples, including higher numbers of tenors and sopranos, are suggested for the activity evaluation.

CONCLUSIONS

In conclusion, it is possible to observe supraglottic activity and voice disorders in the future professional life of opera and chant singers. Therefore, these artists should be regularly followed up to evaluate their supraglottic activity and acoustic characteristics.

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