Perceived Phonatory Effort and Phonation Threshold Pressure Across a Prolonged Voice Loading Task: A Study of Vocal Fatigue

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Summary: Although the problem of vocal fatigue is not uncommon in people with voice disorders, research on objective quantifiable indicators of vocal fatigue is limited. It has been suggested that a speaker’s perception of increased phonatory effort associated with periods of prolonged voice use is related to increased lung pressure required to initiate and sustain phonation. The purpose of this study was to examine the relationship among perceived phonatory effort (PPE), which was used as a subjective index of vocal fatigue, and phonation threshold pressure (PTP), a quantifiable measure defined as the minimal lung pressure required to initiate and sustain vocal fold oscillation. PTP and PPE were recorded before, during, and after five adult male and five adult female speakers engaged in a prolonged oral reading task designed to induce vocal fatigue. The results supported a direct, moderately strong relationship between PTP and PPE, particularly when PTP was measured during speech produced at comfortable and low-speaking pitch levels. No gender effects were found. PTP returned to baseline levels within 1 hour after the fatiguing task. PPE returned to baseline within 1 day. The data support the use of PTP as an objective index of vocal fatigue.

Key Words: Voice disorders—Vocal fatigue—Perceived phonatory effort—Phonatory threshold pressure.

BACKGROUND AND SIGNIFICANCE

Clinical epidemiologic studies indicate that vocal fatigue appears to be one of the most common and debilitating symptoms of a voice disorder.1,2 In a survey of 250 elementary and secondary school teachers, 80% reported they had problems with vocal fatigue.3 The sequelae of vocal fatigue are not trivial. Vocal fatigue in combination with other vocal symptoms can be debilitating and lead to significant loss of function in both professional and personal domains.2 The economic, personal, and societal costs caused by voice fatigue have not been calculated,
but it seems likely that both are substantial particularly for those who use their voice professionally.

Little is known about the physiological and biomechanical mechanisms, quantitative measurement, or recovery time associated with vocal fatigue despite its importance as a symptom of common voice disorders.

The biomechanical mechanisms underlying vocal fatigue are not understood. An increase in tissue viscosity has been proposed as one of the possible biomechanical factors involved, but there is no empirical data to support this hypothesis. Hyaluronic acid (HA) is a voluminous interstitial protein that binds water and is believed to play a key role in tissue viscosity of the vocal folds. Then have three times more HA deposit per unit area. Therefore, tissue viscosity may be decreased in men compared with women. It is possible that this gender difference in HA may play a role in vocal fatigue. Because women have less HA resulting in greater vocal fold tissue viscosity, they may be more susceptible to vocal fatigue.

Studies describing methods of vocal fatigue measurement are few. Acoustic findings have been inconclusive and contradictory. Jitter or shimmer was found to increase significantly in some subjects after vocal fatigue was experienced but not in others. Several studies have reported that fundamental frequency increased with vocal fatigue, whereas another investigation reported the opposite. To date, the search for an acoustic marker of vocal fatigue is still under way. Stroboscopy and aerodynamic measures have been used to document vocal fatigue in physiological terms. Increased airflow rate, decreased maximal phonation time, and incomplete vocal fold closure have been associated with vocal fatigue. In terms of muscle physiology, possible laryngeal or respiratory muscle weakness or fatigue have been suggested but not yet empirically examined.

From the perspective of human performance, fatigue involves both an increase in the speaker’s perception of effort associated with speaking and a decline in the force of muscle contraction. Of these two variables, phonatory effort has been studied. It is, however, technically difficult to directly measure force produced by laryngeal muscles in vivo.

In lieu of measuring force, Solomon et al reported that phonation threshold pressure (PTP), defined as the minimal lung pressure required to initiate and sustain vocal fold oscillation, increased with vocal fatigue tasks. However, PTP and ratings of effort for speaking did not correspond closely in their study. The authors attributed the weak relationship between the two measures to the fact that they were obtained during two different tasks. PTP was measured during a syllable repetition task, but effort was rated during connected speech.

The relationship between PTP and perceived effort for speaking needs to be further delineated. If PTP is found to vary with speaker’s perceptions of phonatory effort (PPE), PTP may be considered a valid, objective index of vocal fatigue and may then be considered a clinically useful diagnostic tool.

