

# Dynamically Monitoring Vocal Fatigue and Recovery Using Aerodynamic, Acoustic, and Subjective Self-Rating Measurements

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**Summary: Objectives.** This study aimed to quantify the effects of vocal loading and vocal rest using aerodynamic, acoustic, and self-rating measurements.

**Methods.** Ten participants were recruited to perform vocal loading tasks lasting 60 minutes, followed by 30 minutes of vocal rest. Objective parameters (phonation threshold pressure, fundamental frequency, jitter, shimmer, and noise-to-harmonics ratio) and subjective parameters (current speaking effort level and laryngeal discomfort) were taken at different time intervals: before vocal loading (baseline), after 15 minutes (L15), 30 minutes (L30), 45 minutes (L45), and 60 minutes (L60) of vocal loading, as well as after 5 minutes (R5), 10 minutes (R10), 20 minutes (R20), and 30 minutes (R30) of vocal rest.

**Results.** Phonation threshold pressure was found to increase significantly within the first 15 minutes of the vocal loading task ( $P = 0.032$ ), followed by a relatively gentle increase in the subsequent 45 minutes. Subjective self-ratings increased significantly after 30 minutes of loud reading ( $P < 0.05$ ). Phonation threshold pressure recovered faster than subjective parameters after the vocal loading activity had finished. Fundamental frequency was found to consistently increase during vocal loading but return to baseline rapidly within 5 minutes of vocal rest. However, no significant changes in jitter, shimmer, and noise-to-harmonics ratio were observed after vocal loading.

**Conclusions.** Phonation threshold pressure and self-ratings may have the potential to track vocal fatigue and recovery. Furthermore, a dynamic monitor of vocal fatigue was presented, which may further provide a guide for appropriate voice use.

**Key Words:** Vocal fatigue—Vocal recovery—Vocal loading tasks—Aerodynamics—Self-ratings.

## INTRODUCTION

Vocal fatigue is a common complaint of those who suffer from otolaryngologic diseases. To date, vocal fatigue has yet to receive a universally accepted definition. However, most clinicians tend to link vocal fatigue with symptoms of laryngeal tiredness, aching or dryness, neck tightness, or weak voice.<sup>1</sup> A number of different factors lead to vocal fatigue, including overusing or misusing the voice functional voice disorders, pathologic lesions, and neurologic disorders.<sup>2</sup> Without proper vocal rest, vocal fatigue may be worsened by risk factors such as background noise, room acoustics, and poor posture. Many individuals suffering from vocal fatigue lose the fullness, or timbre, of their voice and find it difficult to increase loudness as fatigue progresses.<sup>3</sup> Additionally, vocal fatigue and related compensatory behaviors may predispose phonotrauma and the development of laryngeal pathologies.<sup>4</sup> Thus, voice fatigue may result in limitations in work and social life, absenteeism, and financial loss.<sup>5–7</sup> Occupational voice users, such as teachers or counselors, are vulnerable populations.<sup>8,9</sup>

Vocal loading tasks (VLTs), which are tasks designed to induce vocal fatigue, can be used to further understand the

development process and mechanisms behind vocal fatigue. These tasks are used to delineate important changes in voice during prolonged use. Although they have been commonly used, the patterns of VLTs have not been standardized to be differentiated in terms of loading task and experimental environment. Some studies have observed the effect of vocal loading using a prolonged loud reading,<sup>10,11</sup> whereas others have used a loading task such as singing<sup>12</sup> or repeated vowel sequences.<sup>13</sup> Moreover, VLTs involve several intrinsic and extrinsic factors that can compromise laryngeal function.<sup>14,15</sup> Based on the theoretical formula [ $P = (LT/D)\eta\omega^2\xi^2$ , where  $P$  stands for power dissipation or energy loss;  $L$ ,  $T$ , and  $D$  are vocal fold length, thickness, and depth, respectively;  $\eta$  refers to tissue viscosity;  $\omega$  is the angular frequency of oscillation; and  $\xi$  is the vibrational amplitude], the energy loss during vocal fold vibration is proportional to the square of vibrational amplitude, the square of the fundamental frequency, and the tissue viscosity.<sup>16</sup> Increased speaking intensity and fundamental frequency in the VLTs could accelerate the process of vocal fatigue. In general, the main intrinsic factors include duration of voice use, intensity of voice production, fundamental frequency,<sup>17</sup> and hydration levels,<sup>18</sup> whereas the primary extrinsic factors include room acoustics<sup>15</sup> and ambient noise.<sup>19</sup> Duration of VLTs is the most commonly manipulated variable, varying from 15 minutes to 3.75 hours.<sup>20</sup>

Self-ranking parameters and acoustic parameters have been widely used to quantify the effects of VLTs in the literature. Several subjective self-rating measurements, including speaking effort level and laryngeal discomfort, were observed to increase after the VLTs and return toward baseline after a period of vocal rest.<sup>17,21,22</sup> Nevertheless, acoustic

Accepted for publication March 19, 2018.

