Published in final edited form as:

J Speech Lang Hear Res. 2009 August ; 52(4): 1062–1072. doi:10.1044/1092-4388(2009/08-0110).

Phonation Threshold Pressure Measurement With a Semi-Occluded Vocal Tract

Ingo R. Titze

National Center for Voice and Speech, The Denver Center for the Performing Arts, Denver, CO, and The University of Iowa, Iowa City

Abstract

Purpose—The purpose of this article was to determine if a semi-occluded vocal tract could be used to measure phonation threshold pressure. This is in contrast to the shutter technique, where an alternation between a fully occluded tract and an unoccluded tract is used.

Method—Five male and 5 female volunteers phonated through a thin straw held between the lips. Oral pressure behind the lips was measured. Mathematical predictions of phonation threshold pressures were compared to the measured ones over a range of frequencies.

Results—It was shown that, for a 2.5-mm diameter straw, phonation threshold pressures were obtainable over a 2-octave range of fundamental frequency by all volunteers. In magnitude, the pressures agreed with the 0.2–0.5 kPa values obtained in previous investigations. Sensitivity to viscoelastic and geometric properties of the vocal folds was generally not compromised with greater oral impedance, but some differences were predicted theoretically in contrast to an open mouth configuration.

Conclusion—Because phonation threshold pressure is always dependent on vocal tract interaction, it may be advantageous to choose an exact and fixed oral semi-occlusion for the measurement and interpret the results in light of the known acoustic load.

Keywords

phonation; pressure measurement; semi-occluded vocal tract

Phonation threshold pressure (PTP), originally defined as oscillation threshold pressure (Titze, 1988), is the minimum lung pressure required to initiate vocal fold oscillation. It is based on an instability criterion for airflow in a soft-walled pipe that leads to flow-induced oscillation of the wall. In nonlinear dynamics, such an instability is typically associated with a Hopf bifurcation (Lucero, 1999), one in which damped oscillation (characterized by a point attractor in phase space) changes to self-sustained oscillation (characterized by a limit cycle attractor in phase space). This bifurcation is a key element in understanding the nature of vocal fold vibration. Its measurement, direct or indirect, holds much potential for

diagnosis of voice disorders because phonation near threshold involves the tissues that are generally affected by lesions, inflammation, and other tissue disorders.

A number of analytical treatments have been conducted to relate PTP to physical properties of the vocal folds and the vocal tract. Ishizaka and Matsudaira (1972) were the first to develop a criterion (the Routh-Horwitz criterion) for self-sustained oscillation. The mathematics did not lead to simple closed-form solutions because the equations were fourth-order, which made the criterion a little difficult to interpret in terms of fundamental tissue properties. Titze (1988) simplified the approach by assuming a mucosal surface wave propagating on the vocal folds and small-amplitude conditions. Inertive and resistive supraglottal acoustic loading conditions were included, and some simple closed-form analytical solutions were given for PTP as a function of vocal fold adduction, glottal convergence, vocal fold tissue damping, mucosal wave velocity, and vocal fold thickness and length.

Lucero (1996, 1998, 1999) extended the mucosal surface wave approach to include larger-amplitude oscillation and hysteresis effect between phonation onset and offset. He also optimized the results for the lowest PTP or the easiest phonation with a given set of mechanical and geometrical constants. More recently, Lucero and Koenig (2005) have extended the theory to include the fundamental frequency (F_0) dependency of PTP.

Chan and Titze (2006) developed additional closed-form relations in terms of G' and G'' , the elastic shear modulus and viscous shear modulus of the vocal folds. A physical model was constructed to test the theoretical results for viscoelastic materials resembling those found in vocal folds (fat, fibronectin, and hyaluronic acid). Measurement and prediction were in good agreement.

The latest theory about PTP includes both subglottal and supraglottal resistances and inertances (Titze, 2006). This theory is used in the current study. Oscillation is considered small-amplitude, without vocal fold collision.

