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Measurement of Phonation Threshold Power in Normal and Disordered Voice Production

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Abstract

Objectives—Phonation threshold pressure (PTP) and phonation threshold flow (PTF) are useful aerodynamic parameters, but each is sensitive to different disorders. A single comprehensive aerodynamic parameter sensitive to a variety of disorders might be beneficial in quantitative voice assessment. We performed the first study of phonation threshold power (PTW) in human subjects.

Methods—PTP and PTF were measured in 100 normal subjects, 19 subjects with vocal fold immobility, and 94 subjects with a benign mass lesion. PTW was calculated from these two parameters. In 41 subjects with a polyp, measurements were obtained before and after excision. Receiver operating characteristic (ROC) analysis was used to determine the ability of the three parameters to distinguish between controls and disordered groups.

Results—The PTW ($p < 0.001$), PTP ($p < 0.001$), and PTF ($p < 0.001$) were different among the three groups. All parameters decreased after polyp excision. PTW had the highest area under the ROC curve for all analyses.

Conclusions—PTW is sensitive to the presence of mass lesions and vocal fold mobility disorders. Additionally, changes in PTW can be observed after excision of mass lesions. PTW could be a useful parameter to describe the aerodynamic inputs to voice production.

Keywords

aerodynamic parameters; artificial neural network; mass lesion; phonation threshold power; vocal fold paralysis; voice analysis

INTRODUCTION

Most clinical voice assessments depend on perceptual and subjective assessments. Although valuable, such measurements can be imprecise and unreliable.¹ Aerodynamic measurements offer objective, quantitative data reflective of general vocal health.² During phonation, the larynx transforms aerodynamic energy generated in the lungs into acoustic energy, which we

perceive as voice.³ Some persons can volitionally modify their vocal output through compensatory mechanisms that result in a voice of approximately normal acoustic quality, even though the mechanism used to produce that voice may be quite effortful. It is much more difficult to develop mechanisms that would normalize aerodynamic input while preserving that approximately normal acoustic output, as the presence of a laryngeal disorder decreases the efficiency by which aerodynamic energy can be transduced into acoustic energy.

Aerodynamic parameters respond to changes in the biomechanical properties of the vocal folds and can indicate an abnormal vocal fold configuration. Titze et al⁴ discussed the influence of changes in biomechanical properties on phonation threshold pressure (PTP), the minimum subglottic pressure required to initiate sustained vocal fold oscillation. The PTP rises with increases in vocal fold thickness, tissue damping, prephonatory glottal width, and mucosal wave velocity.⁴ Because it is also influenced by disease,⁵ vocal fold scarring,⁶ wound healing,⁷ vocal fatigue,⁸ and dehydration,^{8,9} it is a clinically valuable parameter.

Phonation threshold flow (PTF), the airflow required to initiate sustained vocal fold oscillation, is a fairly recently proposed aerodynamic parameter that may also have clinical value.¹⁰ For a particular vocal tract configuration that is fixed and does not contain a velopharyngeal leak, the mean airflow exiting the larynx is roughly equal to the mean airflow exiting the mouth.¹¹ Thus, it is possible to estimate glottal airflow by using a device external to the vocal tract. Zhuang et al¹² measured PTF in 41 normal subjects, 21 subjects with vocal fold nodules, and 23 subjects with a vocal fold polyp. The PTF values were significantly different between controls and subjects with a vocal fold polyp. When a polyp or nodule is present, the glottal closure is limited, thus increasing air leakage during phonation and resulting in higher-than-normal airflow measurements.¹² Previous experiments using excised canine larynges have shown PTF to increase with the size of a posterior glottal gap,¹³ vocal fold elongation,¹⁴ and surface dehydration.¹⁵ Hottinger et al¹³ determined that PTF is more sensitive than PTP to changes in posterior glottal width, demonstrating the potential value of the flow parameter in evaluating disorders that are characterized by glottal insufficiency.