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Journal of Voice, Vol. 33, No. 5, pp. 809.e11–809.e18

0892-1997

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<https://doi.org/10.1016/j.jvoice.2018.03.014>

parameters, including jitter, shimmer, fundamental frequency (F0), and noise-to-harmonics ratio (NHR), were found to be inconsistent after VLTs in various studies. Some studies did not achieve significant differences in acoustic variables,<sup>23,24</sup> whereas other studies obtained measurable changes in acoustic variables after VLTs.<sup>22,25,26</sup> Questions were raised as to the reliability of self-reported measures and the variability of acoustic variables.<sup>20</sup> This is because acoustic variables may be controlled for changes related to F0 and speaking intensity.

In addition to perceptual or self-reported measures, aerodynamic measures have recently been used to evaluate the effects of vocal loading. Despite phonation threshold pressure (PTP) being expected to be a sensitive variable in describing biomechanical properties of vocal folds, limited research has utilized it as a quantitative measurement.<sup>21</sup> PTP varies with vocal fold thickness, tissue damping, prephonatory glottal width, and mucosal wave velocity.<sup>27</sup> Any biomechanical changes affecting the transfer of energy from the lungs to the vocal folds, including functional dysfunction (eg, vocal fatigue or vocal dehydration) and vocal pathology (eg, vocal nodules or polyps), could influence PTP. Most of the related studies focused on effects of VLTs on PTP for a specific duration,<sup>28–30</sup> whereas other research emphasized the relationship between PTP and perceived phonation effort.<sup>10</sup>

Apart from PTP being utilized as an evaluation indicator in only a few studies, most current research regards VLTs as a whole rather than a dynamic process. The effects of VLTs should be considered as an incremental development process that takes into consideration the duration of loading and recovery periods, as well as the intensity of phonation. Only by filling these gaps can we better understand the underlying mechanisms of vocal fold damage caused by intense voice use. This will further provide a guide for appropriate voice use and further aid in developing a clinical tool to identify healthy speakers who are at risk of developing vocal pathologies. Therefore, this study was sought to test the extent to how different duration VLTs affected related parameters of a healthy population. It was hypothesized that PTP and subjective rankings could delineate the dynamic variation of laryngeal function, whereas acoustic variables may not be sensitive to vocal load and rest. The delineation would be characterized by a significant increase during VLTs, followed by a return to baseline after voice rest.

## METHODS

### Subjects

A total of 10 subjects (6 male, 4 female) were recruited. All subjects were undergraduate and graduate students from Fudan University. Subjects were included in the analysis if (1) they were above the age of 18; (2) nonsmoking; (3) had no history of health concerns from extensive alcohol use; (4) no laryngeal pathologies, established by anamnesis and laryngostroboscopic examination; (5) no complaint or history of voice disorders; (6) no hobby that implied frequent voice use; and (7) no acute respiratory infections within 2 weeks

of participation in the study. In addition, only subjects without previous singing instruction were included to avoid the confounding effects of vocal training. Ethical approval was obtained from the Research Ethics Committee of the Institution of Eye & ENT Hospital of Fudan University (protocol no. 2017057).

To control for systemic and vocal fold physiological confounders, participants were instructed to avoid any extensive vocal behavior (ie, singing, loud talking, shouting, or yelling), spicy foods, carbonated or caffeinated drinks, alcohol or mucosa-affecting medication for 48 hours before participation and 24 hours after participation. They were also asked to refrain from eating 2 hours before testing, but to consume a healthy amount of water to avoid dehydration. Female subjects were not tested 3 days before or after ovulation and menstruation to avoid the confounding effects of sex hormones.

### Protocol

All subjects performed a VLT for 60 minutes in the presence of ambient noise, followed by 30 minutes of vocal rest. A series of aerodynamic, subjective, and acoustic data were obtained to track the changes to the subject's voice.

Subjects' voices were loaded by reading aloud a novel of their choice for 1 hour in the presence of ambient, multitalker babble noise. Voice intensity was controlled between 75 and 80 dB, which was measured at 40 cm from the subject's lips with a sound level meter in dB(A). The background noise was delivered at 75 dB and was calibrated using a sound level meter before the experiment. During vocal rest, participants remained silent for 30 minutes. Throughout the procedure, the researcher advised the participants to drink 100 mL of water every 15 minutes to ensure that they remained hydrated.

