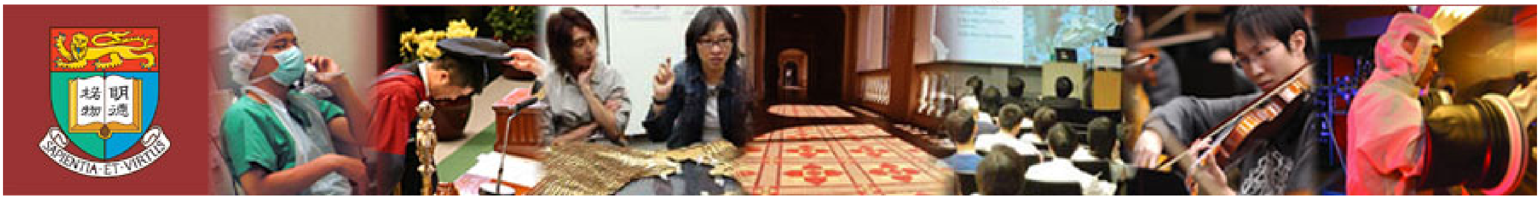

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Vocal tract dimensions and vocal fold vibratory characteristics of professional singers of different singing voice types

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Abstract

This study aimed to examine the relationship between different singing voice types and their vocal fold vibratory characteristics and vocal tract dimensions. A total of 19 tenors, 10 baritones, 29 sopranos, and 4 mezzo-sopranos participated in the study. Electroglottography (EGG) was used to measure the vocal fold vibratory characteristics, based on which parameters including open quotient (Oq) and fundamental frequency (F0) were derived. During the experiment, the participants sang the song “Happy Birthday” with constant loudness level and at the most comfortable pitch level. A pharyngometer was used to measure singers’ vocal tract dimensions. Results showed that tenors had significantly higher Oq/F0 gradient than baritones in chest and head registers, while sopranos had generally higher Oq/F0 gradient than mezzo-sopranos in chest and head registers. Regarding vocal tract dimensions, sopranos generally exhibited greater vocal tract length and volume values than mezzo-sopranos. The present study provides insights to applying both vocal fold vibratory characteristics and vocal tract dimensions in voice classification for male and female singers.

Introduction

Vocal tract refers to the resonance chamber bounded by the lips and glottis, comprising the oral, nasal and pharyngeal cavities (Seikel, King & Drumright, 2005). To facilitate production of different speech sounds and singing, vocal tract configuration can be adjusted by altering the location, size and shape of various articulators including the lips, jaw, tongue, and soft palate. During phonation and singing, vocal folds are set into vibration by passing air from the lungs through the glottis. According to the source-filter theory, all speech sounds are products of sound source and filter. The sound source is an acoustic energy generated by a transglottal airflow which produces a sound of many frequencies, and the filter is the vocal tract which selectively resonates a subset of frequencies (Titze, 1994). As such, both vocal tract and vocal folds are important in voice production and singing.

In Western music, singing voices are commonly classified into soprano, mezzo-soprano, and alto for females, and tenor, baritone and bass for males (Sell, 2005). Singing voice classification is important for professional singers in order to make the best use of their voices. If a singer sings out of his/her capability, i.e., singing at a voice type beyond his/her voice range, his/her vocal folds would be placed under extra stress and, if prolonged, could be harmed (Sell, 2005). In addition, singing at an inappropriate voice range might not have immediate hazard and could make singers develop unhealthy or even harmful singing habits over time (McKinney, 1994). Traditionally, singing teachers rely on singing apprentices' voice range, tessitura (the area in ones voice which sounds and performs the best and is most comfortable) (Sell, 2005), size of voice, timbre characteristics to classify them into different voice types according to their experience (Sell, 2005; Smith & Sataloff, 1999; To, 2010). However, this method of classification is highly subjective and can be inaccurate. Different teachers may perceive voices differently based on their perception of voices. This way of classifying singing singers is apparently in lack of scientific basis and can be unreliable and inefficient. An objective means to classify singing types is necessary in order to avoid the adverse consequence of misclassification of singers.

Previous studies suggested various objective measures for voice classification, including singing fundamental frequency (F0) range (Titze, 1994), vocal fold length (Roers, Murbe & Sundberg, 2009), vocal fold width (Larsson & Hertegard, 2008), singing formant frequency (Dmitriev & Kislev, 1979; Sundberg, 1995; Tsoi, 2009; To, 2010; Mok, 2011), frequency at which register changes (Callaghan, 2000), timbre transformation (Erikson, Perry & Handel, 2001; Erickson, 2003), vocal tract length (Dmitriev & Kislev, 1979; Tsoi, 2009; Mok, 2011), and vocal tract volume (Tsoi, 2009; To, 2010; Mok, 2011). Yet, few studies examined the relationship between different voice types and their vocal fold vibratory characteristics for voice classification. Vocal characteristics after all determine the quality and timbre of singing voices.

In a study investigating the relationship between singing voice type and vocal fold contact time using electroglottography (EGG) by Sundberg and Högset (2001), thirteen professional singers consisted of baritones, tenors, and countertenors sang notes at the same pitches and intensities using both modal and falsetto registers. Register is a musical descriptor that refers to a particular vocal quality that could be maintained over certain ranges of pitch and loudness (Titze, 1994). Typical singing registers are chest, head, and falsetto (Titze, 1994). In their study, it was found that the closed quotient differences between modal and falsetto registers sung by baritones were larger than the closed quotient differences of tenors and countertenors. However, generalization of results should be made with caution as only 13 participants participated in the study, representing only a small pool of the singer population.