At a clinical level, PTP has been measured as a function of F_0 and external hydration (Verdolini-Marston, Titze, & Drucker, 1990), as a function of vocal fatigue and systemic hydration (Solomon & DiMattia, 2000), as a function of phonatory effort and vocal loading (Chang & Karnell, 2004), as a function of aerosolized lubricants (Roy, Tanner, Gray, Blomgren, & Fisher, 2003), and as a function of oral breathing and superficial drying of the vocal fold mucosa (Sivasankar & Fisher, 2002). The technique used on human participants requires an indirect assessment of PTP because direct measurement of lung pressure is invasive. The indirect approach usually involves an oral pressure measurement during a brief occlusion of the vocal tract (the voiceless stop consonant /p/) followed by a vowel such as /æ/, with the assumption that the oral pressure during occlusion equals the lung pressure during the vowel. The validity of the technique was addressed by Smitheran and Hixon (1981) for super-threshold pressures, critiqued by Rothenberg (1981), readdressed by Hixon (1981), and applied by Fisher and Swank (1997). For threshold pressures, the technique has been technically revised by Jiang, O'Mara, Conley, and Hanson (1999) with amore controlled shuttering of the vocal tract.

An inherent problem is that PTP is dependent on the vocal tract acoustic load, as all of the theoretical and empirical results on models have shown. Thus, the choice of a vowel during the nonoccluded voicing segment cannot be arbitrary. For example, using the /p/ – /æ/ alternation may not yield the same results as the /p/ – /a/ alternation or the /p/ – /i/ alternation. Furthermore, any shuttering method that alternates between full occlusion of the mouth and a nonocclusion requires some steady plateaus to be reached in each segment. These plateau requirements force the participants to slow down the alternation rate. But if the alternation rate is too slow, the lung pressure in the voiced segment may not equal oral pressure in the occlusion segment. Smitheran and Hixon (1981) worked out a protocol for managing these temporal considerations for super-threshold measurements, but our experience has been that participants need considerable training in alternation rate and firmness of bilabial closure when thresholds are targeted. Hence, a more stable measurement with less articulatory variation is sought. More important, relating PTP to theoretical calculations requires an absence of vocal fold collision and small-amplitude vibration. The shuttering techniques have generally not been designed for these conditions, with the exception of Jiang et al.'s (1999) approach.

The present study was designed to answer the following questions: (a) Can a constant semi-occlusion (rather than an alternation between a full occlusion and a vowel) be used to measure PTP directly? (b) if so, does the measurement have a sensitivity to the changes in physical parameters of the vocal folds similar to PTP computed with a nonoccluded tract? and (c) can participants produce threshold conditions reliably with a semi-occlusion over a wide F_0 range? The objective in this article is not to compare the method to shuttering methods in terms of speed of measurement, reliability, etc., but simply to test the feasibility of this alternative technique. The direct clinical comparisons will follow in a later article.

Theoretical Background

Analytical calculations of PTP depend on the assumptions that (a) small amplitude oscillation occurs around a no-contact (abducted) vocal fold position and (b) a mucosal wave propagates along the medial surface of the vocal folds from bottom to top. Glottal airflow is never completely shut off because of the absence of collision. If vocal fold collision was to occur, the mean displacement of vocal fold tissues would be amplitude dependent, making the analytical treatments much more difficult. To set up this small amplitude and vocal fold separation condition in human phonation, a semi-occlusion in the vocal tract is created so that the combination of a positive supraglottal pressure and a positive subglottal pressure maintains a mean positive intraglottal pressure throughout the cycle. This mean positive pressure in the glottis then keeps the vocal folds separated.

Steady-Flow Conditions and Vocal Fold Separation

Phonation into a narrow straw placed between the lips can produce the desired semi-occlusion and, there-with, the desired vocal fold separation. Consider the simple steady-flow circuit of Figure 1. R_o is the oral semiocclusion resistance, R_g is the glottal resistance, R_e is the epilaryngeal resistance (false folds up to aryepiglottic folds), P_o is the oral pressure, P_i is the input pressure to the vocal tract, P_{tg} is the transglottal pressure, and P_L is the lung pressure. Because R_o is chosen to be relatively high (e.g., a thin flow-resistant straw), any

other steady flow resistance in the vocal tract between the aryepiglottic folds and the lips is negligible.

