A Comparison of Indirect and Direct Methods for Estimating Transglottal Airflow Rate

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Summary: Objective. The purpose of this study was to compare indirect estimates of transglottal airflow rate using measures of phonation quotient with direct measures of mean airflow rate derived from a pneumotachograph.
Study design. This study used prospective, repeated measures design.
Methods. Nineteen male and female participants, matched for age, completed tasks for maximum phonation time and vital capacity in addition to the comfortable sustained phonation protocol of the Phonatory Aerodynamic System (PAS), Model 6600. Phonation quotient was calculated from the vital capacity and phonation time measures, whereas actual transglottal airflow was obtained from the flow waveforms recorded on the PAS system. Statistical analyses compared transglottal airflow rate measures as a function of instrument and separately as a function of gender.
Results. Statistically significant differences were present only as a function of gender on airflow measures but not as a function of the instrument. There were no interaction effects present between instrument and gender.
Conclusions. Phonation quotient can be used as an estimate of transglottal airflow in the absence of a pneumotachograph-based system.
Key Words: Transglottal airflow–Mean flow rate–Phonation quotient–Spirometer–PAS.

INTRODUCTION

An overarching goal for the use of multidimensional diagnostic tools during the clinical assessment of vocal function is to accurately detect and characterize the underlying physiological impairment causing dysphonia. These diagnostic tools often include the application of various patient history and self-perception survey tools, auditory-perceptual, tactile, laryngeal imaging, acoustic, and aerodynamic assessments.[1,2] Aerodynamic assessments can include measurements of lung capacity, phonation efficiency, subglottal pressure, and transglottal airflow (TAF).[3] The diagnostic value and importance of aerodynamic assessments for detecting and characterizing physiological impairments underlying dysphonia is supported through their inclusion by leading authorities as a recommended process for comprehensive voice evaluations.[4,5]

TAF is an aerodynamic phenomenon of phonation where pulses of air move through the glottis as the vocal fold tissue oscillates. As a clinical measurement, the rate of TAF represents the volume of air moving through the glottis and vocal tract over time during phonation, and is typically measured in liters per second (L/second) or milliliters per second (mL/second). Thus, the clinical measurement of TAF is a direct measure of an estimate of TAF. TAF and resulting measurements can be influenced by several factors, including respiratory driving pressure, glottal configuration, medial compression force, and tissue stiffness. TAF rates for healthy individuals have been reported within the approximate range of 70–200 mL/second.[3] Physiological impairments affecting the larynx can have a substantial influence on the characteristics of TAF. For example, pathologies resulting in glottal insufficiency (eg, adductor paralysis, vocal fold bowing) often result in elevated volumes of air flowing through the glottis and larger TAF rates.[6–8] Alternatively, impairments that add resistance to the glottal closure force (eg, muscle tension dysphonia) often result in lower TAF rates.[7,9,10]

Direct measurement of estimated TAF in the clinical setting can be acquired using pneumotach-based instrumentation (ie, a "pneumotachograph").[11–16] By eliciting expiration or phonation into a facemask, transducers positioned in line with the mask and pneumotach can measure the air pressure differential on either side of a resistive screen. The pressure differential and resistive properties of the screen can be used to calculate airflow by applying Ohm's law. Although available commercial systems from Glottal Enterprises Inc. or KayPentax Corp for direct measurement of TAF rate are characterized by detailed measurement precision, available technical support, and a robust body of scientific literature,[11–16] they are also expensive to acquire, which potentially makes them unavailable for many clinical practices.

As an alternative to direct measurements, indirect estimates of TAF using the phonation quotient (PQ) have also been used as a clinical aerodynamic measurement. PQ is derived from the ratio of vital capacity (VC) to maximum phonation time (MPT), as in the formula VC/MPT, and is reported in the same unit of measurement as direct TAF measurements (mL/second). PQ was originally described by Hirano et al[17] as a measure of air consumption during phonation. Although PQ often overestimates direct measures of TAF (the volume of air used during MPT trials is less than VC),[18] Hirano et al along with Rau and Beckett[19] found strong correlations between PQ and transglottal flow rates obtained from pneumotachographs. A robust body of scientific literature also supports the use of PQ for baseline measurements of estimated TAF rate and the response of PQ to treatment in dysphonic speakers.[1,18,20–23]

In a series of recent papers,[24,25] our research team has reported on the validity and reliability of low-cost handheld spirometers for measuring VC and the application of those spirometer-derived measures toward the calculation of PQ. Handheld spirometers typically utilize an internal turbine, which is

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responsive to airflow. As airflow moves the turbine, it rotates a dial across a visual measurement scale (ie, analog spirometers) or triggers a digital sensor (ie, digital spirometers) which records the total volume of expired air. VC using a specific low-cost analog handheld spirometer was found to be strongly associated with and not statistically different from VC measured from a pneumotach-based system for both male and female participants.[24,25] Subsequent measures of PQ using VC measures from the spirometer and pneumotachograph were also not statistically different.