Other studies reported similar findings regarding vocal fold contact time associated with different laryngeal mechanisms (Sundberg and Högset, 1999; Henrich, d’Alessandro, Doval & Castellengo, 2005; Salomao & Sundberg, 2009). In general, three scientifically-defined laryngeal mechanisms were identified (labeled as M0, M1, M2). The three laryngeal mechanisms musically correlate well with singing registers. M0 correlates with vocal fry, M1 correlates with chest, modal, and male head register, and M2 correlates with falsetto for male and head register for female (Roubeau, Henrich & Castellengo, 2009). Vocal fold open quotient was also found to correlate with vocal intensity and F0 in different laryngeal mechanisms (Henrich et al., 2005).

The relationship between voice source characteristics and different performance genres has also been examined. For example, Barlow and LoVetri (2010) investigated the voice source characteristics of 20 adolescent singers using “classical” and “musical theatre” singing styles. They found a significantly higher average closed quotient value for the “musical theatre” style than the “classical” style, suggesting a systematic difference in vocal fold vibratory characteristics in different singing types. Results from previous studies consistently show a solid correlation between vocal fold vibratory characteristics and different vocal registers, intensity and F0 (Sundberg and Högset, 1999; Henrich et al., 2005; Salomao & Sundberg, 2009). The present study attempted extend these studies and examine the contribution of vocal fold vibratory characteristics to voice classification, taking into account vocal registers, loudness and pitch used, based on a larger sample of professional singers.

In addition to vocal fold vibratory characteristics, vocal tract dimension should also be taken into consideration when classifying singing voice types as vocal tract dimension directly affects the quality or timbre of the singing voice. According to the source-filter theory, the acoustic signal generated by the source (vocal fold vibration) is being filtered by the filter (vocal tract which resonance), contributing to the formation of formants (Titze, 1994). It was suggested that formants that are formed by the flexible vocal tract determine the tessitura, while vocal tract dimension also contributes to the voice timbre formation (Sell, 2005). As tessitura and timbre characteristics are important criteria for traditional voice classification by singing pedagogues, the objective measurement of vocal tract dimensions is needed for more accurate and reliable voice classification.

However, a review of the literature indicates that only a handful of studies on singing vocal tract have been reported (e.g., Dmitriev & Kislev, 1979; Tsoi, 2009; To, 2010; Mok, 2011). Dmitriev and Kislev (1979) found that voice classification was correlated with singers' vocal tract length and the acoustic characteristics (low and high singing formants) of their productions. However, x-ray technology was used and only two-dimensional images of the vocal tract could be obtained, with a lack of vocal tract volume measurement. Tsoi (2009) found that baritones had significantly larger vocal tract volumes than tenors, and sopranos had shorter vocal tract length than mezzo-sopranos. To (2010) also showed that the oral volumes and total vocal tract volumes of baritones were significantly larger than those of tenors. However, their participants were recruited from different organizations, and voice classification criteria were different, leading to decreased validity of their findings (To, 2010; Mok, 2011). In fact, some of their participants were recruited from choral singing groups and some from operatic singing groups. Choral and operatic singing could be different, for example, the use of voice timbre and voice use (Sundberg, 1987). With such a heterogeneous group of participants, results of these studies could not be generalized to the entire operatic singing population. The present study attempted to examine the contribution of vocal tract dimension to different operatic singing voices using a consistent set of voice classification criteria. Findings should provide confirmatory data on the use of vocal tract dimensions for voice classification.

Previous researchers have used x-ray (Dmitriev & Kiselev, 1979; Roers et al. 2009; Sundberg, 1982), x-ray computed tomography (Tom, Titze, Hoffman & Story, 2001) and

Acoustic Reflection Technology (ART) (Tsoi, 2009; To, 2010; Mok, 2011) to measure vocal tract dimensions of professional singers. However, using x-ray has the adverse effect of exposing the participants to radiation, which could cause hazardous effects. Also, x-ray images could not give three-dimensional measurements of vocal tract volume. In the present study, a pharyngometer (Eccovision, Hood Laboratories, USA.) was used for measuring the participants' vocal tract dimensions. The device has commonly been used in assessing patients with obstructive sleep apnea (OSA) (e.g., Brigadier, 2004; Gozal & Burnside, 2004). It is an objective, efficient and non-invasive way to obtain vocal tract dimensional measures, by making use of the Acoustic Reflection Technology (ART) to measure the three-dimensional shape and size of vocal tract, including oral, nasal and pharyngeal cavities. The device contains a generator which links to a wave tube. A mouthpiece which links the device to the oral cavity of the participant is attached to the end of the wave tube. The generator emits an acoustic wave which is directed to the vocal tract of the participant via the wave tube and the mouthpiece. The acoustic wave is then partially reflected when it reaches the wall of the vocal tract. Based on the variations of the reflected wave, the cross-sectional areas of the upper airway can be calculated, so as the vocal tract length and volume.

For the measurement of vocal fold vibration characteristics, electroglottography (EGG) was used. It monitors the degree of vocal fold contact by measuring the change in electrical impedance to a weak alternating current across the larynx during phonation. It is non-invasive, easy-to-handle, and not being affected by ambient noise, providing a direct way of monitoring vocal fold vibrations during phonation (Kitzing, 1990). It has been found useful in documenting voice quality, investigation of vocal registers, intonation contour, voice roughness and voice pitch, diagnosis and treatment of dysphonia clinically (Kitzing, 1990; Henrich et al., 2005). Moreover, EGG utilizes real-time visual displays. It is suggested that quantifying the vocal fold vibration characteristics of different professional singing voices types using EGG and displaying them in a meaningful manner could provide an objective basis for singing training (Howard, 1995). The real-time visual display of EGG was found useful to serve as visual feedback to improve the efficiency of the student singers' learning of different singing types (Rossiter, Howard, & Decosta, 1996; Garner & Howard, 1999).