The mean intraglottal pressure has been derived previously (Titze, 1988),

$$P_g = P_L \left(\frac{a_1 - a_2}{a_1} \right) + P_i \frac{a_2}{a_1}, \quad (1)$$

where a_1 is the glottal entry area (where the mucosal wave motion begins inferiorly on the vocal fold), and a_2 is the glottal exit area. From the flow circuit, the pressure into the vocal tract is

$$P_i = \frac{R_e + R_o}{R_g + R_e + R_o} P_L \quad (2)$$

and the intraglottal pressure is related to vocal fold stiffness as

$$P_g = \frac{K\bar{x}}{LT}, \quad (3)$$

where $\bar{x}$ is a steady outward vocal fold displacement when intraglottal pressure builds up, K is the stiffness of the vocal fold tissue, L is the vocal fold length, and T is the vocal fold thickness.

With this steady outward displacement, the glottal entry and exit areas can further be written as

$$a_1 = 2L (x_{01} + \bar{x}) \text{ and} \quad (4)$$

$$a_2 = 2L (x_{02} + \bar{x}), \quad (5)$$

where x_{01} is the neutral position (relative to the glottal midplane) of the bottom of the vocal fold before pressure P_g is applied, and x_{02} is the neutral position of the top of the vocal fold before pressure is applied.

Substituting Equations 2-5 into Equation 1 yields a nonlinear equation in $\bar{x}$:

$$(x_{01} + \bar{x}) \frac{K\bar{x}}{LT} = P_L \left[x_{01} - x_{02} + \frac{R_e + R_o}{R_g + R_e + R_o} (x_{02} + \bar{x}) \right]. \quad (6)$$

For any lung pressure P_L and a given neutral vocal fold configuration, the lateral displacement of the tissue can be computed. The equation is at least quadratic but can be of higher order if the tissue stiffness K is dependent on x . In the remainder of the derivations, a nonlinear stiffness was chosen to be of the form

$$K_{nl} = K (1 + 100\bar{x}^2). \quad (7)$$

Also, the steady flow resistances R_o , R_g , and R_e will be shown to be nonlinear with flow (and hence with P_L), which further complicates an algebraic solution.

A very simple algebraic solution results, however, if the oral occlusion resistance R_o is much greater than the laryngeal resistances R_g and R_e , and if K was to be a linear spring constant. Then Equation 6 yields

$$\bar{x} = LT P_L / K \quad R_o \gg R_g + R_e, \quad (8)$$

which shows that the vocal folds tend to be separated beyond their neutral position in proportion to the lung pressure and inversely in proportion to vocal fold stiffness. Byway of an example, if $P_L = 0.6$ kPa (6,000 dyn/cm²), $L = 1.0$ cm, $T = 0.5$ cm, and $K = 30$ N/m (30,000 dyn/cm), then $\bar{x} = 0.1$ cm or 1.0 mm. This is a relatively large separation (2-mm glottal gap) that would probably not occur near threshold. We show that threshold pressures are usually between 0.3 and 0.5 kPa. A 2-mm separation also does not occur because the spring constant is nonlinear. Suffice it to say that a significantly large resistance R_o as an oral semi-occlusion can create and maintain a noncontact condition if vibrational amplitudes are kept small.

Steady Flow Resistances of Straws and Laryngeal Structures

In earlier work on the use of flow-resistance straws for vocal warm-ups (Titze et al., 2002), the steady pressure-flow characteristics of seven commercially available straws were measured. The inside diameter of the straws ranged from 2.0 to 7.5 mm, and length ranged from 11.5 to 30 cm. Figure 2a shows the pressure-flow data (seven solid lines with asterisks as data points) along with a mathematical model developed from basic fluid mechanics (dashed lines), written as

$$P = k_c \frac{1}{2} \rho \frac{U^2}{A^2} + 128 \mu l \frac{U}{d^4}. \quad (9)$$

In the above equation, P is the pressure at the mouth end of the straw, k_c is a contraction coefficient that has been empirically determined, ρ is the density of air (1.14 kg/m³), U is the steady flow, A is the cross-sectional area of the straw, μ is the viscosity of air (0.0186 cp), l is the straw length, and d is the straw diameter. The two individual terms in Equation 9 are known as the *kinetic entry pressure loss* and the *viscous pressure loss*, respectively, for a circular cross-section tube (White, 2002). Note that for a circular cross-section straw, the viscous resistance is inversely proportional to the fourth power of the diameter and directly proportional to the straw length. The kinetic term appears also to be inversely related to the fourth power of the diameter because $A = \pi (d/2)^2$. But this relation is modified by the contraction coefficient, which for an overall best match to this data set was determined to be

$$K_c = 1.6 \left(\frac{d}{2.0} \right), \quad (10)$$

where d is in mm. Thus, the true dependence of the kinetic term on diameter is $1/d^3$. The match of Equation 9 to the data is not without the potential for improvement but is sufficient for the present study.

