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Measurement Reliability of Phonation Threshold Pressure in Pediatric Subjects

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**Objectives/Hypothesis:** Phonation threshold pressure (PTP), the minimum subglottal pressure (Ps) required for phonation, is sensitive to changes in laryngeal biomechanics and is often elevated with pathology. Little is reported on PTP in children; challenges with task performance and measurement reliability represent barriers to routine clinical assessment.

**Study Design:** Pilot study evaluating PTP and Ps measurement reliability in children using labial and mechanical interruption.

**Methods:** Twenty-two subjects aged 4 to 17 years (10.7 ± 3.9 years) participated. Ten trials were performed for each method; task order was randomized. For labial interruption, subjects produced /p/ five times at softest (onset PTP) and comfortable amplitude. For mechanical interruption, subjects produced a sustained /α/ while a balloon valve interrupted phonation five times for 250 ms each; mechanical interruption was performed with a mouthpiece and mask. PTP was recorded as the difference between Ps and supraglottal pressure at phonation cessation (offset PTP). Mean PTP and Ps and intrasubject coefficients of variation were compared. Correlations with age were evaluated.

**Results:** Mean PTP (P < .001) and Ps (P = .005) were higher for labial interruption. Intrasubject coefficients of variation for PTP (P = .554) and Ps (P = .305) were similar across methods. Coefficient of variation was related to age for mechanical-mask trials only (r = −0.628, P = .00175).

**Conclusions:** Differences in means are likely related to differences in task and PTP hysteresis effect. Reliability is comparable with all methods; using a mouthpiece may be preferable to a mask for mechanical interruption. Measurement of PTP is noninvasive, reliable, and may be a useful adjunct in pediatric voice assessment.

**Key Words:** Phonation threshold pressure, pediatric, aerodynamic, subglottal pressure, voice, airflow interruption.

**Level of Evidence:** 3b

**INTRODUCTION**

Pediatric dysphonia is common. Prevalence rates vary, with estimates of 1% based on the 2012 National Health Interview Survey and 6% for a large cohort of 8-year-olds in the United Kingdom. Children with dysphonia experience anxiety, discomfort, anger, sadness, and frustration. Assessment should include videostroscopic, perceptual, acoustic, and aerodynamic evaluations.

Pediatric Subjects

Aerodynamic parameters quantify the inputs to voice production, provide insight into the effort required to produce speech, and represent an important aspect of pediatric voice evaluation. Complete assessment requires measurement of subglottal pressure (Ps) and phonation threshold pressure (PTP).

PTP is the minimum Ps required to initiate vocal fold oscillation. It is dependent on vocal fold thickness, tissue damping coefficient, prephonatory glottal width, and mucosal wave velocity. Multiple studies have demonstrated elevated PTP in disease states, including vocal fatigue, vocal fold scar, benign mass lesions, and dehydration. Though a potentially useful component of voice assessment, standard implementation is limited in part by measurement reliability.

The most commonly used method of noninvasive Ps measurement is labial interruption, or measurement of intraoral pressure during repeated utterances of /p/ or /pa/. During the bilabial stop phase of /p/, intraoral pressure equilibrates with Ps. This allows for indirect, noninvasive estimation of Ps. This method is accurate; however, it can be somewhat challenging to master the technique and obtain consistent results. Furthermore, to estimate PTP, the subject must produce serial utterances at their softest level. This study was funded by grant number R01 DC008153 from the National Institutes of Health, National Institute on Deafness and other Communicative Disorders, and the Diane M. Bless Endowed Chair, Division of Otolaryngology–Head and Neck Surgery at the University of Wisconsin–Madison, Madison, Wisconsin, U.S.A.

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An alternative method is mechanical interruption. This approach uses an external mechanical valve to temporarily interrupt subject airflow, thus allowing for equilibration of supraglottal pressure with $P_s$; pressure is then measured within the device.\textsuperscript{19,20} Jiang et al. presented a modification that allowed for measurement of PTP, recorded as $P_s$ minus the supraglottal pressure at the time that phonation ceases during the interruption.\textsuperscript{20} This method has been used to demonstrate differences in laryngeal function in Parkinson’s disease\textsuperscript{21} and vocal fold nodules,\textsuperscript{12} but has never been applied to pediatric subjects.

Chapin et al. compared labial and mechanical interruption for measurement reliability of $P_s$, mean flow rate, and laryngeal resistance in adult subjects with normal voice.\textsuperscript{22} Intrasubject variability was compared for each parameter. Mean intrasubject variability was similar for $P_s$ and mean flow rate, but higher for laryngeal resistance with the labial interruption technique. PTP was not evaluated.