Method

Participants

A total of 61 professional singers were recruited from the Xinhai Conservatory of Music (星海音樂學院) in Guangzhou, China as participants of the research, including 19 tenors, 10 baritones, 29 sopranos, and 4 mezzo-sopranos. All singers were classified into different singing voice types using the same criteria. Their singing quality was consistently confirmed by experienced pedagogues. Their ages ranged from 18 to 30 years, with duration of singing training ranged from 1 to 7 years. All singers had no reported history of any craniofacial abnormalities, and no upper respiratory tract diseases at the time of data collection.

Speech/Singing Materials and Procedures

For vocal tract dimension measurements, the participant sat upright in a straight-backed chair. During the experiment, the participant was asked to gently bite on the mouthpiece of the pharyngometer, while the other end of the device was carefully held by the investigator. The participant was directed to breathe out from his/her mouth while imagine producing the vowel /a/ simultaneously. A curve of cross-sectional area versus distance along the path of vocal tract was thereby obtained. A total of four measurements were taken, three via mouth-breathing and one via nose-breathing. The same method of data collection has been adopted and described by Tsoi (2009), To (2010), and Mok (2011).

For EGG measurement, two surface electrodes of a laryngograph were attached to each side of the thyroid cartilage and were placed about 1 cm apart at the front of the neck. The participants were asked to sing the first verse of the song ‘happy birthday’ using the same loudness level of mezzo-forte at the pitch that they found most comfortable. The participants were asked to maintain a consistent loudness and voice quality throughout their production. The subjects were required to repeat the above singing task using different vocal registers (male: chest register, head register and falsetto register; female: chest and head). The EGG signal was recorded by a two-channel laryngograph (Electroglottograph EG2-PCX2, Glottal Enterprises, NY). Both audio and EGG signals were recorded on a DAT recorder through separate channels by a microphone and an electroglottograph unit at the same time. The whole procedure lasted for about 20 minutes.

Data Analysis

To quantify vocal fold vibratory characteristics, the open quotient (Oq), which refers to the percentage of time within each cycle during which the vocal folds are open, and fundamental frequency (F0) values were obtained. The DECOM (dEGG Correlation-based Open quotient Measurement) method as described by Henrich et al. (2004) was used to derive the Oq and F0 from the differentiated electroglottographic (dEGG) signals. The sung vowel /æ/ was extracted from the first syllable of the word ‘happy’ of the song ‘happy birthday’ and used for later analysis. As previous research studies suggested that the Oq could be affected by vocal intensity and F0 (Henrich et al., 2005), the absolute Oq differences between different voice types might not directly indicate the difference between singing voice types. Thus the sentence that was sung with the same vocal intensity (mezzo-forte) was used for analysis in order to eliminate the possible effect of vocal intensity on open quotient value. The gradient [Oq/ log(F0)] was also used for analysis to eliminate the effect of F0 on Oq.

For vocal tract dimensions, comparison was made between the cross-sectional area versus distance graphs obtained from mouth- and nose-breathing to locate the oral pharyngeal junction (OPJ) as described by Kamal (2003), Xue, Hao, & Mayo (2006) and Mok (2011). Using the location of OPJ, the selected cross-sectional area-distance curve was then divided into the oral and pharyngeal regions. The oral cavity was defined as the area from the incisors to the OPJ, while the pharyngeal cavity was defined as the area from OPJ to the opening of the vocal folds (Hood Laboratories, USA.). Based on this definition, six vocal tract dimension parameters including the oral length (OL), pharyngeal length (PL), total length (TL), oral volume (OV), pharyngeal volume (PV), total volume (TV) were identified.

Results

Vocal Fold Vibratory Characteristics

Male singers. Descriptive data of vocal fold vibratory characteristics in chest, head and falsetto registers obtained from tenors and baritones are illustrated in Table 1.

To assess the effect of voice type and register, two-factor mixed-design analysis of variances (ANOVAs) (voice type x register) were performed on Oq/F0 gradient.

As there was a significant interaction effect between voice type and register with respect to Oq/F0 gradient [$F(2, 54) = 17.142$, $p < .001$] (see Figure 1), each independent variable (voice type and register) was tested individually.

Table 1

Mean and standard deviation values of Oq/F0 gradient of male singers with different singing voice types.

	Oq/F0 gradient (SD)		
Voice types	Chest register	Head register	Falsetto register
Tenors (N = 19)	0.22 (0.03)	0.20 (0.03)	0.28 (0.04)
Baritones (N = 10)	0.25 (0.03)	0.25 (0.02)	0.26 (0.02)