The steady pressure-flow relations for laryngeal resistances were measured by Alipour, Scherer, and Knowles (1996) and by Alipour, Jaiswal, and Finnegan (2007). Figure 2b shows data from the second of the two studies that differentiated laryngeal resistance into (a) glottal resistance only (lower data points) and (b) glottal resistance plus the ventricular fold structures (upper data points). Note that the total laryngeal resistance increases when the false folds are included. In Alipour et al.'s (2007) study on excised canine larynges, the epilaryngeal structures were systematically dissected away, first the epiglottis and then the false folds. But there was no direct control over the adduction of the false folds and the aryepiglottic folds. In some cases (F. Alipour, personal communication, October 15, 2008), the false folds or the aryepiglottic folds began to oscillate, which could overestimate the resistance to the steady flow component.

It is interesting to note that the pressure-flow curves for laryngeal tissues are nearly linear (as opposed to quadratic for the straws). This near linearity comes from the fact that the tissue walls yield with increasing pressure (Equation 8), thereby creating a greater opening and a greater flow for a given pressure than in a rigid tube. A model of this linearization is produced as follows. Assume that an equation similar to Equation 9 holds for the laryngeal airway, one kinetic term representing glottal entry, another kinetic term representing false fold entry, and a viscous term representing the pressure loss through the epilarynx tube, which is about 2–3 cm long. Instead of a circular cross-section, the glottis is rectangular, and the area A can be written as the glottal exit area a_2 according to Equation 5. The trans-laryngeal pressure P_{tl} then becomes

$$P_{tl} = k_{c1} \frac{1}{2} \rho \frac{U^2}{4L^2 (x_{02} + \bar{x})^2} + k_{c2} \frac{1}{2} \rho \frac{U^2}{\pi^2 (d_e/2)^4} + 128\mu L_e \frac{U}{d_e^4}. \quad (11)$$

In the above, k_{c1} and k_{c2} are again entry pressure coefficients, L_e is the epilarynx tube length, and d_e is an equivalent circular epilarynx tube diameter for a tube that has rather complicated geometry from the false folds to the rim of the epiglottis. For $k_{c1} = k_{c2} = 1.0$ and $L_e = 2.5$ cm, Figure 2b shows the trans-laryngeal pressure flow predictions (lower two dashed lines going through the data points).

The steep dashed curve above the data points is not intended to be a match to the data set but represents a hypothetical high-wall-stiffness case for which the glottal wall yields very little ($x \approx 0.05$ mm with $K = 1,000$ N/m and 1 kPa of wall pressure). For this stiff-walled case, the epilarynx tube diameter was also chosen to have a large diameter, $d_e = 20$ mm, so that the laryngeal resistance comprised only the glottal resistance (first term in Equation 11). The pressure-flow curve for this high-wall-stiffness case is then nearly quadratic, resembling the straw pressure-flow curves. If the vocal fold tissue were to vibrate at this high stiffness, the F_0 would be 700 Hz, assuming a vibrating mass of 0.05 g (1.0 cm length $\times$ 0.5 cm thickness $\times$ 0.1 cm depth $\times$ 1.0 g/cm³ density).

At most speech fundamental frequencies, however, the tissue is much more yielding, as the lower curves indicate. The excised canine vocal folds in Alipour et al.'s (2007) study oscillated around 150 Hz on a laboratory bench. To model this data set, the epilarynx tube diameter was chosen to be 7 mm (uniform from false folds to the tip of the epiglottis, which is a major simplification), and the vocal fold stiffness K was chosen to be 50 N/m to obtain a mass-spring natural frequency of 150 Hz. For this stiffness, Equation 7 suggests that the lateral displacement x of the vocal folds to be 1.0 mm at 1.0 kPa of wall pressure, which is 20 times greater than for the stiff wall. Note again that the pressure-flow curves now have a lesser and more constant slope (or even bend slightly downward) because of this large yielding wall effect.