### Data collection

Data were taken at baseline, followed by time points at 15 minutes (L15), 30 minutes (L30), 45 minutes (L45), and 60 minutes (L60) of loading. Data were also taken after 5 minutes (R5), 10 minutes (R10), 20 minutes (R20), and 30 minutes (R30) of vocal rest. Twenty-four hours after the prolonged reading task, the participants were required to document their recovery level using subjective variables (R24h).

Aerodynamic data were collected using the Phonatory Aerodynamic System Model 6600 (KayPENTAX, Montvale, NJ). PTP was measured according to the method described by Sivasankar and Fisher.<sup>31</sup> The device was calibrated each time before PTP measurement to guarantee the accuracy. Subjects were instructed to phonate the labial plosive /pi/ as softly as possible, but not whisper, at a conversational pitch while wearing a face mask with an oral tube inserted 2 cm into the subject's mouth. The mask was firmly pressed onto the subjects' faces to create an airtight seal to avoid air leaks. Participants were required to phonate within a single exhalation at a rate of 1.5 syllables/s. Every five /pi/ syllables constituted one trial and every subject produced five such trials. After discarding the first and the last /pi/ syllable in every trial, the mean values of these five trials were included in the statistics.

Two perceptual ratings, based on the method described by Eric and Hunter,<sup>21</sup> were also used to monitor the signs of vocal changes<sup>1</sup>: current speaking effort level (EFFT, 1–10 scale; 1 for no effort, 10 for an extreme effort to speak)<sup>2</sup>; laryngeal discomfort (DISC, 1–10 scale; 1 for no discomfort, 10 for extreme discomfort). The subjects were asked to sustain the vowel sound /a/ at a comfortable level and then to assign numbers to each of these ratings.

Using the *Multi-Dimensional Voice Program* Model 5105 (KayPENTAX), it was possible to quantify the acoustic entities of F0, jitter, shimmer, and NHR. The data were recorded using a unidirectional moving-coil microphone located 15 cm diagonally from the mouth. A sampling rate of 44.1 kHz was used. Subjects produced the sustained vowel /a/ three times at a comfortable pitch and intensity. Subjects were given a 5-second break between each of these three phonations to minimize vocal fatigue. The mean of these three values was used for statistical analysis.

### Statistical analysis

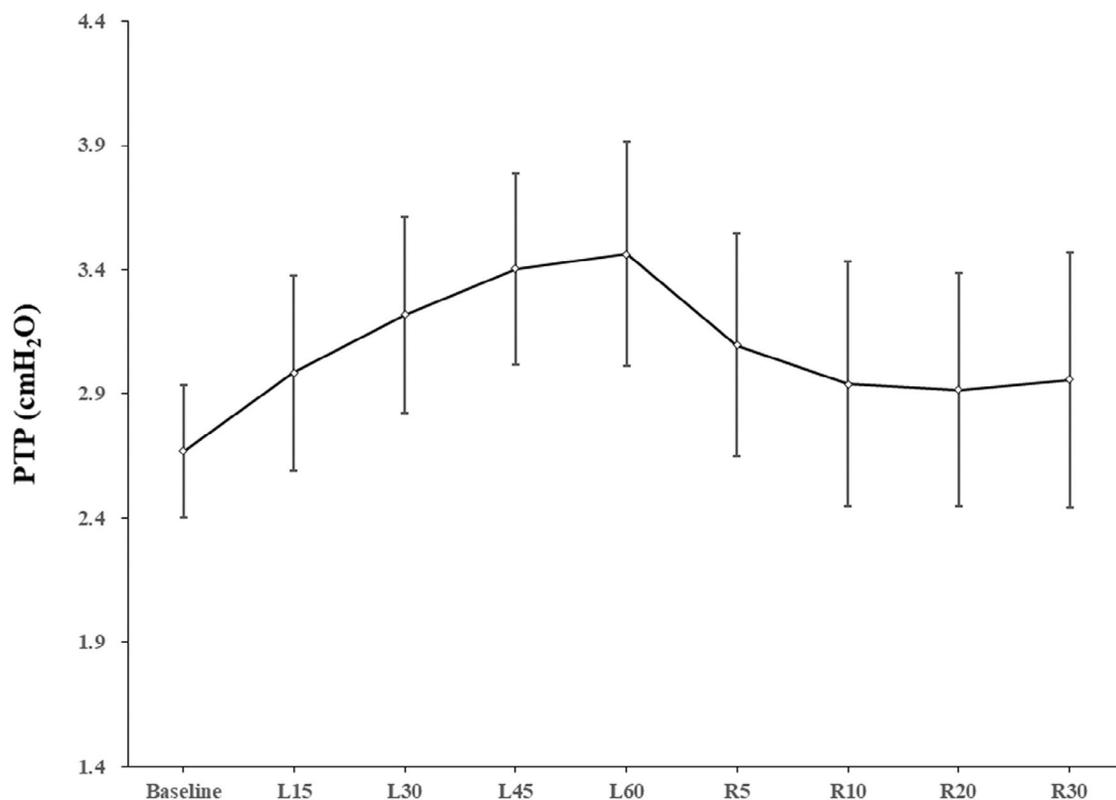
Statistical analysis of the data was carried out using *Sigma-Plot 12.3* (Systat, San Jose, CA). One-way analysis of variance with repeated measures was performed to monitor intrasubject comparisons in PTP and acoustic parameters. One-way analysis of variance with repeated measures on ranks was performed to evaluate EFFT and DISC. To locate the moment at which this difference took place, a Tukey multiple comparison test was used as *post hoc* analysis in all measurements with  $\alpha$  set at 0.05.