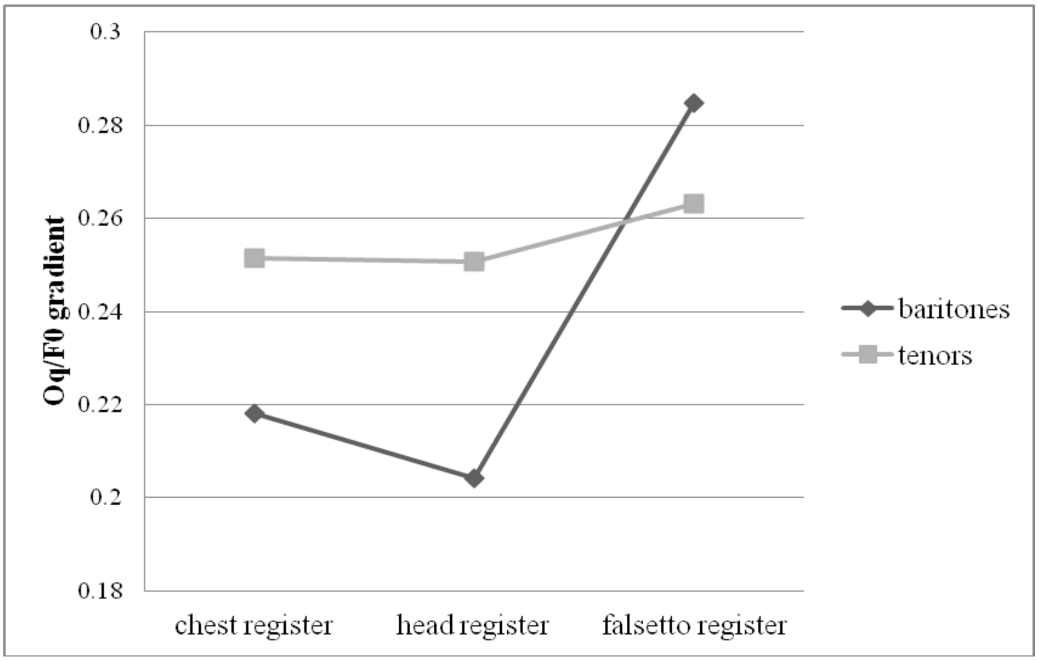

Figure 1. Oq/F0 gradient of different male voice types in different registers.

Effects of singing voice types. Independent-samples t-tests were carried out to determine the effect of voice types on Oq/F0 gradient in different registers (chest, head, and falsetto). Results indicated that baritones had significantly greater Oq/F0 gradient than tenors in chest register [$t(27) = -3.061$, $p < .01$] and in head register [$t(26.66) = -4.956$, $p < .001$]. No significant difference on Oq/F0 gradient was observed in falsetto register between baritones and tenors [$t(27) = 1.680$, $p = .104$].

Effects of registers. A one-way ANOVA was carried out to study the effect of register on Oq/F0 gradient in different voice types (baritones and tenors). Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(2) = 8.56$, $p < .05$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .603$). The results showed that there was a significant main effect for register [$F(1.21, 10.86) = 58.498$, $p < .001$] on Oq/F0 gradient in baritones. For tenors, Mauchly's test also indicated that the assumption of sphericity had been violated, [$\chi^2(2) = 7.075$, $p < .05$], therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .746$). No significant effect of register was found in tenors [$F(1.49, 26.86) = 1.596$, $p = .222$]. Pairwise comparisons with Bonferroni adjustment showed that the Oq/F0 gradient in baritones was significantly higher in falsetto register than in chest register ($p < .001$) as well as in head register ($p < .001$), while that Oq/F0 gradient in chest and head register were not significantly different from each other ($p = .309$).

Effects of singing voice types on differences between registers. Independent samples t-tests were carried out to compare the Oq/F0 gradient differences between registers (chest/head, head/falsetto, chest/falsetto) of the two voice classes (baritones and tenors). Results showed that baritones had significantly larger Oq/F0 gradient differences between chest and falsetto registers [$t(30) = 3.664$, $p < .01$] as well as between head and falsetto registers [$t(30) = 5.810$, $p < .0001$] than those of tenors. There was no significant difference in chest-head Oq/F0 gradient differences between baritones and tenors [$t(30)= -.208$, $p = .837$].

Female singers. The descriptive data of vocal fold vibratory characteristics in chest and head registers obtained from mezzo-sopranos and sopranos are illustrated in Table 2. For the effect of voice type, mezzo-sopranos had a lower mean value of Oq/F0 gradient than sopranos in both chest and head registers generally. On the other hand, for the effect of registers, Oq/F0 gradient associated with chest register was slightly higher than that with head register for both mezzo-sopranos and sopranos (see Figure 2).

Dependent-samples t-test was carried out to compare the Oq/F0 gradient produced in chest and head registers for sopranos. There was no significant difference between the Oq/F0 gradient in chest and head register [$t(28) = 1.239$, $p = .226$] for sopranos.

Table 2

Mean and standard deviation values of Oq/F0 gradient of female singers with different singing voice types.

	Oq/F0 gradient (SD)	
Voice types	Chest register	Head register
Mezzo-sopranos (N = 4)	0.23 (0.04)	0.21 (0.04)
Sopranos (N = 29)	0.27 (0.04)	0.26 (0.03)

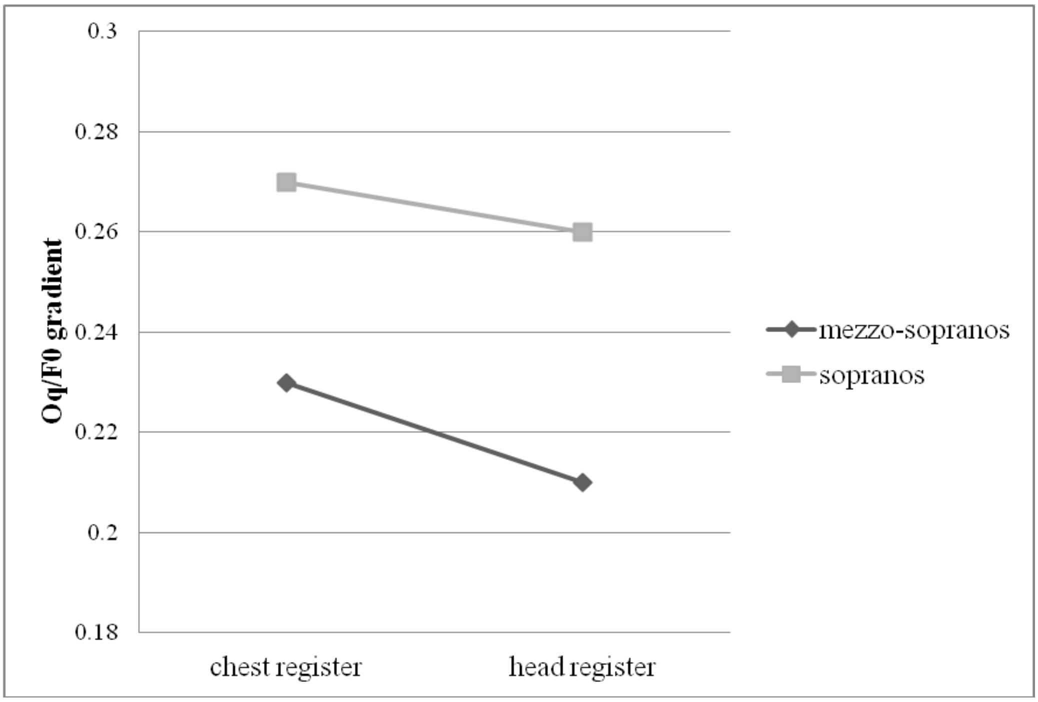

Figure 2. Oq/F0 gradient of different female voice types in different registers.