Figure 3 shows theoretical computations (with all foregoing equations) of how pressures are distributed in the vocal tract with different “straws” at the mouth. Each family of five curves represents straw diameters of 1.5, 3.0, 4.5, 6.0, and 7.5 mm, respectively. Straw length was kept constant at 10 cm in all calculations. For the smallest-diameter straw (1.5 mm), there is a 1:1 correspondence between oral pressure P_o and lung pressure P_L (see Figure 3a), as shown by the top diagonal line. This means that laryngeal resistances are completely negligible in the flow circuit of Figure 1. The input pressure to the vocal tract, defined as P_i in Figure 1, is also equal to P_L . This is shown in the top line of Figure 3b. Likewise, the intraglottal pressure P_g , which drives the vocal folds apart, is equal to the lung pressure, as shown in Figure 3f. Equation 1 confirms this; when $P_i = P_L$, then $P_g = P_L$, regardless of the entry and exit areas. Figure 3e shows how the vocal folds are driven apart laterally with a displacement x , ranging between 0.0 and 1.0 mm with increasing lung pressure.

The high oral pressure at the straw reduces the transglottal pressure P_{tg} to essentially zero (see Figure 3d, lowest curve). This situation of high intraglottal pressure and low transglottal pressure is ideal for sensing PTP with a semi-occlusion at the mouth. Since $P_o = P_L$, a measurement of P_o is a direct measurement of PTP if a threshold condition can be established with the straw. As straw diameter increases above 1.5 mm, some departures from ideal conditions are seen. The best metric for this is the resistance ratio

$$r = \frac{R_e + R_o}{R_g + R_e + R_o}, \quad (12)$$

which was previously discussed with regard to Equation 6. Note that this ratio reduces systematically from the ideal value of 1.0 to values less than 0.5 (see Figure 3c) when the straw diameter is increased from 1.5 mm to 7.5 mm. Correspondingly, the vocal tract pressures P_o , P_i , and P_g are no longer equal to P_L with greater straw diameter but are a fraction of it. Note also that the transglottal pressure P_{tg} rises sharply with increasing straw diameter (see Figure 3d).

PTP Changes With Physical Parameters

Mathematical derivations (Titze, 1988, 2006) have shown that PTP increases with vocal fold abduction, glottal convergence, supraglottal resistance, tissue viscosity, and mucosal wave velocity. Conversely, PTP decreases with vocal fold thickness and supraglottal vocal tract inertance. Because supraglottal resistance and supraglottal inertance change PTP in opposite

directions, the expectation is that the two effects might offset each other (to some degree) with the use of a straw, leaving threshold pressures in the normal 0.0–0.5 kPa range.

Figure 4 shows supraglottal impedance calculations (right panel) for vocal tract shapes (left panel) without a straw and with five different straw diameters. The calculations follow those of Story, Laukkanen, and Titze (2000). The straw length is 10 cm, and straw diameters range from 1.5 mm (bottom) to 7.5 mm (second from top). Thick lines are reactances, and thin lines are resistances for oscillatory (acoustic) pressure-flow relations in the tubes. The horizontal axis is logarithmic frequency. The four vertical straight lines indicate F_0 , $2F_0$, $3F_0$, and $4F_0$ for a 150-Hz frequency of oscillation. The formant frequencies of the combination of a neutral vocal tract and a straw occur where the resistances have local peaks and where the reactances change direction. Note that all straws cause F_1 to drop below 220 Hz, but the thinnest straw lowers F_1 to about 130 Hz. For the no-straw condition (top row), F_1 is at 500 Hz, as expected for a 17.5-cm vocal tract length with uniform cross-section.

Using these impedances, Figure 5 shows PTP calculations as derived by Titze (2006, pp. 363–366) for the no-straw condition and the thinnest (1.5-mm) straw. There are multiple simultaneous equations to be solved for P_{th} . (P_{th} is the mathematical symbol used for PTP.) In the interest of space, the equations are not repeated here. Reactances from Figure 4 were divided by $2\pi F_0$ to obtain inertance for the calculations. Each of the curves shows the sensitivity of P_{th} to a physical parameter of the vocal folds, namely (a) glottal convergence, (b) vocal fold abduction (prior to phonation), (c) damping ratio of the vocal folds, (d) mucosal wave velocity, (e) epilaryngeal tube diameter, and (f) vocal fold thickness. Dashed lines are for no straw, and solid lines are for the thinnest 1.5-mm diameter straw. Note that in some cases, the sensitivity to the physical properties is reduced with the use of the very thin straw, but in other cases, it is increased. The sensitivity to glottal convergence is not changed much, the sensitivity to vocal fold abduction (prior to phonation) is reduced, the sensitivity to damping ratio is not affected, the sensitivity to mucosal wave velocity is increased, the sensitivity to epilarynx tube diameter is reduced, and the sensitivity to vocal fold thickness is increased. Thus, the theory predicts that a P_{th} measurement with an open mouth is not more diagnostic of changes in vocal fold parameters than a P_{th} measurement with a straw.