### RESULTS

The dynamic changes of mean values of PTP at different time points are shown in [Figure 1](#) and [Table 1](#). The differences in the mean values among intrasubject duration conditions were statistically significant, as shown in [Table 1](#) ( $P < 0.001$ ). In *post hoc* comparisons between baseline and intervention time points, significant differences were observed between baseline and L15, L30, L45, L60, R5 ( $P = 0.032$ ,  $P < 0.001$ ,  $P < 0.001$ ,  $P < 0.001$ ,  $P < 0.001$ , respectively). Comparisons between each loading time point showed a significant increase between L15 and L45, L60 ( $P = 0.001$ ,  $P < 0.001$ , respectively). Results between each rest time point demonstrated significant differences between L60 and R5, R10, R20, R30 ( $P = 0.006$ ,  $P < 0.001$ ,  $P < 0.001$ ,  $P < 0.001$ , respectively) ([Figure 1](#)).

The results for EFFT showed that duration had a significant effect ( $P < 0.001$ ) ([Figure 2](#)). In *post hoc* comparisons between baseline and each intervention time point, significant differences ( $P < 0.05$ ) were observed between baseline and L30, L45, L60, R5, R10. Comparisons between each loading time point showed a significant increase ( $P < 0.05$ ) between L15 and L45, L60. The results between each rest time point demonstrated significant differences ( $P < 0.05$ ) between L60 and R20, R30, and R24h, between R5 and R30, R24h, and between R10 and R24h.

For DISC, a significant difference between effects of intrasubject factor was found ( $P < 0.001$ ). In *post hoc* comparisons between baseline and each intervention time point, significant differences ( $P < 0.05$ ) were observed between baseline and



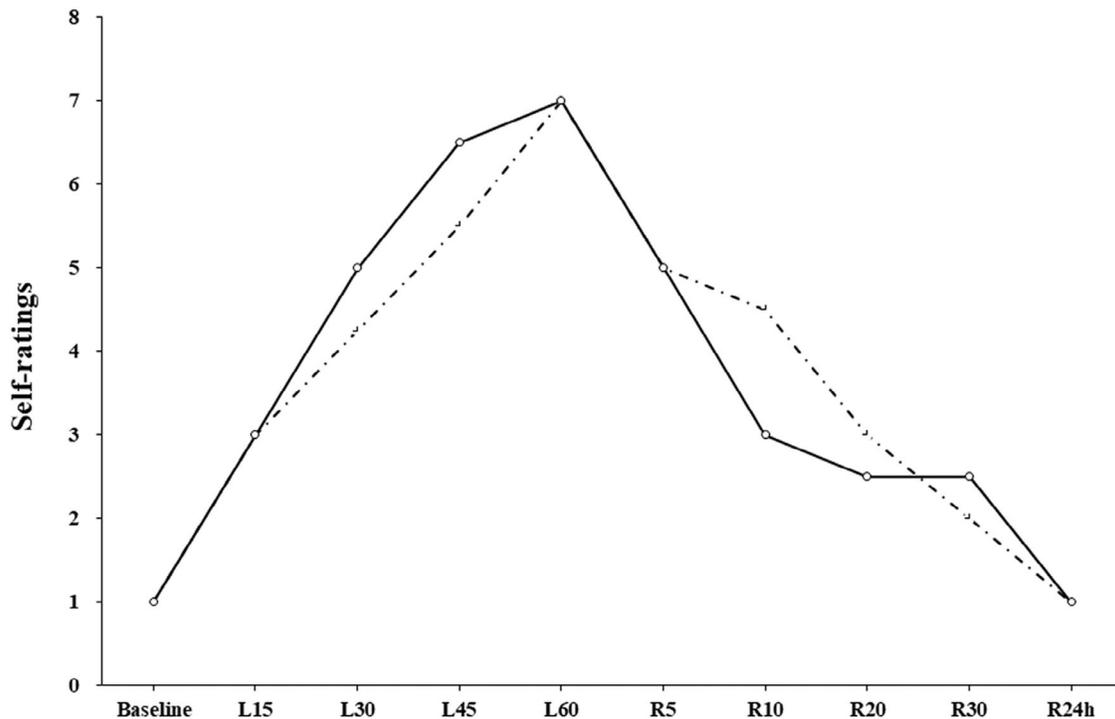
**FIGURE 1.** Dynamic variation of PTP during vocal load and vocal rest.