Vocal Tract Dimensional Characteristics

The mean and standard deviation values of the six vocal tract dimensions in male and female singers were summarized in Table 3.

Male singers. Independent-samples t-tests were carried out to compare the six vocal tract dimensions of different voice types. There were no significant differences between baritones and tenors in all the six vocal tract dimensions: oral length [$t(27) = -.545$, $p = .590$], pharyngeal length [$t(27) = .212$, $p = .834$], vocal tract length [$t(27) = -.290$, $p = .774$], oral volume [$t(27) = -.099$, $p = .922$], pharyngeal volume [$t(27) = .422$, $p = .676$], and vocal tract volume [$t(27) = .064$, $p = .949$].

Table 3

Mean (and standard deviation) values of oral length (OV), pharyngeal length (PV), total vocal tract length (TL), oral volume (OV), pharyngeal volume (PV), and total vocal tract volume (TV) of male and female singers of different singing voice types

	Vocal tract dimensions					
Voice types	OL (cm)	PL (cm)	TL (cm)	OV (mL)	PV (mL)	TV (mL)
Baritones (N = 10)	9.66 (0.68)	8.79 (0.81)	18.45 (0.99)	60.81 (11.77)	26.50 (3.82)	87.30 (13.08)
Tenors (N = 19)	9.82 (0.84)	8.73 (0.83)	18.55 (0.81)	61.20 (10.57)	25.78 (5.04)	86.99 (13.80)
Mezzo-sopranos (N = 4)	9.63 (0.73)	7.61 (0.73)	17.24 (1.13)	54.28 (11.37)	22.03 (5.35)	76.31 (12.13)
Sopranos (N = 29)	9.27 (1.06)	7.46 (1.17)	16.72 (0.76)	48.00 (8.82)	18.73 (5.18)	66.73 (11.62)

Note: OL = Oral length; PL = Pharyngeal length; TL = Total vocal tract length; OV = Oral volume; PV = Pharyngeal volume; TV = Total vocal tract volume.

Female singers. Statistical analyses were not carried out due to insufficient number of subjects. As shown in Table 3, the mean values showed that mezzo-sopranos had generally longer oral length (OL), pharyngeal length (PL), and total vocal tract length (TL); larger oral volume (OL), pharyngeal volume (PL), and total vocal tract volume (TV) than sopranos.

Discussion

Vocal Fold Vibratory Characteristics

The present results suggested quite different Oq values for different singing voice types when register was taken into account, with F0 and vocal intensity being controlled. The effect of F0 was eliminated by using the Oq/log(F0) gradient and the effect of vocal intensity was eliminated by using a similar loudness level (mezzo-forte) for comparison. It was found that tenors had significantly higher Oq/F0 gradient than baritones when using chest and head registers, corresponding to a higher Oq in tenors than baritones in chest and head registers when the effect of F0 and intensity was eliminated. No significant difference was found between the two voice types in falsetto register. By definition, Oq equals to (1 - contact quotient) within a vibratory cycle. The greater is the Oq, the lower is the contact quotient. It follows that, when F0 and vocal intensity were kept constant, tenors had shorter vocal fold contact time than baritones in chest and head registers, but had similar contact time in falsetto register.

The difference in vocal characteristics as indicated by the Oq/F0 gradient between baritones and tenors in chest and head registers might be due to the possible anatomical differences in their vocal structures. Singers of different singing voice types are associated with different vocal configurations. For example, Roers et al. (2007) found that different singing voice types consistently exhibited different mean vocal fold lengths; basses tended to have longer anteroposterior vocal fold dimension than baritones, and baritones longer than tenors. The shorter vocal fold length in tenors might contribute to a shorter anterior-posterior time lag, a shorter vocal fold contact time, and thus a higher Oq/F0 gradient in tenors compared with baritones in chest and head registers.

On the other hand, no significant difference was found between baritones and tenors in the Oq/F0 gradient in falsetto register. One explanation for such differences between chest and head and falsetto register may be related to the different vibratory modes between the chest and head registers. Both registers in male singers are produced using the scientifically-defined M1, while falsetto register was produced using M2 (Roubeau et al., 2009). According to Titze (1994), the entire cover including the ligament layer is relatively more lax for vibration in M1. On the contrary, in M2, only the border of the mucosa layer can be relatively relaxed for vibration, while the ligament layer remains firm and was not involved in vibration (Titze, 1994; Miller, 1996). As a result, the vocal folds involved in M1 are generally more massive and thicker. Also, the thyroarytenoid muscles tend to be more active in M1 and could increase the vocal fold mediation, resulting in a greater contact surface area during vibration (Titze, 1994). On the other hand, the edge of the vocal folds involved in M2/falsetto register is extremely thin and only make brief contact. Besides, the posterior portion of vocal folds was damped in M2/falsetto register, which reduces the length of vibrating surface (Seikel et al., 2005). As only a short, thin and superficial contact is involved in falsetto register, the effect of the vocal fold length and mass differences between the two voice types could be largely reduced. This might lead to the observed similar vocal fold contact durations in falsetto register for both baritones and tenors.

