Vertical Phase Difference and Glottal Efficiency in Musical Theater and Opera Singers

*,†Elliana Kirsh, ‡,§Stephanie R.C. Zacharias, †,‡Alessandro de Alarcon, †,‡Dimitar Deliyski, ¶Meredith Tabangin, and †Sid Khosla, *†‡§¶*Cincinnati, Ohio*

Summary: Objective. The objectives of this study were to (1) determine the relationship between vertical phase difference (VPD) and glottal efficiency (GE) in singers and (2) to compare VPD and GE between musical theater and opera singing styles.

Methods. Five opera and three musical theater singers (Mean age = 25.3, 100% male) performed a series of vocal tasks at two pitches (low pitch C#3, 133 ± 5 Hz; high pitch C#4, 277 ± 5 Hz) for three levels of loudness (soft, baseline, and loud), while undergoing flexible distal chip videostroboscopy. Aerodynamic and acoustic information for each vocal task was recorded using the *Phonatory Aerodynamic System*. VPD was qualitatively measured *via* visual-perceptual judgments of repeated comparison tests, where a blinded rater was asked to select the video in which the subject demonstrated the greatest VPD. Aerodynamic data were analyzed for differences in GE.

Results. Qualitative visual-perceptual analysis indicated that increased magnitude of VPD was correlated with tasks involving increased loudness or higher pitch. GE was similarly correlated with increased loudness or higher pitch. GE was minimally correlated with subglottal pressure at high pitch.

Conclusion. This prospective study reveals novel human subject evidence that VPD may correlate with GE. Future studies will further explore the implications of VPD with respect to GE, subglottal pressure, and laryngeal mechanics.

Key Words: Voice–Glottal efficiency–Laryngeal mechanics–Singers–Vertical Phase Difference.

INTRODUCTION

During vocal-fold vibration, the glottis can take on a convergent-divergent shape as a result of the vertical mucosal wave traveling in an inferior-superior direction, as noted by empirical investigations in the field of laryngeal biomechanics over the past few decades.[1–3] Specifically, during the closing phase of vocal-fold vibration, the glottis can take on a divergent shape where the superior aspect is larger than the inferior aspect. Based from the mechanism of the divergent ducts described in fluid mechanics,[4] this divergent shape results in flow separation from the medial aspect of the folds before exiting the glottis.[5–7] According to contemporary computational and animal models, the intraglottal flow separation leads to intraglottal vortices, which produce negative pressures downstream of the separation point, both above and inside the glottis.[8–10] Such flow separation vortices and negative pressures are quantifiable in excised canine larynges.[11]

Ongoing projects in our laboratory have focused on further elucidating the mechanisms involved in creating and increasing the strength of intraglottal vortices. The magnitude of negative pressure produced by the vortices has been observed to increase as the divergence angle of the glottis increases.[12] This has led to the definition of a so-called maximum divergence angle (MDA), or the maximum angle formed between one fold and the vertical plane of the glottis upon closing (Figure 1A). Although quantitative measurement of MDA is achievable *in vitro* in excised human and canine laryngeal model, qualitative assessment may be accomplished *in vivo* in humans by evaluating the magnitude of vertical phase difference (VPD), as shown in Figure 1B.[13,14] As such, VPD may be used as a qualitative measure of MDA.

Experiments on excised canine larynges suggest that increasing the MDA may cause an increase in the strength of intraglottal vortices.[12] Our recent papers have demonstrated that increased strength of these vortices is correlated with quantifiable measures attributed to optimal voicing, including skewing of the volumetric flow rate waveform, maximum flow declination rate, acoustic intensity, and glottal efficiency (GE).[15,16] GE is a quantitative measure of the ability of the larynx to convert the aerodynamic power generated by the pulmonary system into acoustic power transmitted through the vocal tract and measured at the lips.[17,18]

Although skewing of the velocity and flow rate waveforms has been theorized to be associated with vocal tract inertance, recent experiments on excised canine larynges lacking vocal tracts have indicated that vortices are independently associated with such results, as well as area skewing and GE.[19] It is also known that, up to a point, greater MDA produces vortices of greater strength. Thus, experiments using canine models may suggest that in humans, increased magnitude of the VPD may correlate with increased GE.

As such, the first objective of this study was to ascertain the relationship between vertical VPD and GE in singers. It was hypothesized that VPD would be correlated with GE in singers. The second objective was to compare VPD and GE between musical theater and opera singing styles. Musical theater singing

Accepted for publication November 30, 2015.

Presented at the 44th Symposium of The Voice Foundation: Care of the Professional Voice. Platform. Philadelphia, PA, May 27–31, 2015.