Valid translation of PQ for representation of TAF necessitates comparisons to direct measurements such as those obtained from pneumotachograph-based instrumentation. It has been more than 30 years since such comparisons have been scientifically tested and reported in the literature. Comparisons of PQ to TAF have also not been validated against contemporary instrumentation. The purpose of this study was to compare indirect estimates of TAF using a handheld spirometer and derived measures of PQ with direct measures of TAF derived from a commercially available pneumotachograph. Based on previous findings, our hypothesis was that PQ associated with an analog handheld spirometer would not be significantly different from TAF derived from a pneumotachograph, for both male and female participants.

METHOD

Participants

A total of 38 participants, 19 male and 19 female, were recruited for this study. The participants were between 25 and 70 years of age and age-matched within a year for both genders. All participants had a perceptually normal voice quality (self-reported and verified by the lead author), and no self-reported history of smoking, voice, respiratory, pulmonary, neurological, or auditory disorders. The study was approved by the Institutional Review Board at the University of Houston and Texas Christian University.

Instruments

A low-cost handheld spirometer (<$300) and a pneumotachograph were the instruments utilized. The analog windmill-type (Baseline® Measurement Instruments, Fabrication Enterprises, Inc., White Plains, NY) was the spirometer used. The Phonatory Aerodynamic System (PAS) Model 6600 (KayPENTAX Corp, Lincoln Park, NJ; cost >$1000) was the pneumotachograph-based system of choice. A windmill spirometer consists of an analog dial, an internal resistance screen housed in a lightweight handheld plastic body, and a disposable mouthpiece. The quantity of air flowing through the mouthpiece can be read on the dial of the spirometer. This spirometer is capable of registering capacities up to 7000 mL. The PAS consists of a facemask connected to a pneumotach with inline sensors located on either side of an internal resistive screen. The transducers are connected to a desktop personal computer, where proprietary *PAS* software is used for recording and data analyses.

Both instruments were calibrated before use with each participant. The PAS flow head was calibrated as per the PAS Instruction Manual.[26] Calibration of the spirometer was also completed using the 1.0-L PAS calibration syringe.[24] The mouthpiece of the windmill spirometer was connected to the syringe with an adaptor and the plunger of the syringe was depressed. When an acceptable value was obtained (within 1% of 1.0 L), the calibration was completed.

Procedure

After consenting procedures, participants began the testing session by completing three trials of MPT followed by tasks on the aerodynamic instrumentation (windmill spirometer, PAS). The specific instructions for MPT elicitation were as follows: "I would like you to take a deep breath and produce the vowel /a/ for as long as you can, until you completely run out of air." The duration of the phonation produced was measured using a stopwatch on a smartphone. The order of the aerodynamic instruments was counterbalanced to prevent an order effect. Participants completed three trials of VC using the spirometer and completed the Comfortable Sustained Phonation Protocol on the PAS. Participants wore a disposable nose clip when using the spirometer to prevent any escape of air through the nose. Instructions for eliciting VC using the spirometer were as follows: "I would like you to inhale as deeply as possible, place your lips completely around the flow tube, and breathe out all of your air into the tube, until you have no air left." The Comfortable Sustained Phonation Protocol involved sustaining the /a/ vowel at comfortable pitch and loudness for 4 seconds per trial, from which the mean airflow rate (mL/second) was obtained. PQ values were obtained from the spirometer data by dividing the largest VC trial (milliliters) by the longest MPT (seconds). For a more detailed description on the procedure used for obtaining PQ, readers are referred to Joshi and Watts.[24,25]

Analyses

Statistical analyses were performed using *SPSS 23.0*.[27] The primary independent variable (factors) of the statistical model was instrument (windmill spirometer vs. PAS), whereas the dependent variable was TAF (in mL/second). To investigate the characteristics of the data set, we initially applied univariate analyses of variance (ANOVA) to data of participant age, MPT, VC, PQ, and TAF as a function of the gender of the speaker. To investigate the primary main effect, we subsequently applied a separate univariate ANOVA to the TAF data from the spirometer (PQ) and PAS for male and female participants.