The recovery time from an episode or period of vocal fatigue is also of clinical interest. It has been proposed that recovery time for athletes who stress their muscular tissues regularly might be directly proportional to the amount of local tissue injury. Professional voice users, such as teachers, singers, auctioneers, and others may be considered “vocal athletes.” The duration of vocal recovery time needed after vocal fatigue has yet to be identified.

Theoretically, the process of cell repair that results from excessive vocal fold tissue collision and the replacement in the lamina propria that follows may take a few hours up to as much as 3 days. Data are needed to clarify the length of time required to recover from vocal fatigue associated with extensive voice use. Such data could establish the basis from which vocal use guidelines could be developed that, if followed, could maximize performance of professional voice users while minimizing the effect of fatigue.

The purpose of this research was to test the theory that phonation threshold pressure increases in response to vocal fatigue and is thus a useful objective index of vocal fatigue. This study was designed to answer three specific questions:

1. Is PTP a valid index of vocal fatigue?
2. Do men and women differ in response to vocal fatigue?
3. How long do the effects of vocal fatigue persist?
METHODS

Subjects
Five women and five men ranging from 20 to 37 years in age (mean = 28 years) with no reported history of voice disorders or laryngeal pathologies participated as subjects. All subjects were normal-hearing nonsmokers with no history of voice training.

Procedures
The subjects were asked to avoid singing, loud talking, and any other vocally abusive behaviors from the day before initial data collection until after they completed participation in this research. To reduce the possibility of hemorrhage and excessive dryness of the vocal folds during the experiment, the subjects were requested not to take aspirin, caffeine, or alcohol for 2 days before testing. All subjects were blind to the purpose of the experiment.

Rating perceived phonatory effort (PPE)
The subjects were asked to sustain /a/ at their most comfortable minimum and maximum effort levels and then to assign numbers to each of these effort levels, which would serve as “anchors” for the scale. The subjects were instructed as follows:
You are to rate your perceived phonatory effort using your own numerical rating system. You will be asked to produce your most comfortable, minimum, and maximum phonatory effort levels and assign numbers you associate with these effort levels.

Following the paradigms of Wright and Colton and Colton and Brown, each subject used his/her own rating scale. Seven subjects used a 1-5-10 scale where minimum effort was 1, most comfortable effort was 5, and maximum effort was 10. The remaining three subjects used unique scales: 50-100-200, 1-3-10, and 1-1-10. These three unique scales were later converted to a common 1-5-10 scale as described in Appendix A.

Three trials were performed to establish consistency. The experimenter recorded the three numbers representing the most comfortable maximum and minimum effort levels on paper to serve as a reminder for the subjects during the experiment.

For the purposes of this research, any increase in subject ratings of vocal effort in response to the fatiguing task relative to baseline was considered evidence of an increase in vocal fatigue for that subject. Thus, vocal fatigue was not considered to occur at a single point in time at which vocal function completely failed but, rather, as a continuum during which increases in vocal effort were perceived by the subjects.

Phonation at PTP
Each subject was instructed to produce a string of five /pae/ syllables at phonation threshold (lowest loudness level possible without whispering) across preselected low (men = F2 or 87 Hz, women = F3 or 174 Hz), intermediate (men = B2 or 123 Hz, women = B3 or 246 Hz), and high (men = A4 or 440 Hz, women = G5 or 800 Hz) pitches. These levels were determined from pilot data obtained before completion of this research. Falsetto was permitted during the high pitch, if the subject used it consistently throughout the measurement process.

The criterion for ensuring threshold phonation included the presence of occasional voiceless token(s) within a string of voiced /pae/ syllables. The subjects were instructed to decrease speaking intensity level until this occurred and then to increase the intensity slightly so that all tokens in a trial became voiced. Strictly speaking, if a person is phonating at threshold, 50% of the time the sample should be voiceless and another 50% should be voiced. As PTP was defined as “the minimal lung pressure required to initiate and sustain vocal fold oscillation,” only trials with all voiced tokens were measured. Although it is possible that factors other than decreased subglottic pressure (reduced glottal adduction, changes in fundamental frequency) could have accounted for the occasional voiceless productions, subglottal pressure was considered the primary control variable altered given that pitch was held constant and measurements were obtained only during voiced utterances.