Both PTP and PTF have the potential to be clinically useful quantitative aerodynamic parameters; however, each is sensitive to different changes in laryngeal biomechanics. PTP is a better descriptor of disorders characterized by stiffness, whereas PTF is a better descriptor of disorders characterized by incomplete glottal closure. A single aerodynamic parameter inclusive of both PTP and PTF may be useful in clinical and research settings. The product of laryngeal airflow and subglottic pressure is equal to aerodynamic power.^{16,17} At the phonation threshold, this quantity is termed phonation threshold power (PTW). PTW varies with both subglottic pressure (PTP) and laryngeal airflow (PTF). Importantly, all three parameters vary with glottal configuration. Thus, PTW measurements must be qualified as the critical power necessary for the initiation of sustained vocal fold oscillation for a given glottal configuration.

Regner and Jiang¹⁸ evaluated PTW in excised canine larynges, analyzing variables such as posterior glottal gap, vocal fold elongation, and vocal fold lesions. PTW was sensitive to

changes in posterior glottal width and the presence of a vocal fold lesion, and a weaker positive relationship occurred between PTW and vocal fold elongation.¹⁸ Although basic science investigations have demonstrated the potential utility of PTW, this parameter has not been measured in humans. The objective of this study was to measure PTW in normal subjects, subjects with a vocal fold mass lesion, and subjects with a vocal fold mobility disorder, and to determine the ability of PTW to distinguish between controls and subjects with either of the two voice disorders.

MATERIALS AND METHODS

Subjects

Measurements were recorded from 100 normal subjects (age, 38.21 ± 12.32 years; 42 male, 58 female), 22 subjects with a vocal fold cyst (age, 38.14 ± 8.20 years; 14 male, 8 female), 72 subjects with a vocal fold polyp (age, 36.46 ± 7.30 years; 25 male, 47 female), and 19 subjects with a vocal fold mobility disorder (age, 44.11 ± 13.50 years; 10 male, 9 female). Additionally, 41 subjects (age, 35.98 ± 8.36 years; 14 male, 27 female) with a vocal fold polyp underwent a second aerodynamic assessment 6 weeks after excision of the polyp. The vocal fold mobility disorder group consisted of 11 subjects with vocal fold paralysis and 8 subjects with arytenoid dislocation. Subjects with either a polyp or a cyst were combined into one group, termed the mass lesion group.

Data Collection

This study was conducted at the Zhongshan Hospital of Xiamen University under the approval of the Zhongshan Hospital ethics committee. We measured PTP and PTF with the KayPENTAX phonatory aerodynamic system (KayPENTAX, Montvale, New Jersey). PTF was measured according to the method described by Zhuang et al.¹² The subjects produced a sustained /α/ into a cardboard tube. The subject's lips were wrapped tightly around the tube to prevent air leakage, and the tube rested above the tongue, approximately 1 inch into the mouth. A nose clip was also worn during trials to prevent flow through the nares. The subject was asked to initiate phonation at a soft intensity and slowly decrease the intensity over 3 to 5 seconds until no phonation was detected. PTF was defined as the airflow at the point at which phonation ceased. The short time of recording eliminated any potential impact of vocal fatigue. Each subject was asked to repeat the process 3 times, resting for 5 seconds between trials. The mean PTF for each subject was used for statistical analyses.

PTP was measured according to manufacturer specifications, which are based on the method of airflow interruption by full lip occlusion, as described by Smitheran and Hixon.¹⁹ The subjects wore both a nose clip and a face mask. An oral tube was inserted 2 cm into the subject's mouth, with attention paid to ensuring that the tube was not covered by the tongue. The subjects were asked to utter the syllable /pi/ 6 to 7 times per breath, starting at a low volume, similar to a whisper. The subjects were then asked to gradually increase the volume until the voicing of the /i/ appeared to be clear. The peak pressure was measured just before this point. Three practice trials were allowed before data collection, and the first and final trials were deleted. The data were analyzed according to the Voicing Efficiency protocol (KayPENTAX). PTW was calculated as the product of PTP and PTF.

Data Analysis

The phonation offset airflow and the phonation onset pressure were recorded as PTF and PTP; the PTW was calculated as the product of these two values. An analysis of variance on ranks and pairwise comparisons using Dunn's method were performed to evaluate potential differences among controls, subjects with a mass lesion, and subjects with a vocal fold mobility disorder. Non-parametric testing was employed because of the unequal sample sizes in the three groups. To evaluate the responsiveness of each parameter to polyp excision, we performed paired *t*-tests to evaluate potential differences between pretreatment and posttreatment measurements. All statistical analyses were two-tailed, with a significance level (α) of 0.05.