**TABLE 1.**  
**One-way ANOVA With Repeated Measures for Aerodynamic, Self-rating, and Acoustic Variables (n = 10 Subjects)**

Parameters	Moments of the Intervention										ANOVA (P)
	Baseline	L15	L30	L45	L60	R5	R10	R20	R30	R24h	
<b>PTP</b>											
Mean	2.669	2.985	3.219	3.404	3.464	3.097	2.940	2.917	2.957		<0.001*
SD	0.269	0.393	0.394	0.385	0.450	0.447	0.494	0.471	0.512		
<b>EFFT</b>											
Median	1.000	3.000	4.250	5.500	7.000	5.000	4.500	3.000	2.000	1.000	<0.001*
IQR	0.250	0.500	2.250	2.250	3.000	2.375	2.125	2.375	1.250	1.000	
<b>DISC</b>											
Median	1.000	3.000	5.000	6.500	7.000	5.000	3.000	2.500	2.500	1.000	<0.001*
IQR	1.000	0.250	2.250	3.125	2.250	3.625	3.250	2.500	1.500	1.000	
<b>Jitter</b>											
Mean	1.061	1.181	1.405	1.076	1.061	1.432	1.297	1.594	1.749		0.002*
SD	0.785	0.838	1.101	0.905	0.604	0.894	0.796	0.919	1.189		
<b>Shimmer</b>											
Mean	3.663	3.767	3.811	3.881	4.009	4.610	4.438	4.770	5.049		<0.001*
SD	1.067	1.064	1.113	0.683	0.939	1.017	0.636	1.536	1.559		
<b>F0</b>											
Mean	175.289	181.516	184.664	182.858	189.451	177.796	179.771	178.483	181.292		0.013*
SD	49.440	55.263	58.027	57.733	59.676	51.938	54.457	56.410	56.812		
<b>NHR</b>											
Mean	0.154	0.147	0.149	0.140	0.141	0.153	0.141	0.140	0.151		0.482
SD	0.021	0.018	0.018	0.017	0.011	0.019	0.017	0.028	0.021		

\*  $P < 0.05$ .

Abbreviations: IQR, interquartile range; SD, standard deviation.



**FIGURE 2.** Dynamic variation of EFFT (dotted line) and DISC (solid line) during vocal load and vocal rest.

L30, L45, L60, R5. Comparisons between each loading time point showed a significant increase ( $P < 0.05$ ) between L15 and L60. The results between each rest time point demonstrated significant differences ( $P < 0.05$ ) between L60 and R10, R20, R30, and R24h, and between R5 and R24h.

Regarding jitter, duration had a significant effect ( $P = 0.002$ ). In *post hoc* comparisons between baseline and each intervention time point, significant differences were observed between baseline and R30 ( $P = 0.013$ ). No significant differences were observed in comparisons between loading time points. The results between each rest time point demonstrated significant differences between L60 and R30 ( $P = 0.014$ ).

Concerning shimmer, a significant difference was found in duration ( $P < 0.001$ ). In *post hoc* comparisons between baseline and each intervention time point, significant differences were observed between baseline and R20, R30 ( $P = 0.030$ ,  $P = 0.002$ , respectively). Comparisons between each loading time point and each rest time point failed to acquire significant differences.