Importantly, PTP exhibits a hysteresis effect, where the minimum pressure required to initiate phonation (onset PTP) is lower than that required to sustain it (offset PTP).\textsuperscript{9,23} This has been demonstrated in mathematical models,\textsuperscript{9,24,25} physical models,\textsuperscript{9} and excised larynx experiments.\textsuperscript{9,24} Measurement of PTP via labial interruption at the point of softest phonation represents an onset pressure, whereas measurement of PTP via mechanical interruption at the time phonation ceases represents an offset pressure. This is important to consider when comparing mean values between the two methods.

There have been prior large-scale studies evaluating aerodynamic parameters in children\textsuperscript{26} but few studies reporting specifically on PTP. McAllister and Sundberg used labial interruption at softest phonation to measure PTP in seven children, with a mean of 3.6 cm H$_2$O without specifically reported intrasubject or intersubject variability.\textsuperscript{27} Stathopoulos and Sapienza measured $P_s$ in 20 children aged 4 years and 20 children aged 8 years at three vocal intensities, with the lowest being 5 dB below the subjects’ comfortable SPL.\textsuperscript{28} Mean pressure at the soft intensity was approximately 6 cm H$_2$O, but may have been above the phonation threshold. Hsu et al. measured multiple voice parameters including PTP in Mandarin-speaking children after cochlear implantation as well as a group of normal controls.\textsuperscript{29} PTP was measured via production of serial /pi/ tokens and found to be higher in the implanted subjects.\textsuperscript{29} Intersubject variability was fairly low (4.6 ± 1.4 cm H$_2$O for implanted subjects vs. 2.6 ± 0.4 cm H$_2$O for controls), but intrasubject variability was not reported.

In this study, we conducted an initial pilot study measuring PTP and $P_s$ in children aged 4 to 17 years using both mechanical interruption (with a mouthpiece and a mask) and labial interruption. This is the first application of mechanical interruption to pediatric subjects and the first study to date in pediatric subjects focusing specifically on PTP measurement reliability. We compared measurement reliability using both mechanical and labial interruption methods. It may be easier for children to produce the sustained vowel required for mechanical interruption, but they may be more easily startled or distracted by the balloon valve interruption. On the other hand, children may find it challenging to maintain consistency with repeated labial plosives or have difficulty achieving the softest possible phonation, but may prefer the more predictable nature of a subject-controlled interruption. As a component within this aim, we evaluated whether mechanical interruption with a mask versus a mouthpiece was more reliable for measurement of PTP. We evaluated how measurement reliability changed with increasing age.

First, we hypothesized that measurement reliability for mechanical interruption would be higher with a mouthpiece rather than a mask, as obtaining a tight seal with a mask may be more challenging with children. Second, we hypothesized that measurement reliability would be comparable for the mechanical and labial approaches, but mean PTP would be lower for mechanical interruption, as it represents an offset PTP and is not dependent on production of softest possible phonation. Last, we hypothesized that measurement reliability would improve with increasing age.

**MATERIALS AND METHODS**

**Subjects**

This study was approved by the institutional review board of the University of Wisconsin–Madison, Madison, Wisconsin. Parents provided written consent, and subjects provided written or verbal assent to participate. Twenty-two subjects (13 females, nine males) without history of dysphonia, aged 4 to 17 years (mean = 10.7 ± 3.9 years), participated (Table I). Subjects were recruited via flyers. Each subject underwent perceptual voice analysis using the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V)\textsuperscript{30} prior to testing to ensure they were not dysphonic. All ratings were completed by a voice-specialized speech pathologist (M.N.B.).

Subjects were tested using both labial and mechanical interruption methods. Four tasks were performed, 10 times each, for a total of 40 trials: labial interruption at comfortable amplitude, labial interruption at softest amplitude, mechanical interruption at comfortable amplitude using a mask, and mechanical interruption at comfortable amplitude using a mouthpiece. Task order was randomized across subjects to prevent learning bias. The subject’s parent was allowed to be present during testing. For younger subjects, parents could provide encouragement to maintain attention.

**Experimental Setup**

The experimental setup is similar to that described previously (Fig. 1).\textsuperscript{20,31} The airflow interruption setup was used rather than the KayPENTAX Phonatory Aerodynamic System that was used in the Chapin et al. study\textsuperscript{22} to allow for more precise audio recording required for estimation of PTP during mechanical interruption. The same device was used for labial and mechanical interruption. The device consisted of a polyvinyl chloride tube containing a condenser microphone (AKG CK77; Harman International Industries, Inc., Stamford, CT) connected to a preamplifier (MP13 Mini-Mic Preamp; Rolls Co., Murray, UT), pressure port, two airflow ports with intervening constant resistance screen, and balloon valve (series 9540; Hans Rudolph, Inc., Shawnee, KS) at its distal end. Pressure data were sampled using a Pneustach amplifier (series 1110; Hans Rudolph, Inc.) at 10 kHz. Auditory signals were sampled at 10 kHz. Data were
collected using a data acquisition board (model USB-6341; National Instruments, Inc., Austin, TX).