The experimenter presented the preselected pitch on an electronic keyboard (Casio model MA 120, Tokyo, Japan) at the rate of 92 beats/minute indicated by a metronome. The rate of 92 beats/minute was based on Holmberg et al’s finding for maximizing the validity and reliability of estimating transglottal pressure via oral pressure. The subject was instructed to first match the pitch, which was
verified by a pitch tuner (Quartz model HU 8400, Arion, Chicago, Ill). After the accurate pitch was confirmed, the experimenter presented the target pitch five times again at the desired rate of 92 beats/minute indicated by a metronome. The subject then attempted to phonate /pae/ syllables as softly as possible while matching both the target pitch and target rate. Once the subject demonstrated ability to perform the task, data recording was initiated.

Instrumentation

Figure 1 shows a schematic of the instrumentation setup. Intraoral air pressure was sampled using a 15-cm section of intramedic polyethylene translabial tubing (1.77 mm inner diameter) connected to a Micro Switch pressure transducer (pressure range 0–27 cm H2O) routed to a Biocommunication Electronics amplifier (Honeywell International, Morris- town, NJ) and linked to a Keithley 178 digital multimeter (Keithley Instrument, Cleveland, Ohio) for calibration purposes. The opposite end of the tube was placed in the patient’s mouth, just past the lips and perpendicular to the direction of the airflow.

Audio signals were recorded using a Realistic dynamic microphone (model 33-984) and amplified by a Nakamichi preamplifier (Singapore) and Tascam tape recorder (model 22-4) (Tokyo, Japan). Simultaneous recording of pressure and audio signals were facilitated by attaching the pressure transducer to the side of the microphone with adhesive tape. The pressure sensing tubing extended approximately 1.5 inches in front of the microphone.

Both the pressure and audio signals were then directed to a Wavetek Rockland model 432 filter (San Diego, Calif). PTP and audio signals were both low-pass filtered at 100 Hz. Signals from the filter were input to the analog-to-digital converter running in a Gateway 2000 model P5-120 computer (Ponway, Calif) with 16-bit resolution and sampled at a rate of 2000 samples/second for each channel. A signal acquisition and analysis program (Windaq version 1.53) was used for signal digitization and analysis. The audio and PTP signals were also recorded on a Sony PC108M digital tape recorder and monitored throughout the recording process via Sony stereo receiver (Tokyo, Japan).

Measurement protocol

PTP was indirectly estimated during CVC /pae/ syllable repetitions. By interpolating the peak pressure of the consonants /p/, the subglottal pressure contour for the vowel could be estimated.\textsuperscript{22,23}
PTP measures as well as ratings of PPE were recorded at 15 different points in time. Both measures followed the measurement timetable shown in Figure 2. Initially, three baseline PTP measurements were obtained 24 to 48 hours before the fatiguing task described below. Measurements were separated by a 20-minute interval. On the day of the experiment, before the fatiguing task, three more PTP measurements were obtained at 20-minute intervals. These six measurements served as baseline and to estimate the range of natural variability of PTP within and across days. Next, a 2-hour fatiguing task was implemented. Each subject read aloud from the book *Vocal Exercise Physiology*\(^\text{24}\) for 2 hours. Subjects were seated 18 inches in front of a sound level meter and read aloud at the intensity level of 75–85 dB (C-scale). The experimenter monitored the subject’s reading intensity throughout the 2-hour fatiguing task and diligently prompted the subject to raise or lower loudness level to maintain the target intensity level. PTP was obtained at 30-minute intervals during the fatiguing task. All measures were repeated 15 minutes, 1 hour, and 2 hours after conclusion of the fatiguing task. The measures were again repeated at approximately 24 and 72 hours after the fatiguing task.

**Predicted patterns of PTP and PPE**

Figure 2 shows the predicted patterns for PTP and ratings of PPE. For PTP, the baseline values were predicted to be the lowest. During the 2-hour fatiguing task, PTP was expected to continue to increase as fatigue was induced until the end of the fatiguing task (session 10). After a 15-minute break (session 11), PTP was expected to decline. At 72 hours postfatiguing task (session 15), PTP was expected to return to the baseline range, assuming complete recovery had taken place.
Baseline PPE ratings (sessions 1 through 6) were expected to indicate normal effort of phonation. Throughout the fatiguing task (sessions 6–10), PPE ratings were expected to increase with time. After the fatiguing task, PPE was expected to decrease. It was expected that PPE would return to the baseline level within approximately 72 hours, under the hypothesis that increased PPE is caused by increased PTP.