The results for F0 demonstrated a significant main effect from duration ( $P = 0.013$ ). In *post hoc* comparisons between baseline and each intervention time point, significant differences were observed between baseline and L60 ( $P = 0.006$ ). No significant differences were observed in comparisons between loading time points. The results between each rest time point demonstrated significant differences between L60 and R5 ( $P = 0.046$ ).

For NHR, there was no significant effect from duration ( $P = 0.482$ ). No significant differences were observed in comparisons between both loading and rest procedures.

## DISCUSSION

Although research has been carried out on vocal fatigue, there is still very little scientific understanding of its critical identifying features and its physiological source. Several attempts have been made to explore the mechanisms behind vocal fatigue and VLTs. Titze characterized vocal fatigue into two possible aspects.<sup>32</sup> The first is laryngeal muscle fatigue, potentially caused by excessive muscle contractions. This can be studied using laryngeal electromyography, which has been widely accepted to evaluate the state of laryngeal muscles. Despite having this technique, the behavior and characteristics of muscle fatigue and recovery procedure can be synchronous, which still makes it difficult to assess. Furthermore, the invasiveness and uncertainty of laryngeal electromyography further obstructs its application to study vocal fatigue.<sup>33,34</sup> In contrast, the unbalancing of muscle chemistry and the reduction of strength and speed of contraction can result in increased speaking efforts, soreness, and discomfort in the neck region. Thus, subjective ranking measures can be convenient and appropriate parameters to reflect laryngeal muscle fatigue. The second vocal fatigue aspect is laryngeal tissue fatigue, caused by collision stress and inertial stress.<sup>35</sup> The potential change of the structural matrix of the basement membrane and fluid

accumulation within tissue further results in deterioration of the viscoelastic properties of the tissue.<sup>36–38</sup> As increased tissue viscosity contributes to greater PTP, this measurement has the potential to track the tissue changes.<sup>39</sup>

Many studies aim to evaluate the effects of loading tasks on the voice, but only a few utilize PTP as one of the evaluation indicators. Instead of regarding VLTs as a dynamic procedure, the majority of these articles using PTP simply conducted measurements before and after a period of vocal loading. Such approaches fail to address the development or recovery process and physiological source of vocal fatigue. To our best knowledge, Chang and Karnell are the only authors who have monitored the pattern of PTP data over several sessions.<sup>10</sup> However, they focused on the correlation between PTP and perceived effort of phonation after fatiguing tasks. Therefore, to fill in this gap of knowledge, our study aimed to quantify the effects of various vocal load and rest durations. Additionally, the objective of this study was also to determine which variables can best describe the process as a whole to help better understand the physiological mechanism of vocal fatigue. Our results confirmed the hypothesis that aerodynamic and subjective parameters are sensitive to the vocal loading and rest procedure, while acoustic parameters fail to reflect the entire progression.

## Aerodynamics

Shear and collision stress during excessive phonation may lead to the death of epithelial cells and the separation of collagen and elastin fibers from the structural matrix at the basement membrane.<sup>36</sup> The results from several animal studies provided support for the hypothesis that intensity of phonation alters transcript levels of vocal fold intercellular tight junction proteins and disrupts the vocal fold epithelial barrier.<sup>40–42</sup> Moreover, the laryngological findings in Scherer et al's study detected large amounts of swelling and edema in vocal folds after fatigue tasks in both vocally trained and untrained subjects, which may further confirm tissue damage during vocal fatigue.<sup>43</sup> The variation of vocal tissue then results in the deviation of vocal viscoelasticity, which contributes to the increase in PTP and further facilitates the development of vocal fatigue.

Our results were consistent with most previous research, showing PTP increase after a specific duration of vocal loading, followed by a decline after vocal rest. In Enflo et al's study, both trained singers ( $n = 5$ ) and untrained singers ( $n = 5$ ) were required to repeat a vowel sequence at a minimum of 80 dB for 20 minutes.<sup>30</sup> PTP increased after 20 minutes of vocal loading in the untrained group, whereas PTP remained stable in the trained group. Erickson-Levendoski and Sivasankar recruited 16 healthy participants for their study.<sup>28</sup> The results revealed that PTP<sub>10</sub> and PTP<sub>80</sub> (PTP measures were collected at the 10th and 80th pitches) significantly increased after 35 minutes of vocal loading and after 70 minutes of vocal loading ( $P < 0.01$ ). Sundarajan et al recruited 13 healthy, older subjects ( $> 65$  years) to complete 45 minutes of vocal loading in the presence of 65-dB

background noise. Measures of PTP<sub>10</sub> and PTP<sub>20</sub> (PTP measures collected at the 10th and 20th pitches) demonstrated statistically increasing loading effects ( $P=0.002$ ,  $P=0.001$ , respectively) after the loading task.<sup>29</sup>