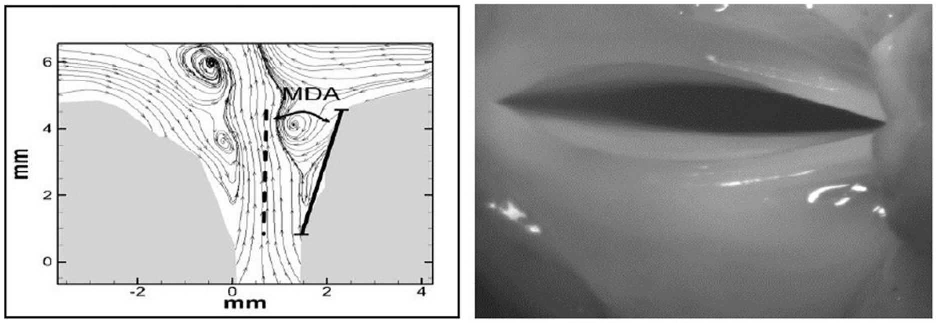
From the *Department of Voice, College-Conservatory of Music, University of Cincinnati, Cincinnati, Ohio; †Department of Otolaryngology, Head and Neck Surgery, University of Cincinnati, Cincinnati, Ohio; ‡Center for Pediatric Voice Disorders, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio; §Division of Speech and Language Pathology, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio; and the ¶Division of Biostatistics and Epidemiology, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio.

Address correspondence and reprint requests to Stephanie R.C. Zacharias, Center for Pediatric Voice Disorders, Cincinnati Children's Hospital Medical Center, 3333 Burnet Avenue MLC 4001, Cincinnati, OH 45229. E-mail: stephanie.zacharias@cchmc.org

Journal of Voice, Vol. 31, No. 1, pp. 130.e19–130.e25

0892-1997

http://dx.doi.org/10.1016/j.jvoice.2015.11.025



(A) (B)

FIGURE 1. (**A**) Velocity field image demonstrating how maximum divergence angle (MDA) can be measured in the laboratory *via* canine model. A best-fit line is drawn from the superior to the inferior aspects of the vocal fold, and then MDA is obtained by measuring the resulting angle with respect to the vertical plane. (**B**) Vertical phase difference (VPD) in a canine model obtained *via* high-speed imaging during the closing phase of vocal-fold vibration. The VPD refers to the lagging superior edge relative to the inferior edge. This figure demonstrates how VPD can be qualitatively assessed.

has been described as a mode of singing typified by unusually high-energy, frequency-rich phonation that may include a high level of nasality, while opera singing is frequently cited as the mode of singing associated with Western classical vocal technique.[20] Thus, it was hypothesized that there would be a stronger correlation between VPD and GE in opera singers compared with those in musical theater singers. Elucidating the relationship between VPD and GE may serve as a starting point for qualitatively assessing GE in the clinic, perhaps *via* visualization of VPD.

METHOD

Subjects

The subjects consisted of five opera and five musical theater male singers with the age of 19–32 years (M = 25.2, SD = 3.87) (Table 1). The subjects were recruited from a pool of current or past students of the musical theater and opera degree programs at the College-Conservatory of Music of a Midwestern University. Before evaluation, each singer completed the Voice Handicap Index and Singing Voice Handicap Index to screen for self-reported perceptions of vocal pathology. Female singers were excluded from the study to control for gender-related difference. Two participants (MT1 and MT10) were excluded from the study because of incomplete data. The final study group consisted of five opera and three musical theater male singers. The Cincinnati Children's Hospital Medical Center Institutional Review Board approved this study.

TABLE 1.
Descriptive Assessment of Singers*

Singer Characteristics	N = 10
Musical Theater	
N. %	5 (50)
Age	23(4.1)[19–30]
Voice classification	
Baritone N. %	1 (20)
Tenor N. %	4 (80)
Years of training	11–15 [3–15]
Opera	
N. %	5(50)
Age	27.5(2.6)[25–32]
Voice classification	
Baritone N. %	2(40)
Tenor N. %	3(60)
Years of training	11–15 [6–15]

* Data reported as means with standard deviations in parentheses and ranges in brackets unless otherwise noted.

ACOUSTIC AND AERODYNAMIC INSTRUMENTATION

Acoustic and aerodynamic recordings were executed in a soundproof booth at the Center for Pediatric Voice Disorders in the Cincinnati Children's Hospital Medical Center. Acoustic data collection and analysis were recorded using the Kay Elemetrics Computerized Speech Lab (CSL) (Kay Elemetrics Corp., New Jersey) with the CSL Real-time Pitch. Vocal tasks (described below) were recorded using a microphone set 5 in away from the mouth and placed in an off-axis position. Aerodynamic data were collected using the *KayPENTAX Phonatory Aerodynamic System* (Model 6600; *PAS*), designed to measure airflow and pressure related to speech and voice production.

Videolaryngostroboscopy evaluation

Flexible distal chip transnasal endoscopy was chosen as the method for evaluations to achieve accurate examination of the vocal folds during vocal tasks (described below). Before inserting the flexible endoscope, a topical anesthesia mix of Afrin/Pontocaine and viscous Lidocaine (Cincinnati Children's Hospital, Cincinnati OH) was applied to one nostril of each subject. A 3.2-mm distal chip endoscope (KayPENTAX, Montvale, NJ, or Olympus Corp, Center Valley, PA) was inserted through the nostril and guided until optimal visualization of the vocal folds was achieved. Subjects were then instructed to perform the specified vocal tasks.