RESULTS

Mean and standard deviations for age, MPT, spirometer-derived VC, PQ, and PAS-derived TAF for male and female participants are provided in Table 1. These data for age, MPT, and VC for both genders are graphically illustrated in Figure 1. As noted in Table 1, mean ages and MPT as a function of gender were not statistically different. As expected, VC data as a function of gender were statistically different. Results of an ANOVA for main effects of gender on age, MPT, VC, PQ, and airflow obtained on the PAS are provided in Table 1.

A one-way ANOVA for TAF revealed main effects for gender ($F = 25.332$, df = 1, $P < 0.001$) but not for instrument ($F = 0.237$, df = 1, $P = 0.627$). There was no interaction effect of gender and instrument. Descriptive analyses suggested that PQ measures of

TABLE 1.
Mean Values and Standard Deviations (SDs) and Analysis of Variance Results for Age, Maximum Phonation Time (MPT), Vital Capacity (VC), and Phonation Quotient (PQ) for Windmill Spirometer and Mean Airflow Rate Obtained on the Phonatory Aerodynamic System for Male and Female Participants

Measure	Gender	Mean	SD	*F*-Value	*P*-Value
Age (y)	Male	38.37	14.69	0.66	0.779
	Female	39.58	14.43		
MPT (s)	Male	25.00	8.00	0.105	0.748
	Female	24.26	5.87		
VC (mL)	Male	4955	1090	38.039	<0.001
	Female	3170	640		
PQ (mL/s)	Male	211.90	65.04	18.030	<0.001
	Female	136.88	41.25		
Mean airflow (mL/s)	Male	225.26	104.75	10.405	0.003
	Female	139.12	50.76		