As dynamic observation was conducted in our research, significant differences in PTP were obtained between baseline and L15, indicating that only 15 minutes of vocal loading was needed to affect the biomechanical properties of the tissue. During vocal rest, no significant difference was obtained between baseline and R10, indicating that with 10 minutes of vocal rest it was possible for the vocal folds to recover at the histologic level after 60 minutes of vocal loading. Thus, irreversible and permanent tissue damage has not yet occurred during 60 minutes of vocal loading. Considering ethical reasons, participants were required not to exceed their limits to avoid possible permanent injury. Whereas it could conceivably be hypothesized that if vocal fatigue proceeded to overload, increased PTP would exacerbate again or even reach beyond the normal range. Some permanent injury, manifested as a voice pathology, would then occur. Based on a proposed series of hypothetical curves for tissue injury and recovery period, Titze implicated that short-term recovery takes place whenever we cease or momentarily stop phonating, and the greater the accumulation of injury, the longer the recovery time would be; all in accordance with our results.<sup>32</sup>

### Subjective self-ratings

One hour of voicing time translates to about 500,000 vocal fold collisions if a fundamental frequency of 150 Hz is used as a mean in participants. Because subject speaking intensity was required to be between 75 and 80 dB, vocal fold vibration amplitude was expected to be drastic. These repetitive and intense collisions may be contributors to vocal muscle fatigue and increased subjective measurements after VLTs. In addition, a possible explanation for the relief of laryngeal symptoms after vocal rest may be that muscle chemistry gets reset and by-products of muscle contractions are removed during this period.<sup>44</sup>

Most of the previous research agreed with our results. In Sundarrajana et al's study, deteriorated perceived phonatory effort and perceived vocal tiredness were observed after the 45-minute vocal loading challenge ( $P=0.002$  and  $P<0.001$ , respectively).<sup>29</sup> Sixteen normophonic teachers and 16 dysphonic teachers were recruited for 2-hour reading tasks in Remacle et al's study.<sup>25</sup> All self-ratings (voice quality, phonation effort, vocal fatigue, and laryngeal discomfort) worsened over time and more complaints were obtained in the dysphonic group than in the normophonic group. In Laukkanen et al's study, more tiredness of the throat was reported in 79 teachers after a working day.<sup>22</sup> Eighty-six volunteers were tracked for voice recovery after a 2-hour vocal loading exercise by Eric and Hunter.<sup>21</sup> The most prevalent response is characterized by an intense worsening of subjective rankings after vocal loading and a general improvement over the recovery period, which had a similar outcome in Chang et al's and Whittington et al's studies.<sup>10,45</sup>

Contrary to these findings, however, some research found no evidence of changed subjective rankings. Six group fitness instructors were recruited by Dallaston and Rumbach for a 60-minute exercise class. No significant changes in self-ratings of voice quality occurred before and after instruction.<sup>24</sup> In consideration of nonuniform loading patterns and uncontrolled speaking intensity, it would be hard to compromise laryngeal function with this limited dose of vocal loading. Moreover, the only significant increases were found in fundamental frequency and intensity after instruction, which better supported the hypothesis that this exercise resulted in vocal warm-up rather than vocal fatigue. Voice measures were collected by Erickson-Levendosk and Sivasankar in 16 healthy adults before and after 70-minute VLTs. Perceived phonatory effort did not increase after vocal loading. This inconsistency may also be due to the low intensity of the VLTs, which involved singing in 65-dB background noise. Additionally, half of the participants had received vocal training, which may partly explain why these participants could be spared from vocal fatigue. In Scherer et al's study, the subjective ratings in an untrained subject deteriorated consistently throughout the fatiguing tasks within 1.5 hours, whereas a well-trained subject only deteriorated to some degree after 1.5 hours of the fatiguing tasks.<sup>43</sup> These results support the idea that different vocal training levels lead to diverse consequence in subjective ratings during VLTs.

The dynamic tracking that showed significant differences in both considered subjective parameters were obtained between baseline and L30, indicating that laryngeal symptoms started to occur after 30 minutes of vocal loading. Furthermore, no significant difference was acquired between baseline and R20, indicating that vocal function returned to baseline after 20 minutes of vocal rest. Hunter and Titze indicated that these two ratings were moderately correlated, which was consistent with our outcome.<sup>44</sup> Vibration exposure could result in laryngeal discomfort and increased speaking effort. Although with some crossover, these two combined subjective ratings allowed us to better track vocal loading and recovery from different aspects of the same vocal event.