For the effect of register, the results showed that the Oq/F0 gradient was significantly higher in falsetto register (M2) than chest and head register (M1) when the effect of voice type was not considered. This trend was also found in earlier studies which showed a higher open quotient in M2 than M1, suggesting thinner vocal folds in M2 than in M1 that lead to a smaller phase lag between the upper and lower layer of vocal fold (Sundberg & Högset, 2001; Henrich et al., 2005). However, the difference in Oq/F0 gradient between M1 and M2 was only significant for baritones but not tenors. Though, for tenors, falsetto register yielded a higher Oq/F0 value than chest and head registers (see Figure 1) as observed in previous researches (Sundberg & Högset, 1999; Henrich et al., 2005), the difference does not reach statistical significance. Also, in the studies of Sundberg and Högset (2001) and Henrich et al. (2005), no statistical analysis was carried out to testify the difference between mechanisms as well as their interaction with voice types due to limited number of participants. Thus the present results seemed to suggest a new finding that the effect of mechanism (or register) on Oq was also dependent on the singer's voice types. Higher singing voice type (tenors) seems to have smaller/non-significant difference between mechanisms than lower singing voice type (baritones). Results of comparison of inter-register Oq/F0 differences between baritones and tenors also supported this finding. The results showed that the Oq/F0 gradient differences between head and falsetto register, and between chest and falsetto register were significantly larger in baritones than in tenors. Similar trend was also showed by Sundberg and Högset (2001) that baritones had larger Oq differences between mechanisms as compared with tenor and counter tenor, though without statistical analysis to support. One contributing factor for the non-significant difference between M1 and M2 in tenors was that tenors used relatively high values of Oq in M1 and lower values in M2. This might be contributed by the shorter vocal fold length in tenors discussed previously. Also, as tenors often need to sing at high pitches than do baritones, they might have more frequent use of combinations of chest, head and falsetto registers. As noticeable register transitions are generally unacceptable in classical operatic singing (Titze, 1994), tenors might try to bridge the differences in voice quality by using higher value of open quotients in chest and head registers and lower value in falsetto register so as to smoothen the difference in open quotient at the transition.

For female singers, it is shown that the Oq/F0 gradient was generally higher in sopranos than mezzo-sopranos in both registers (see Figure 2). This corresponds to a higher Oq in sopranos when the effect of fundamental frequency and vocal intensity were eliminated. This result coincides with that of male singers in the present study who also showed a higher Oq in higher singing voice type (tenor). One possible explanation could be related to the anatomical difference in the vocal fold structures between the two voice types. Similar to the trend in male singers, higher singing voice type (sopranos) showed shorter vocal fold length than lower singing voice type (mezzo-soprano) (Roers et al., 2007). This might contribute to shorter contact duration and thus higher Oq in sopranos.

Nevertheless, for female singers, there was no significant difference in Oq/F0 gradient between chest and head registers for sopranos, suggesting that that the Oq values were similar in both chest and head registers when F0 and vocal intensity were kept constant. Similar trend was also observed in the mean Oq/F0 gradient values of mezzo-sopranos. According to Roubeau et al. (2009), female chest register is related to the scientifically defined M1, while female head register is related to M2. Yet, no studies have examined the difference in Oq between the two mechanisms among female singers. Only male singers involved in M1 and M2 were examined in previously reported studies (Sundberg & Högset, 2001; Henrich et al., 2005). This seems to suggest that the chest and head registers produced by female singers might have similar vibratory characteristics, and thus similar Oq values. Further investigation of the laryngeal mechanism of female singers is needed to verify this finding, as only four mezzo-sopranos were included in the present study.

Vocal Tract Dimensions

For male singers, the present results show that voice types (baritones, tenors) did not have significant effect on oral length, pharyngeal length, total vocal tract length, oral volume, pharyngeal volume, and total vocal tract volume. This is consistent with Mok (2011) in which vocal tract dimensions did not significantly affect the voice types in male singers. However, on the contrary, Dmitriev and Kislev (1979) reported a close correlation between vocal tract length and singing voice type; higher voice types (e.g. tenor) had shorter vocal tract length than lower voice types (e.g. baritones and basses). In addition, Tsoi (2009) reported greater total vocal tract volume in baritones. To (2010) found larger oral and total vocal tract volumes in baritones compared with tenors.

A different trend is observed in female singers. The present results showed that all the six vocal tract dimensions were larger in lower singing voice type (mezzo-sopranos) than in higher singing voice type (sopranos). The difference was more obvious in oral volume, pharyngeal volume, and total vocal tract volume (see Table 3). This finding matches with that of Dmitriev and Kislev (1979), in which a decreasing vocal tract length from mezzo-sopranos to sopranos was found, as well as Mok (2011), which found significantly shorter oral and vocal tract lengths, and smaller oral and vocal tract volumes in sopranos than mezzo-sopranos. However, this significant difference was not observed in the studies of Tsoi (2009) and To (2010).

Overall, the present results seem to contradict with some previous studies; correlation between the vocal tract dimensions and different singing voice types appeared to be inconsistent. Certain limitations in previous studies might have led to such inconsistent findings, including small sample size (Dmitriev and Kislev, 1979; Tsoi, 2009), inclusion of choral singers, and inconsistent source of participants (To, 2010; Mok, 2011), which might have decreased validity of results. The present study with a larger sample size and consistent source of participants suggested that vocal tract dimensions measured at rest might not be reliable parameters for voice classification for male singers. Combined with the findings in vocal fold vibratory characteristics, where greater difference was found between baritones and tenors in Oq, it is suggested that vocal fold vibratory characteristics might contribute more to the voice quality difference between baritones and tenors than vocal tract dimensions do. For female singers, differences were found between mezzo-sopranos and sopranos in both the vocal fold vibratory characteristics (Oq/F0 gradient) and vocal tract dimensions. This suggested that both factors might contribute to the voice quality difference in different female singing voice types.