RESULTS

Group PPE and PPT means and standard deviations for each data collection session are presented in Table 1. The description of the findings presented below is organized according to the three research questions stated previously: (1) Is PTP a valid index of vocal fatigue? (2) Do men and women differ in response to vocal fatigue? and (3) How long do the effects of vocal fatigue persist?

Is PTP a valid index of vocal fatigue?

To address this question, it was necessary to first examine the patterns of the PPE and PTP data relative to expected outcomes. Next it was necessary to examine the strength of the relationship between PPE and PTP.

The patterns of PPE

Group mean PPE ratings by session are presented in Figure 3. As expected, the mean ratings were fairly stable (within 1 scale value) throughout the six baseline rating sessions (session 1–6). Thereafter, the ratings increased substantially as the fatiguing task was implemented (sessions 710). After the fatiguing task (sessions 11–15), ratings of effort declined toward the baseline level.

To further examine the stability of the PPE ratings over the six baseline sessions, an ANOVA for repeated measures was performed and was found to be statistically significant [F (5,45) ratio = 3.75 (p < 0.05)]. The sessions ordered according to the subjects’ group average baseline PPE ratings from lowest to highest was session 4 < 5 < 6 < 1 < 2 < 3. A Dunn–Sidak multiple comparison procedure performed to determine which mean baseline effort ratings significantly differed from the others indicated a significant difference between session 3 and session 4 as well as between session 3 and session 5. When day 1 was compared with day 2 collectively, ie, sessions 1–3 combined versus sessions 4–6 combined, baseline day 1 ratings were found to be significantly higher than baseline day 2 ratings. No significant difference was found between session 1 and session 3 on day 1 or session 4 and session 6 on day 2, confirming that phonatory effort was relatively stable within baseline days.

As expected, the mean ratings increased steadily during the 2-hour fatiguing task (sessions 7–10). After the fatiguing task, as the subjects rested, the mean ratings of PPE declined, also as anticipated (sessions 11–15).

The results of a split-plot ANOVA for repeated measures are presented in Table 2. The main effect for session was statistically significant [F (14,112) = 37.53 (p < 0.05)]. The Dunn–Sidak multiple comparison procedure was used to compare the means of the six baseline sessions with the other nine subsequent sessions. The results indicated that the mean PPE ratings for sessions 7–13 were all significantly different from the baseline average (Figure 1). Sessions 7 through 10 occurred at 30-minute intervals during the fatiguing task. Session 11 occurred after 15 minutes of vocal rest. Sessions 12 and 13 were 1 hour and 2 hours after the fatiguing task was
completed, respectively. These findings support our expectation that the subjects perceived effects of fatigue because of the exertion associated with performing the reading task extended somewhat beyond the time when the reading task ended. They also show that the mean effort ratings appeared to return to baseline or near-baseline levels after 2 hours of vocal rest.

The patterns of PTP

The mean group PTP measurements for low-pitch, comfortable, and high-pitch conditions over sessions are presented in Figure 4. Baseline (sessions 1–6) mean PTP demonstrated very little variation. The standard deviations for the comfortable, high, and low pitches were 0.09, 0.11, and 0.13 cmH$_2$O, respectively, which represented 3.4%, 2.2%, and 4.6% of the group means for these conditions.

Repeated measures ANOVAs were performed to determine the stability of baseline PTP values at each pitch condition. Type I error rate for the F-test was controlled at 0.05 for all three pitch conditions simultaneously using the Dunn–Sidak correction procedure. No significant differences were found across the baseline sessions for the three pitch conditions tested ($p < 0.05$).

A split plot ANOVA for repeated measures indicated a statistical significant main effect for pitch at $p < 0.05$ (Table 3) when baseline, fatigue, and recovery sessions were analyzed. Paired Dunn–Sidak post hoc testing revealed that PTP values at the high-pitch condition were significantly higher than those at the comfortable and low-pitch conditions. Because of the statistically significant main effect for pitch, additional statistical analysis of PTP measures in the present study was conducted with an ANOVA for repeated measures performed for each pitch condition.