Receiver operating characteristic (ROC) curves were used to determine the ability of each of the three aerodynamic parameters to differentiate between controls and subjects with a mass lesion, between controls and subjects with a vocal fold mobility disorder, and between controls and subjects with either a mass lesion or a vocal fold mobility disorder. The ROC curves display the false-positive rate ($1 - \text{specificity}$) on the abscissa and the true-positive rate (sensitivity) on the ordinate. The false-positive rate was calculated as the number of false-positive classifications divided by the number of both true-negative and false-positive classifications.²⁰ The true-positive rate was calculated as the number of true-positive classifications divided by the number of both true-positive and false-negative classifications.²⁰ The area under the curve (AUC) was used to quantify the ability of each aerodynamic parameter to distinguish between controls and the disordered groups. The AUC values ranged from 0.5, meaning the parameter is no better than chance at distinguishing between the two groups, to 1, which signifies that the parameter can perfectly differentiate between the two groups.²⁰

RESULTS

Summary data are presented in Table 1. All three parameters were significantly different across the three groups ($p < 0.001$). PTW data are presented in Fig 1A. Pairwise comparisons resulted in statistically significant differences between controls and subjects with each category of disorder, but not between vocal fold mobility disorders and mass lesions. Statistically significant decreases were observed in all three parameters after excision of the vocal fold polyp (Fig 1B).

The AUC values for the ROC analysis are presented in Table 2. The highest AUC value obtained in comparing controls and subjects with a mass lesion was 0.936 for PTW (Fig 2A), followed by 0.918 for PTP. In comparing controls versus the group with vocal fold mobility disorders, the highest AUC value was 0.899 for PTW (Fig 2B), followed by 0.880 for PTF. PTW also had the highest AUC of 0.930 for comparisons of controls and subjects with either disorder (Fig 2C).

DISCUSSION

Regner and Jiang¹⁸ demonstrated the sensitivity of PTW to alterations in posterior glottal width in a study on excised larynges. As certain characteristics of ex vivo experiments, such

as the lack of a vocal tract, can sometimes lead to results that do not parallel those observed in humans,²¹ further research in human subjects was necessary to explore the utility of this parameter. This study provides preliminary evidence that PTW is affected by vocal fold immobility and benign mass lesions, and that PTW is sensitive to polyp excision.

This study had two key limitations. First, PTP and PTF, the two components of PTW, were measured on different tasks. Additionally, PTP was measured at the phonation onset, whereas PTF was measured at the phonation offset. Although each method used to measure these parameters has been described and justified previously, it would be preferable to measure PTW using a single task. Improved measurement methodology may increase the clinical utility of this parameter. Second, PTW is dependent on both PTF and PTP; theoretically, therefore, a disorder that increases one parameter but decreases the other may appear to exhibit a “normal” PTW. As the range of normal values observed in this study is relatively large, with a standard deviation approximately one half of the mean, it seems that comparisons of isolated measurements of PTW across patients are likely to have less value than serial measurements over time within patients.

Our results demonstrated that there were significant differences for PTW among controls, subjects with a mass lesion, and subjects with a vocal fold mobility disorder. Pairwise comparisons between the latter two groups did not reveal a significant difference. Altering properties related to the prephonatory conditions, such as the viscoelasticity of vocal fold tissues and the degree of vocal fold adduction, affects the efficiency with which the larynx transduces aerodynamic power to acoustic power.²² Mass lesions such as nodules or polyps not only add mass to the vocal folds, but also affect stiffness and viscosity.²³ These changes increase the amount of aerodynamic power consumed as internal friction, and as a result, additional aerodynamic power is required to initiate vocal fold vibration.²⁴ Furthermore, vocal fold mobility disorders such as vocal fold paralysis and arytenoid dislocation can lead to incomplete glottal closure, thus affecting the transfer of energy from the lungs to the vocal folds.²⁴ These biomechanical changes resulting from the presence of nodules, polyps, or vocal fold mobility disorders often increase PTP and PTF values, and thus also increase PTW.

In contrast to comparisons of either disordered group to the control group, comparisons between the two disordered groups showed no significant differences for any of the three parameters. This result was expected, as the effects of the two types of disorders on aerodynamic measurements are similar.