Figure 6 shows a scatter plot of the oral pressure P_o versus P_{th} for all the data calculated in Figure 5 (6 parameters $\times$ 5 values each = 30 data points). Note that all points fall on a diagonal line, indicating that oral pressure is indeed a direct measure of P_{th} when the straw resistance is high.

Measurement on Human Participants

Ten adult volunteers (5 males, 5 females) were recruited. Each volunteer phonated into the straw with the lowest possible intensity for which voicing could be maintained (just above threshold). Male volunteers phonated at pitches A_2 (110 Hz), E_3 (165 Hz), A_3 (220 Hz), E_4 (330 Hz), and A_4 (440 Hz), whereas female volunteers phonated at pitches E_3 (165 Hz), A_3 (220 Hz), E_4 (330 Hz), A_4 (440 Hz), and E_5 (660 Hz). The duration of each phonation was on the order of 3–5 s. A nose clamp was used to ensure that the velum was closed (no air

leakage through the nose). They were instructed to keep their lips firmly sealed around a 2.5-mm diameter stirring straw (13.0 cm in length). A plastic tube (1.5 mm in diameter) was also held between the lips, at the corner of the mouth, to measure oral pressure. The system for pressure measurement was the Glottal Enterprises PTW-1 transducer with the MS-100A2 electronics. An electroglottograph (EGG) system was also used to infer vocal fold contact area (Kay Elemetrics Model 6103; Kay Elemetrics, Lincoln Park, NJ).

There were five repetitions for each pitch. Hence, each participant produced 25 threshold pressure values. Figure 7 shows the results. Male participants are represented in the top row and female participants in the bottom row. Means and standard deviations (*SDs*) across the five tokens on each frequency were calculated. Figure 7(a, c) shows the mean values in kPa, and Figure 7(b, d) shows the corresponding *SDs*. Note that threshold pressures at low frequencies are in the range predicted (0.2–0.5 kPa). They also agree (in range) with typical values measured with the shuttering technique (Jiang et al., 1999; Chang&Karnell, 2004; Fisher&Swank, 1997). All male volunteers could obtain PTP values over a two-octave pitch range with the straw, but 1 male volunteer noted difficulty with the high frequencies (circle data points). His PTP values were comparatively large at 330 and 440 Hz.

Another male volunteer (triangle data points) had one peculiarly high PTP at 220 Hz. This value was rechecked and confirmed not to be a random or systematic instrumentation error. Apparently, this male volunteer used a lot of inertive vocal tract reactance to maintain the lower PTP values below 200 Hz, but when vocal tract reactance changed above the first resonance of the vocal tract–straw combination (see Figure 4, right side), his PTP increased. This may give support to the concept that PTP is sensitive to vocal tract acoustic loading, at least for some individuals.

Female volunteers were divided into two groups. Three females kept their PTP values below 0.4 kPa throughout the entire two-octave range. One of these females had a monotonically decreasing PTP with increasing frequency (triangle data points). Two females had peculiarly high PTP values over the entire range of frequencies. They were totally uninitiated to straw phonation and may have overblown the threshold condition, despite the instructions. The broad increase and decrease of PTP values around 440 Hz for 4 of the 5 females may also be related to vocal tract reactance. Again referring to Figure 4 (right panel), the first and second harmonic would be riding on the upslope of F_2 , which is inertive reactance territory. The reactance increases dramatically after 440 Hz for both F_0 and $2F_0$, which may account for the lowering of PTP in most of the female participants at 660 Hz. The details of PTP dependency on vocal tract loading will be dealt with in subsequent investigations.

As a final data set, we show samples of the EGG waveforms with straw phonation for 1 participant at all five frequencies (see Figure 8). In addition, one control waveform (see Figure 8f) for phonation without a straw is shown. Note that the contact waveforms with the straw are all near-sinusoidal, suggesting little or no impulse-like contact between the vocal folds. In contrast, the phonation sample without a straw shows the typical impulse-like contact. Inspection of the EGG waveforms of all other participants showed similar results.