The patterns of PTP by pitch

The group average PTP values differed significantly across the 15 sessions ($p < 0.05$) in all three
TABLE 2. Analysis of Differences among PPE by Session and Sex (All 15 Sessions Included)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>p</th>
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<td></td>
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<td>1.11</td>
<td>0.32</td>
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</tr>
<tr>
<td>Within subjects</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Sessions</td>
<td>14</td>
<td>16.63</td>
<td>37.53</td>
<td>0.05</td>
</tr>
<tr>
<td>Sessions × gender</td>
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<td>0.30</td>
<td>0.67</td>
<td>0.80</td>
</tr>
<tr>
<td>Error (session)</td>
<td>112</td>
<td>0.44</td>
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</tbody>
</table>

pitch conditions. For the comfortable pitch condition, the Dunn–Sidak post hoc test demonstrated that the average PTP on sessions 7–11 was significantly different from the baseline average. The Dunn–Sidak post hoc test yielded significant differences for sessions 7–10 for the high-pitch condition and sessions 7–11 for the low-pitch condition (Figure 4).

The correlation between phonatory effort and PTP

Pearson’s correlation coefficients were computed to determine the correlation between the mean ratings of PPE and mean PTP measures. The coefficient between effort ratings and PTP-comfortable pitch was 0.91, between effort and PTP-high pitch was 0.82, and between effort and PTP-low pitch was 0.91, respectively. When only considering data recorded on the day of the fatiguing task, mean PTP at all three pitch conditions were strongly correlated with mean PPE ($r = 0.96$, 0.93, and 0.97 for the comfortable, high-pitch, and low-pitch conditions, respectively). These Pearson correlations should be interpreted with caution because the PPE data do not represent ratio level of measurement.

A Fisher z transformation was used to determine whether the correlation coefficients were significantly greater than 0.70 because a coefficient at this level accounts for 50% of the variance in the data. The results indicated that the correlations at the comfortable and low pitches were significantly greater than 0.70, but the correlation at the high pitch was not.

Do men and women differ in response to vocal fatigue?

To determine whether women demonstrated evidence of fatigue sooner than men during the fatiguing task, split plot ANOVAs were used to test for a possible gender-by-session interaction effect for sessions 6–10. Session 6 was used to represent baseline on the day of the experiment because no significant difference was found among the three baseline sessions 4–6. Sessions 7–10 represented sessions during the fatiguing task. Statistical analysis focused on these five sessions rather than the entire 15 sessions.

Consistent with the analysis described previously, the results failed to support a significant main effect for gender for either PPE or PTP. However, a significant pitch-by-gender interaction effect was found for PTP [$F(2,16) = 4.45, (p < 0.05)$]. Post hoc tests revealed that the gender differences in PTP values (women greater than men) at the high-pitch condition were significantly greater than those at the other two pitch conditions ($p < 0.025$). No significant gender-by-session interaction effects were found among any pitch conditions for PTP or for PPE.

How long do effects of vocal fatigue persist?

As described previously, results of the Dunn–Sidak post hoc test demonstrated that sessions 14–15 (24 hours and 72 hours postfatiguing task) of the PPE ratings were not significantly higher than the baseline average (sessions 1–6) (Figure 5). This suggests that it took more than 2 hours but less than 24 hours after the fatiguing task for the mean PPE ratings to decline to the baseline level.

For PTP measurements recorded at the comfortable and the low-pitch conditions, the Dunn–Sidak tests showed that only session 11 (15 minutes postfatiguing task) was significantly higher than the baseline average (sessions 1–6) (Figure 2). For the high-pitch condition, no recovery sessions were significantly higher than the baseline average. In short, PPE returned to the baseline within 1 day. PTP values generally returned to the baseline level within 1 hour.

DISCUSSION

Is PTP a valid index of vocal fatigue?

The results of this investigation support the existence of a relatively strong, direct relationship between PTP and ratings of PPE. However, the correlations between mean PTP and the mean ratings of PPE for the comfortable and low-pitch conditions were higher ($r = 0.91$) than for the high-pitch condition.
condition \((r = 0.82)\). One possible explanation for the lower correlation coefficient in the high-pitch condition involves the difficulty of the task. Phonating at a high frequency (800 Hz for women or 440 Hz for men) at the softest possible volume may have been more challenging for the subjects, resulting in greater across-day variation.