The ROC curves demonstrated higher AUC values for PTP in comparisons of controls and subjects with mass lesions, and higher values for PTF in comparisons of controls and subjects with vocal fold mobility disorders. These results support previous findings that PTF is more sensitive to changes in the prephonatory glottal area¹² and suggest that PTP may be more sensitive to the presence of mass lesions.

Consideration of both pressure and airflow is necessary for a complete representation of vocal fold physiology and pathophysiology. As a product of PTP and PTF, PTW has the potential of representing the transfer of energy from the lungs to the vocal folds in an even

wider range of disorders. The ROC analysis of comparisons of controls versus subjects with mass lesions, controls versus subjects with vocal fold mobility disorders, and controls versus a group combining subjects with both disorders resulted in higher AUC values for PTW than for either PTP or PTF. These results suggest that PTW, a parameter inclusive of both pressure and flow, is better able to distinguish among these groups than is PTP or PTF individually.

To be clinically valuable, a parameter must be sensitive to changes induced by treatment. We investigated the effect of polyp excision on PTW in 41 subjects. Because changes in both PTP and PTF have been observed after polyp excision, PTW should also change after treatment.^{16,25} As expected, analysis of pretreatment and posttreatment measurements in subjects with a vocal fold polyp showed a statistically significant difference ($p < 0.001$) for all three parameters. PTW has the ability to provide quantitative information during initial assessment of voice disorders and during follow-up appointments. Future studies investigating correlations between pretreatment and posttreatment PTW values and perceptual voice assessments, such as the Voice Handicap Index, could further support the benefits of including PTW in quantitative voice assessment.

CONCLUSIONS

Although previous studies have measured PTW in excised larynges, this is the first study to measure it in human subjects. Significantly higher PTW was observed in subjects with a mass lesion or mobility disorder. A significant change in PTW occurred after polyp excision. Relatively high PTW values could possibly indicate the presence of a mass lesion or a vocal fold mobility disorder. PTW also had higher AUC values than either PTP or PTF, demonstrating its superior ability to distinguish among the groups. As this is the first study of PTW in human subjects, further research is needed to determine the utility of PTW in quantitative voice assessment. Additionally, new measurement techniques that can determine PTW by using only a single task should be explored.

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Fig 1.

Box plots of phonation threshold power, measured in centimeters of water multiplied by liters per second. Lower and upper boundaries of boxes represent first and third interquartiles, and whiskers signify 10th and 90th percentiles. Points below and above whiskers represent 5th and 95th percentiles. Medians are denoted by lines within boxes. **A)** Comparison of normal subjects, subjects with mass lesions, and subjects with vocal fold mobility disorder. **B)** Comparison of pre-excision and postexcision measurements in subjects who had vocal fold polyps.

Fig 2. Receiver operating characteristic curves for phonation threshold power in distinguishing 100 control subjects from **A)** 94 subjects with mass lesion (area under curve of 0.936), **B)** 19 subjects with vocal fold mobility disorder (area under curve of 0.899), and **C)** 113 subjects with either mass lesion or vocal fold mobility disorder (area under curve of 0.930).

TABLE 1**SUMMARY DATA**

Parameter	Normal (n = 100)	Mass Lesions (n = 94)	Movement Disorders (n = 19)	Polyp Presurgery (n = 41)	Polyp Postsurgery (n = 41)
Phonation threshold flow (L/s)	0.09 ± 0.04	0.18 ± 0.08	0.22 ± 0.12	0.19 ± 0.08	0.13 ± 0.06
Phonation threshold pressure (cm H ₂ O)	4.22 ± 1.02	7.20 ± 1.84	6.65 ± 2.09	7.39 ± 1.74	5.28 ± 1.42
Phonation threshold power (cm H ₂ O × L/s)	0.38 ± 0.20	1.28 ± 0.68	1.62 ± 1.23	1.42 ± 0.77	0.71 ± 0.54
Data are mean ± SD.					

TABLE 2

AREA UNDER RECEIVER OPERATING CHARACTERISTIC CURVES FOR INDIVIDUAL PARAMETERS

Parameter	Normal vs Mass Lesion	Normal vs Movement Disorders	Normal vs Both Disorders
Phonation threshold flow	0.840	0.880	0.840
Phonation threshold pressure	0.918	0.854	0.890
Phonation threshold power	0.936	0.899	0.930