Clinical implications

The study suggested that Oq/F0 gradient value which measures the vocal fold vibratory characteristics could be one possible objective parameter for voice classification of both male and female singers. Vocal tract dimensions could also be possible parameters for voice classification, at least for female singers. In addition, the knowledge of correlation of Oq/F0 with singing voice types and laryngeal mechanisms could be applied in real-time visual display to complement traditional singing training for different voice types and laryngeal mechanisms. Accordingly, singing students could have a more objective standard and receive more substantial feedback to improve their learning.

Limitations and further investigation

Some limitations are identified in the present study. The number of mezzo-sopranos recruited was limited because the actual ratio of mezzo-sopranos to sopranos was small in the field. The limited number of mezzo-sopranos does not allow the generalization of results to all female singers. In addition, age and singing experience of participants in this study were relatively young. Their singing techniques could still be developing and might not be most representative of their corresponding singing voice types. Furthermore, although all productions used for comparisons were sung at a controlled loudness level (mezzo-forte), there may still be slight variations in intensity among the productions, which might also affect the open quotient values and the Oq/F0 gradient. Further investigation of objective measures for voice classification should take into account the laryngeal mechanism/registers, F0 and vocal intensity being used. A similar procedure to the present study could be used with a larger sample size of mezzo-sopranos and a more even distribution of the participants’ age and years of training received. Vocal fold length could also be another possible parameter to be considered for voice classification, as the present findings seem to support a covariation between singing voice types and vocal fold length. It is also suggested that further study could investigate the effectiveness of applying real-time visual display for learning different vocal registers in different singing voice types.

Conclusion

With regard to vocal fold vibratory characteristics, the present data showed a significant interaction between singing voice type and vocal register, as indicated by the Oq/F0 gradient measures in male singers. A general difference was also found in the Oq/F0 gradient in different voice types of female singers. For vocal tract dimensions measured using pharyngometer at rest, no significant difference was found in all six vocal tract dimensions between the two voice types in male singers. But for female singers, a generally higher value was observed in all the six vocal tract dimensions, especially in vocal tract volumes, in mezzo-sopranos than that in sopranos. The findings suggest that vocal fold vibratory characteristics, as indicated by Oq/F0 gradient, could be one possible parameter for voice classification of professional male and female singers, while vocal tract dimensional characteristics might be used in assisting voice classification for female singers.

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References

Barlow, C., & LoVetri, J. (2010). Closed Quotient and spectral measures of female adolescent singers in different singing styles. *Journal of Voice, 24,* 314-318.

Brigadier, I. K. (2004). Acoustic pharyngometry patterns of snoring and obstructive sleep apnea patients. *Otolaryngology - Head and Neck Surgery, 130*(1), 58-66.

Callaghan, J. (2000). *Singing and Voice Science.* San Diego, CA.: Singular Publishing.

Dmitriev, L. & Kiselev, A. (1979). Relationship between the formant structure of different styles of singing voices and the dimensions of supraglottic cavities. *International Journal of Phoniatrics, 31*(4), 238-241.

Erickson, M. L. (2003). Dissimilarity and the classification of female singing voices: A preliminary study. *Journal of Voice, 17*(2), 192-206.

Erickson, M. L., Perry, S. & Handel S. (2001). Discrimination functions: can they be used to classify singing voices? *Journal of Voice, 15,* 492-502.

Garner, P. E. & Howard, D. M. (1999). Real-time display of voice source characteristics. *Logopedics Phoniatrics Vocology, 24,* 19-25.

Gozal, D., & Burnside, M. M. (2004). Increased upper airway collapsibility in children with obstructive sleep apnea during wakefulness. *American Journal of Respiratory and Critical Care Medicine, 169,* 163-167.

Henrich, N., d'Allessandro, C., Doval, B. & Castellengo, M. (2004). On the use of the derivative of electroglottographic signals for characterization of nonpathological phonation. *Journal of the Acoustical Society of America*, *115*(3), 1321-1332.

Henrich, N., d'Alessandro, C., Doval, B., & Castellengo, M. (2005). Glottal open quotient in singing: Measurements and correlation with laryngeal mechanisms, vocal intensity, and fundamental frequency. *Journal of the Acoustical Society of America, 117*(3), 1417-1430.

Howard, D. M. (1995). Variation of electrolaryngographically derived closed quotient for trained and untrained adult female singers. *Journal of Voice, 9*(2), 163-172.

Kitzing, P. (1990). Clinical applications of electroglottography. *Journal of Voice, 4*(3), 238-249.

Larsson, H. & Hertegård, S. (2008). Vocal fold dimensions in professional opera singers as measured by means of laser triangulation. *Journal of Voice, 22*(6), *734*-739.

McKinney, J. C. (1994). *The diagnosis and correction of vocal faults: a manual for teachers of singing and for choir directors*. Nashville, TN: Genevox Music Group.

Miller, R. (1996). *The structure of singing: system and art in vocal technique*. New York, NY: Schirmer Books.

Roers, F., Murbe, D. & Sundberg, J. (2009). Predicted singers' vocal fold lengths and voce classification - A study of x-ray morphological measures. *Journal of Voice, 23,* 408-413.

Rossiter, D., Howard, D. M., DeCosta, M. (1996). Voice development under training with and without the influence of real-time visually presented biofeedback. *Journal of the Acoustical Society of America*, *99*(5), 3253-3256.

Roubeau, B., Henrich, N., & Castellengo, M. (2009). Laryngeal vibratory mechanism: the notion of vocal register revisited. *Journal of Voice*, *23,* 424-438.

Salomao, G.L. & Sundberg, J. (2009). What do male singers mean by modal and falsetto register? An investigation of the glottal voice source. *Logopedics Phoniatrics Vocology, 34*, 73-83.

Sataloff, R.T. (2005). *Professional voice: the science and art of clinical care.* San Diego, CA: Plural Publishing.