**Do men and women differ in response to vocal fatigue?**

It was anticipated that women would demonstrate evidence of vocal fatigue more quickly than men, in part, because (1) women’s voices vibrate at a higher frequency than men’s and because (2) women may be more prone to developing changes in the vocal fold cover, such as vocal nodules, in response to vocal overuse or abuse. Frequency has been found to be a key variable in fatigue induced by hand-transmitted vibration.\(^{25}\) Higher frequency of vibration is predicted to increase energy loss\(^{26}\) because of more tissue friction caused by more rapid movement of tissue. Smith et al\(^{27}\) reported that the probability of teachers reporting voice problems was approximately two times greater in women than men because of higher Fo in women. Also, because previous research\(^{13,28}\) has proposed that PTP may reflect the integrity of the vocal fold mucosa or cover, it was anticipated that if women were more susceptible to such changes because of vocal fatigue, they would demonstrate a greater change in PTP than would men. However, the results from the current study indicated the patterns of PPE and PTP changes across sessions were similar (parallel) in both sexes.

**Duration of vocal fatigue effects?**

It was hypothesized that it may take up to 72 hours after the fatiguing task for PTP and PPE to return to their baseline level. However, the findings indicated that, on average, PTP recovered within 1 hour, and PPE recovered within 1 day. The recovery

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**FIGURE 4.** Mean group PTP measurements for low-, comfortable, and high-pitch conditions over sessions. The asterisks note the measures found to be significantly different from baseline.
time in PTP in the present study is consistent with that of the Solomon and DiMattia\textsuperscript{18} and Solomon et al\textsuperscript{19} studies, in which the decrease in PTP exceeded 1 cm\textsubscript{H}2O after 15 minutes of vocal silence immediately after the fatiguing task for most trials. Their studies did not follow up the recovery curve beyond 15-minutes postfatiguing task. A similar pattern was observed in the ten subjects who participated in the current study. For 14 of 30 trials (10 subjects × 3 pitches), PTP measured 15 minutes after completion of the fatiguing task approximated the baseline values. Cumulatively, the group mean PTP recovered within 15 minutes after the fatiguing task during the high-pitch condition and within 1 hour during the comfortable and low-pitch conditions.

The group mean ratings of PPE took more than 2 hours but less than 24 hours to decline back to the baseline level. By 15 minutes after the fatiguing task, the mean PPE rating declined substantially from completion of the fatiguing task, but it did not return to the baseline level. This finding is also consistent with the reports of Solomon and DiMattia\textsuperscript{18} and Solomon et al\textsuperscript{19} that effort of speaking decreased after 15 minutes of vocal silence.

Although recovery was not systematically monitored in Stemple et al’s study,\textsuperscript{10} their ten subjects reported that it took 1–8 hours (mean = 3 hours) to completely recover from all physical discomfort. Very similar fatiguing tasks were implemented in Stemple et al’s investigation and the present study. The reported differences in recovery time among subjects in both studies demonstrated considerable individual variability. This variability supports Titze’s\textsuperscript{3} speculation that there may be considerable individual variability in recovery time of the nonmuscular vocal fold tissues, the primary tissues involving in vibration during phonation.

### Implications for laryngeal physiology

Loud talking, elevated pitch, and prolonged voice use have been shown to cause vocal fatigue.\textsuperscript{9,10,12,29,30} Although other influences may be involved, the fatiguing effects demonstrated in the present study along with those described in previous studies using similar approaches\textsuperscript{10,18} are consistent with a theoretical formula that predicts higher vibrational amplitude and higher Fo will lead to more energy loss in response to fatigue. In the formula, Titze\textsuperscript{26} indicates that

\[
P = (LT/D) \eta \omega^2 \xi^2,
\]

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. L, T, D, and \( \omega \) are all associated with vocal fold configuration in pitch/Fo changes. Titze\textsuperscript{4} indicated that whenever tissue vibrates, mechanical energy is dissipated into heat. The power dissipation during vocal fold vibration is proportional to the square of the fundamental frequency, the square of the vibrational amplitude, and the tissue viscosity. Therefore, higher Fo increases energy loss. Greater loudness means greater vibrational amplitude (\( \xi \)), which also causes more energy loss.