### Acoustics

An examination of the literature as a whole supports that acoustic parameters have limited sensitivity to laryngeal changes induced by VLTs.<sup>20</sup> Our results showed no significant difference in jitter, shimmer, and NHR after 1 hour of vocal loading, whereas F0 consistently increased.

F0 and NHR were examined in most previous studies, with largely increased F0 and no measurable changes of NHR. As they are given the opportunity to choose a comfortable frequency level, subjects seemed to prefer a higher fundamental frequency in the tasks. A possible explanation for this might be the strained intrinsic muscles of the larynx. As the muscles become tense, participants may have instinctively found it easier to maintain a higher pitch. Furthermore, electromyography tests in the Boucher and Ayad's study revealed that variation of F0 does not consistently

reflect fatigue in laryngeal structures.<sup>46</sup> In our study, F0 was found to return to baseline immediately after vocal loading, whereas vocal fatigue still existed. F0 rise seemed to show an adequate physiological adaptation of the vocal apparatus to loading rather than a sign of vocal fatigue.<sup>17</sup>

A diverse outcome occurred in jitter and shimmer during the vocal fatigue period in related research. A few studies obtained consequences in jitter and shimmer similar to our results.<sup>24</sup> However, jitter and shimmer were found to increase after 1 hour of the VLTs in Boominathan et al's study.<sup>11</sup> Shimmer decreased after vocal loading in both of Remacle et al's studies.<sup>17,25</sup> Jitter decreased after 2 hours of vocal loading in Stemple et al's study.<sup>26</sup> Additionally, jitter was found to increase only in participants without vocal training, whereas 1 hour of constant loud reading has little effect on the speaking voices of trained singers in Gelfer et al's study.<sup>47</sup> As the variation of jitter and shimmer were diverse in different research, we hypothesized that this discrepancy could be attributed to two aspects of loading impacts. First, an increased laryngeal tension derived from load tasks leads to the observed F0 rise. Jitter and shimmer are known to decrease as F0 increases.<sup>48</sup> Second, as the loud reading tasks continued, subjects found it difficult to sustain voice stability because of vocal fatigue, which could lead to higher jitter and shimmer. These two effects could have been experienced at different degrees per each subject, which may explain why different outcomes arise in various studies. Moreover, this hypothesis could further explain why jitter and shimmer became worse during vocal rest compared with vocal load in our study. F0 returned to baseline rapidly after vocal load, whereas vocal instability may have been sustained because of vocal fatigue, which resulted in deteriorated jitter and shimmer.

### The relationship between parameters

During the entire process of vocal loading and vocal rest, aerodynamic and subjective parameters primarily presented a similar dynamic trend; they increased over the vocal loading and returned to baseline after a period of vocal rest, indicating that these two kinds of parameters were highly correlated and essentially monotonic. Furthermore, PTP deteriorated or recovered faster than subjective parameters during the vocal load and vocal rest activity. This better supports the idea that aerodynamic and subjective variables respectively reflect different aspects of vocal fatigue.

Compared with aerodynamics and self-rankings, acoustic variables failed to track vocal function during the procedure. Theoretically, an increased phonation effort and laryngeal discomfort derived from continuous vibration exposure are unconcealed and inevitable. The subjective ratings would likely note such changes or damage. However, increased laryngeal control and effort with proper breath support may still produce a quality voice even with compromised tissue and muscles due to its adaptable physiology.<sup>21</sup> Acoustic output can be sustained by adjusting the input state of aerodynamics, that is, the acoustic parameters could

remain stable at the price of increased aerodynamics when laryngeal symptoms have appeared.

In a subsequent study, some measurements of the muscle activity and tissue variation would be needed to investigate potential muscle and tissue fatigue as an effect of vocal loading. Moreover, an analysis of postural, respiratory, and articulatory adaptations would be of great interest.

### CONCLUSIONS

The present study addresses the process of vocal loading and vocal rest using aerodynamic measurements, acoustic analysis, and subjective self-rating. PTP was found to increase significantly after 15 minutes of vocal loading, whereas subjective rankings increased significantly after loud reading for 30 minutes. These two parameters continued to deteriorate over the loading tasks. PTP recovered faster than subjective parameters after the vocal loading activity was finished. However, acoustic variable was unable to consistently track the process of vocal loading and rest. These results demonstrated the dynamic variation with diverse variables during the whole process of vocal loading and rest, which may further provide a guide for appropriate voice use.

### Acknowledgments

This study was supported by the National Natural Science Foundation of China (81329001).

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