Seikel, J. A., King, D. W. & Drumright, D. G. (2005). *Anatomy and Physiology for Speech, Language, and Hearing.* Australia: Thomson Delmar Learning.

Sell, K. (2005). *The Disciplines of Vocal Pedagogy: Towards a Holistic Approach.* Aldershot, England: Ashgate Publishing Company.

Smith, B., & Sataloff, R. T. (1999). *Choral Pedagogy.* San Diego, CA: Singular.

Sundberg, J. (1982). X-ray study of articulation and formant frequency in two female singers. *STL-QPSR. 23*(4), 117-134.

Sunberg, J. (1987). *The science of the singing voice.* DeKalb, Ill: Northern Illinois University Press.

Sundberg, J. (1995). The singer's formant revisited. *STL-QPSR. 36*(2-3), 83-96.

Sundberg, J., & Högset, C. (2001). Voice source differences between falsetto and modal registers in counter tenors, tenors and baritones. *Logopedics Phoniatrics Vocology, 26*, 26-36.

Titze, I. R. (1994). *Principles of voice production.* Englewood Cliffs, NJ: Prentice-Hall.

To, T. H. (2010). *Vocal tract dimensional characteristics of professional singers with different styles of singing voices.* Unpublished BSc Honours dissertation, Faculty of Education, University of Hong Kong.

Tom, K., Titze, I. R., Hoffman, E. A., & Story, B. H. (2001). Three-dimensional vocal tract imaging and formant structure: varying vocal register, pitch, and loudness. *Journal of the Acoustical Society of America, 109*(2), 742-747.

Tsoi, K. S. (2009). *Vocal tract dimensional characteristics of professional male and female singers with different styles of singing voices.* (BSc Honours dissertation). Retrieved October 10, 2011, from HKU Scholars Hub.

Mok, K. M. (2011). *Vocal tract dimensional characteristics of professional singers with different singing styles.* Unpublished BSc Honours dissertation, Faculty of Education, University of Hong Kong.

Xue, S. A., Hao, G. J. P. & Mayo, R. (2006). Volumetric measurements of vocal tracts for male speakers from different races. *Journal of Clinical Linguistics and Phonetics, 20*(9), 691-702.

Kamal, I. (2003). Acoustic pharyngometry patterns of snoring and obstructive sleep apnea patients. *Otolaryngology - Head & Neck Surgery, 130*(1), 58-66.

Appendix

Informed Consent Form

TITLE OF THE STUDY

Vocal tract dimensional characteristics and vocal fold vibration characteristics of professional singers with different singing voice types

PURPOSE OF THE STUDY

Traditionally, singing teachers mainly classify singers into different voice types according to their experience, which is lack of scientific basis and can be unreliable. The proposed study aimed to investigate the relationship between different singing voice types in each gender and (1) the vocal tract dimensions in terms of length and volume; (2) the vocal fold vibration characteristics; and (4) the formant frequencies. The study attempts to find out how the above measurements could be used as an objective measure for voice classification.

PROCEDURES

a) Vocal tract dimension measurements - Eccovision Pharyngometer (Hood Laboratories, USA.), which makes use of the Acoustic Reflection Technology (ART), will be used. The participant will sit upright on a straight-backed chair. The mouthpiece will be held to the mouth of the participant on one side. The participant will be instructed to imagine producing the vowel /a/ and breathe out from his/her mouth. Four measurements will be taken totally, from which three by mouth-breathing and one by nose-breathing.

b) Vocal fold vibration characteristics measurements - Electroglottography (EGG) will be used. The participants will be asked to perform a series of singing tasks including: (1) sing a sentence using different loudness (piano, mezzo-forte and forte); (2) sustained vowels: three selected vowels /a/, /e/, /i/, /o/, /u/ were performed at different pitches depending on the singer’s pitch range. The subject will be asked to maintain vowel color, pitch, and loudness during production. After the completion of the above tasks, the participant will be asked to use different vocal registers (male: chest register, head register and falsetto register; female: chest and head) to repeat the tasks. All the produced sounds will be recorded by a microphone at the same time.

The procedure will be take place in the classrooms of Xinhai Conservatory of Music in Guangzhou, China. The whole procedure will take about 25 minutes.

POTENTIAL RISKS/DISCOMFORTS

This procedure has no known risks. If you experience any fatigue or discomforts during the procedure, the experiment can be stopped at any time.

POTENTIAL BENEFITS

There are no direct benefits to you. However, the research project can provide valuable information on an objective way for voice classification in the future.

CONFIDENTIALITY

Codes, not names, are used on all test instruments to protect confidentiality. Any information obtained in this study will be securely transported to the Division of Speech and Hearing Sciences, Faculty of Education at the University of Hong Kong and kept in a secure filing cabinet in a locked room. No one but the investigators will have access to it. The data obtained will be used for research purposes only.

PARTICIPATION AND WITHDRAWAL

Your participation is voluntary. This means that you can choose to stop at any time without negative consequences. You can review the audio -recording of the procedure. We will erase the entire audiotape or parts of it if you want us to do so.

STORAGE OF DATA

We will keep raw data three years after the results are published The data will be destroyed at the end of this project.

QUESTIONS AND CONCERNS

If you have any questions or concerns about this research study, please feel free to contact the supervisor of this research study, Dr. Ng, Manwa Lawrence: Email: [manwa@hku.hk]; or Ms. Edith Chan: Telephone: [+852-6103-8646]; Email: [kau624@hku.hk]. If you have questions about your rights as a research participant, contact the Human Research Ethics Committee for Non-Clinical Faculties, HKU (2241-5267).

If you understand the procedures described above and agree to participate in this study, please sign below.

I _________________________________ (Name of Participant) understand the procedures described above and agree to participate in this study.

______________________________________ __________________

Signature of Participant Date

Date of Preparation: 12th November, 2011

Expiration date: 30th May, 2011