The above formula also predicts that more power is dissipated with increased tissue viscosity (\( \eta \)). The significant increase in PTP after vocal fatigue was induced is consistent with an increase in vocal fold viscosity. Titze\textsuperscript{31} proposed another theoretical equation:

\[
PTP = (2k/T)(Bc)(w/2),
\]

where \( k \) is a transglottal pressure coefficient (around 1.1), T stands for vocal fold thickness, B is a damping coefficient proportional to viscosity, c represents velocity of mucosal wave, and \( w/2 \) is prephonatory
glottal half-width, and viscosity is proportional to PTP. Theoretically, the tissue damage resulting from the prolonged and rigorous tissue vibration during a fatiguing task may increase tissue viscosity. Extensive surface tissue injury and destruction have been demonstrated in hyperphonated canine vocal folds. The data from the current study are consistent with (but not direct evidence of) causation by way of the intervening viscosity variable, as exemplified by the causal model:

\[
\text{Fatigue Increased} \rightarrow \text{Vocal Fold Cover Viscosity}
\]

\[
\text{Increased PTP} \rightarrow
\]

Based on the theoretical formula regulating PTP mentioned above, an increased glottal opening (w/2) could also contribute to greater PTP. This seems reasonable if vocal fatigue occurs to an extent that glottal hypofunction occurs. Anterior glottal chinks and various configurations of incomplete glottal closure have been reported in subjects with induced vocal fatigue and in others that appear to suffer from chronic vocal fatigue. Monitoring prefatigue and postfatigue glottal opening with videostroboscopy may be useful for determining how glottal opening and PTP are affected by fatigue.

Because tissue viscosity was not directly measured in this study, a similar study manipulating water intake (presumably hydration level) during a fatiguing task may be informative in this regard. Solomon et al studied how a fatiguing task and systemic hydration affected PTP, glottal closure patterns, and self-perceived effort. Their results demonstrated that regardless of hydration, PTP generally increased after prolonged loud reading across pitches. The authors speculated that merely varying water consumption for 2 days may not be sufficient to impact systemic hydration. Roy et al reported no significant differences in PTP measurements compared with baseline after subjects used a nebulizer containing lubricating agents intended to test the substance’s ability to improve the viscosity of the vocal folds and the mucous blanket covering the vocal folds. More direct studies of tissue viscosity are needed to examine the relationship between internal hydration and external hydration as well as how to manipulate tissue viscosity for therapeutic purposes.

The fast recovery of PTP is intriguing considering the extent of possible tissue damage involved and the time it takes for injured cells to be replaced. As previously mentioned, Gray and Titze investigated acute vocal fold injury from excessive phonation in canines. Extensive surface damage featured destruction and loss of the microridges and premature desquamation of the squamous epithelium. After 4 hours of phonation, basement membrane damage characterized by detachment of collagen fibers was observed. These tissue damages may disrupt the integrity of the vocal fold cover leading to inefficient tissue vibration. Titze has speculated that it may take as long as 72 hours for the repair process in the extracellular matrix of the lamina propria to be completed. If the injury extended to the basement membrane, healing may take days or weeks. The rapid recovery seen in PTP data in the current study seemed to occur faster than the rate of tissue recovery described by Gray et al. Differences in human versus canine tissue and in experimental design could possibly explain these inconsistencies.

**Limitations and future plan of study**

Future studies with more subjects are needed to better understand how vocal fatigue may affect PTP or PPE. In the present study, each subject used his or her own PPE rating scale, which was adjusted to a standard scale afterward (Appendix A). Other common rating scales, such as the Borg rating scale, which is used widely in sports medicine and exercise science to rate levels of exercise intensity, may be considered in future studies. The significant differences in baseline measures obtained across days warrants additional investigation to determine if this finding was caused by real differences in perceived phonatory effort, scaling artifact, or chance.

Findings from this study provide preliminary support for a relationship between vocal fatigue as it may be reflected in PPE and PTP. In comparison with other aerodynamic studies of vocal fatigue, our findings did not demonstrate the hypofunctional profile presented by some patients with vocal fatigue. This could be caused by the task-dependent nature of fatigue. In the case of acute fatigue resulting from 2 hours of loud reading, the normal subjects did not reach the point where the respiratory or laryngeal
muscles fatigued, leading to loss of subglottal pressure. Further research may investigate patients with chronic vocal fatigue undergoing real-life vocal activities in their natural settings to determine the clinical potential of PTP and specific recovery time needed for high-risk populations.

**SUMMARY**

In search of a quantitative measure sensitive to vocal fatigue, the relationship among vocal fatigue, phonatory effort, and PTP was examined in the present study. A strong correlation was found between PTP and ratings of PPE, supporting the view that PTP was sensitive to vocal fatigue. No gender differences were found in the pattern of PTP or PPE changes, which failed to confirm the expected effects of higher fundamental frequency in women. Finally, post-fatiguing task PTP recovered within 1 hour and PPE recovered within 1 day. Both supported a much more rapid recovery period from vocal fatigue than previously expected.

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