Conclusions

Current approaches to PTP measurement use a shuttering technique that involves alternation of fully occluded and nonoccluded vocal tracts. The technique was designed primarily for super-threshold lung pressure estimation. Because of the dynamics of lip and jaw movement during shuttering, steady-state pressure plateaus are difficult to maintain for accurate measurement at threshold. The semi-occluded vocal tract technique, with the use of a thin straw, eliminates the articulatory movement (or mechanical shuttering as proposed by Jiang et al., 1999) and allows a steady-state measurement. EGG recordings show that the vocal folds are separated, and threshold conditions guarantee small amplitude oscillation. For a direct equivalence between oral pressure and PTP, the flow resistance of the straw must be much larger than the internal resistances of the glottis and epilaryngeal structures. Given that the laryngeal resistances may vary from person to person, the straw resistance requirement may be higher for some individuals than for others. Generally, an inside diameter of 1.5–3.0 mm tends to satisfy the high resistance criterion, but more participants need to be tested. All 10 participants in this study were able to phonate over a two-octave range with a 2.5-cm straw. Thus, the questions about feasibility have been answered.

There is no question that the straw alters the vocal tract acoustic impedance and, hence, the frequency dependence of PTP. There was considerable intersubject variability, both in terms of the average PTP and its change with F_0 . Most previous measurements have shown a monotonic rise in PTP with F_0 . Our measurements show that there may be peaks and valleys, depending on the degree to which an individual uses source–filter interaction in phonation. We suspect that those who use little interaction will have a fairly monotonic change with F_0 , whereas those who use much source filter interaction will show peaks and valleys. With carefully controlled acoustic loading, the sensitivity of PTP to vocal fold viscoelasticity and geometry may be exploited. But acoustic loading may also get in the way of resolving changes that are solely related to vocal fold viscoelasticity. A next step would be to test PTP values of a single individual before and after some acute change in vocal fold tissues has occurred. Smaller frequency steps should be taken to determine where the sensitivity to viscoelastic changes is the greatest.

Acknowledgments

This work was supported by National Institute on Deafness and Other Communication Disorders Grant 5R01 DC004224-08.

References

- Alipour F, Jaiswal S, Finnegan E. Aerodynamic and acoustic effects of false vocal folds and epiglottis in excised larynx models. *Annals of Otology, Rhinology, and Laryngology*. 2007; 116:135–144.
- Alipour F, Scherer R, Knowles J. Velocity distributions in glottal models. *Journal of Voice*. 1996; 10:50–58. [PubMed: 8653178]
- Chan R, Titze IR. Dependence of phonation threshold pressure on vocal tract acoustics and vocal fold tissue mechanics. *The Journal of the Acoustical Society of America*. 2006; 119:2351–2362. [PubMed: 16642848]
- Chang A, Karnell MP. Perceived phonatory effort and phonation threshold pressure across a prolonged voice loading task: A study of vocal fatigue. *Journal of Voice*. 2004; 18:454–466. [PubMed: 15567047]