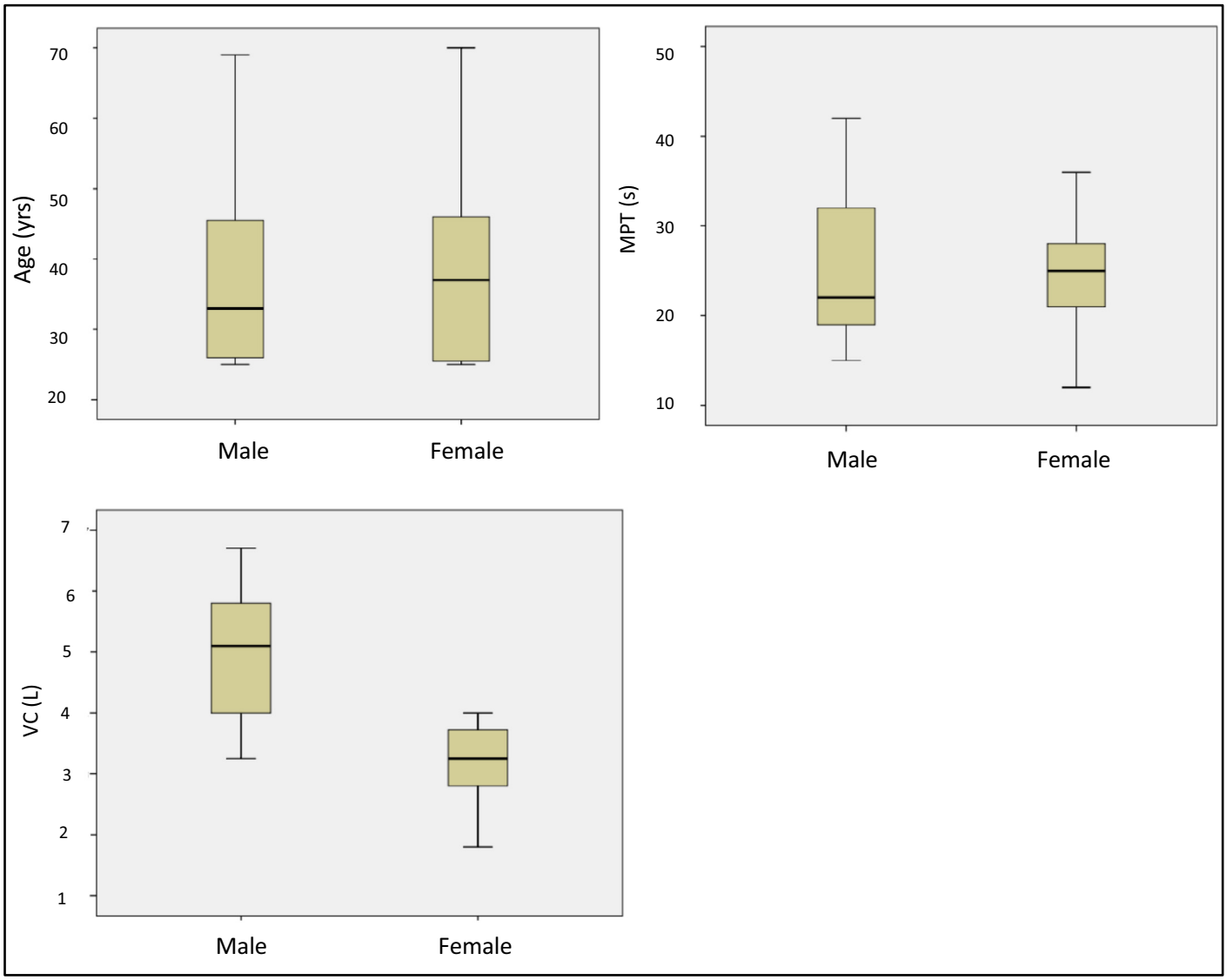

FIGURE 1. Box plots depicting age, maximum phonation time (MPT), and vital capacity (VC) as a function of gender.

male participants were substantially larger than that of female participants, which was supported by the greater VC measures in male participants (given a similar MPT measure, PQ will increase as VC increases). A similar trend was noted in the TAF data obtained from the PAS.

DISCUSSION

The purpose of this study was to compare indirect estimates of TAF using a handheld spirometer and derived measures of PQ with direct measures of TAF derived from a commercially available pneumotachograph. In our previous studies,[24,25] we compared the same handheld spirometer with the PAS and noted no statistical significance between PQ obtained on the two devices demonstrating good measurement reliability for the devices. Results in the current study indicated that indirect estimates of TAF in the form of PQ were not significantly different from direct measures of TAF using a pneumotachograph. The lack of statistical significance in the PQ and TAF data demonstrates the feasibility of using PQ as an estimate for TAF when a pneumotachograph based instrument is not available. This finding is important for clinicians that feel hampered by the lack of resources available and will allow them to perform an aerodynamic assessment with limited equipment. In addition, this study found a statistically significant difference in the PQ and mean airflow (from PAS) data as a function of speaker gender (male > female) in age-matched adults. This finding was consistent with previous literature, further validating the robustness of these data.[3,16,28]

A pneumotachograph-based system will continue to be the preferred instrument for aerodynamics for factors such as greater measurement precision, ease of calibration, and consistency of measurement across devices.[3,11,29] However, a low-cost analog spirometer, in this case a windmill-type, can be used to obtain measures of VC to subsequently derive PQ as an indirect estimate of airflow through the glottis during phonation. Even though measurement of subglottal pressure is an important aspect of aerodynamic assessment and cannot be measured with a spirometer, knowledge of VC and TAF provide substantial information on the respiratory system and its interaction with the laryngeal system. Integrating the results of aerodynamic assessments with visualization, acoustic and perceptual analyses will support comprehensive assessment, impairment detection, and characterization, and facilitate a more valid and potentially holistic treatment plan. PQ can also be used to monitor change and measure treatment outcomes.[1,18,20–23]

A number of limitations necessitate guarded generalizations. The results of this study are limited to the specific instruments utilized and clinicians should seek to collect normative data on their instruments of choice or ensure calibration of their instrumentation to ensure applicability of these findings to their instruments. Future studies should be performed with a wider variety of spirometers and with a disordered voice population to obtain disorder-specific data. The sample size of this study was relatively small for large-scale physiological generalizations, and studies incorporating large sample sizes should be conducted to determine if the findings reported can be replicated.

CONCLUSION

Estimated measures of TAF in the form of PQ obtained with a low-cost spirometer are a viable alternative in the absence of TAF measures obtained with a pneumotachograph-based system. Clinicians can utilize PQ, using a calibrated spirometer for VC and stopwatch or timer for MPT, as a measure of laryngeal aerodynamics. Gender has an effect on measures of VC, which will subsequently influence PQ measures. The findings of this study should be considered within the context of the study limitations.

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