- Fisher KV, Swank PR. Estimating phonation threshold pressure. *Journal of Speech, Language, and Hearing Research*. 1997; 40:1122–1129.
- Hixon T. A reply to Rothenberg. *Journal of Speech and Hearing Disorders*. 1981; 47:218–224.
- Ishizaka, K.; Matsudaira, M. Fluid mechanical consideration of vocal fold vibration (SCRL Monograph 8). Santa Barbara, CA: Speech Communication Research Laboratory; 1972.
- Jiang J, O'Mara T, Conley D, Hanson D. Phonation threshold pressure measurements during phonation by airflow interruption. *Laryngoscope*. 1999; 109:425–432. [PubMed: 10089970]
- Lucero JC. Relation between the phonation threshold pressure and prephonatory glottal width in a rectangular glottis. *The Journal of the Acoustical Society of America*. 1996; 100:2551–2554. [PubMed: 8865659]
- Lucero JC. Optimal glottal configuration for ease of phonation. *Journal of Voice*. 1998; 12:151–158. [PubMed: 9649070]
- Lucero JC. A theoretical study of the hysteresis phenomenon at vocal fold oscillation onset-offset. *The Journal of the Acoustical Society of America*. 1999; 105:423–431. [PubMed: 9921668]
- Lucero JC, Koenig LL. Phonation thresholds as a function of laryngeal size in a two-mass model of the vocal folds. *The Journal of the Acoustical Society of America*. 2005; 118:2798–2801. [PubMed: 16334896]
- Rothenberg M. Interpolating subglottal pressure from oral pressure. *Journal of Speech and Hearing Disorders*. 1981; 49:220–221.
- Roy N, Tanner K, Gray S, Blomgren M, Fisher K. An evaluation of the effects of three laryngeal lubricants on phonation threshold pressure (PTP). *Journal of Voice*. 2003; 17:331–342. [PubMed: 14513956]
- Sivasankar M, Fisher KV. Oral breathing increases Pth and vocal effort by superficial drying of vocal fold mucosa. *Journal of Voice*. 2002; 16:172–181. [PubMed: 12150370]
- Smitheran J, Hixon T. A clinical method for estimating laryngeal airway resistance during vowel production. *Journal of Speech and Hearing Disorders*. 1981; 46:138–146. [PubMed: 7253590]
- Solomon N, DiMattia MS. Effects of a vocally fatiguing task and systemic hydration on phonation threshold pressure. *Journal of Voice*. 2000; 14:341–362. [PubMed: 11021502]
- Story B, Laukkanen A-M, Titze IR. Acoustic impedance of an artificially lengthened and constricted vocal tract. *Journal of Voice*. 2000; 14:455–469. [PubMed: 11130104]
- Titze IR. The physics of small amplitude oscillation of the vocal folds. *The Journal of the Acoustical Society of America*. 1988; 83:1536–1552. [PubMed: 3372869]
- Titze, IR. The myoelastic-aerodynamic theory of phonation. Denver, CO: National Center for Voice and Speech; 2006.
- Titze IR, Finnegan E, Laukkanen A-M, Jaiswal S. Raising lung pressure and pitch in vocal warm-ups: The use of flow resistant straws. *Journal of Singing*. 2002; 58:329–338.
- Verdolini-Marston K, Titze IR, Drucker DG. Changes in phonation threshold pressure with induced condition of hydration. *Journal of Voice*. 1990; 4:142–151.
- White, FM. Fluid mechanics. 5. New York: McGraw-Hill Professional; 2002.

Figure 1.

Steady flow circuit for a semi-occluded vocal tract. P_{tg} = transglottal pressure; P_L = lung pressure; R_g = glottal resistance; P_i = vocal tract input pressure; R_e = epilaryngeal resistance (false folds up to aryepiglottic folds); P_o = oral occlusion pressure; R_o = oral semi-occlusion resistance.

Figure 2.

(a) Steady pressure-flow relations for seven straws (solid lines with asterisks) and Equation 9 (dashed lines) as a mathematical model. (b) Laryngeal pressure-flow relations as measured by Alipour et al. (2007) and Equation 11 (dashed lines) as a mathematical model. L/s = liters per second.

Figure 3.

Calculation of several aerodynamic variables from Figure 1 as a function of lung pressure, with straw diameter as a parameter to define a family of curves: (a) oral pressure P_o at straw input, (b) vocal tract input pressure P_i , (c) resistance ratio as defined in Equation 12, (d) transglottal pressure P_{tg} , (e) vocal fold separation x , and (f) intraglottal driving pressure P_g . dia = diameter; VF = vocal fold.

Figure 4.

Impedance calculations for a neutral vocal tract with various straw diameters and no straw (top).

Figure 5.

Phonation threshold pressure ($P_{th} = \text{PTP}$) calculations for six laryngeal parameters: (a) glottal convergence, (b) pre-phonatory abduction, (c) tissue damping ratio, (d) mucosal wave velocity, (e) epilarynx tube diameter, and (f) effective vocal fold thickness.

Figure 6.
Scatter plot of oral pressure P_o at straw input versus lung pressure at threshold conditions.

Figure 7.

Phonation threshold pressure (PTP) measured on 5 male volunteers (top) and 5 female volunteers (bottom) as a function of frequency. There were five repetitions per frequency to obtain mean PTP values (left panels) and *SDs* (right panels).

Figure 8.

Electroglottographic (EGG) waveforms from 1 male volunteer at five frequencies with straw phonation and at a typical speech frequency without the straw.