For labial interruption, a silicone mask was used. A variety of sizes were available (Vital Signs face masks; Vyaire Medical, Inc., Mettawa, IL). An intraoral pressure tube (0.066-inch diameter, low-density polyethylene tubing) was placed from within the pressure measurement tube to just inside the subject’s lips. We confirmed there was no leak in the system prior to beginning trials by asking subjects to phonate with the balloon valve inflated and confirming phonation was not possible. The balloon valve at the distal end of the device remained attached but was not inflated during trials.

For mechanical interruption, either a mask (the same used for labial interruption) or mouthpiece (series 9063, Hans Rudolph, Inc.; Soft Bite mouthpieces; Trident Diving Equipment, Chatsworth, CA) was used. A variety of sizes were available. For trials with a mouthpiece, subjects used a nose clip (series 9014, Hans Rudolph, Inc.) to prevent air leak through the nose. The balloon valve was operated by a digitally activated custom pressure control valve system. This pressure valve was supplied by a larger pressurized air tank. Data were collected using a customized LabVIEW program (National Instruments, Inc.). The program also provided live feedback during trials on sound pressure level and airflow. Aerodynamic data were calibrated using an analog pressure meter (PC-1H; Glottal Enterprises, Syracuse, NY) and a digital flow meter (FMA-1610A; Omega Engineering, Stamford, CT).

**Labial Interruption**

For each trial, subjects produced five labial interruptions by phonating /pα/ at comfortable amplitude (approximately 75 dB) or as softly as possible into a facemask with the intraoral pressure tube in place. Practice trials were conducted so subjects could learn to create a seal with their lips around the intraoral pressure tube and, for PTP trials, adjust their amplitude to be as soft as possible. Ten trials were performed at comfortable amplitude and at softest amplitude.

**Mechanical Interruption**

For mechanical interruption, subjects produced a sustained /α/ at comfortable amplitude (approximately 75 dB), whereas five interruptions, each lasting 250 ms, were performed at random intervals of 1 to 1.5 seconds. Each interruption completely stopped airflow temporarily. A 250-ms interruption was used instead of the previously described 500-ms interruption due to the decreased lung volume in children and the desire to avoid subjects running out of breath prematurely. Subjects were instructed to maintain constant effort during the interruption. For trials with a mask, subjects were instructed to hold the mask tight to create a proper seal. Real-time visual feedback on sound pressure level and airflow were provided to ensure subjects maintained constant effort during and across trials. Ten trials were performed each with a mask and a mouthpiece.

**Data Analysis**

A customized LabVIEW program was used for analysis. For labial interruptions, PTP or $P_s$ was measured as the peak

<table>
<thead>
<tr>
<th>No.</th>
<th>Age, yr</th>
<th>Sex</th>
</tr>
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<tbody>
<tr>
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<td>2</td>
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<td>F</td>
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</tbody>
</table>

F = female; M = male.
RESULTS

Mean CAPE-V score was 1 ± 2 on a scale of 1 to 100, and all subjects were judged not to have dysphonia perceptually.

Summary data are presented in Table II. Mean PTP (F = 21.086, P < .001) and Ps (F = 5.909, P = .005) were different across methods. PTP was higher for labial trials compared to mechanical interruption with a mask (P < .001) or mouthpiece (P < .001) (Fig. 3). Ps was higher for labial compared to mechanical interruption with a mouthpiece (P = .005). Ps and PTP were not different for the two methods of mechanical interruption. Coefficient of variation for PTP (repeated measures ANOVA on ranks, χ² = 1.182, P = .554) and Ps (F = 1.221, P = .305) did not differ significantly across the three methods (Fig. 4).

There was no correlation between age and mean PTP for labial interruption (r = −0.281, P = .206) or mechanical interruption with a mask (r = 0.169, P = .452) or mouthpiece (r = .0423, P = .852). There was an inverse correlation between coefficient of variation of PTP and mechanical interruption with a mask (r = −0.628, P = .00175). There was no correlation between age and coefficient of variation of PTP for labial interruption (r = −0.174, P = .438) or mechanical interruption with a mouthpiece (r = −0.267, P = .230) (Fig. 5).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Labial Interruption</th>
<th>Mechanical Mask</th>
<th>Mechanical Mouthpiece</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean PTP</td>
<td>4.05 ± 0.87</td>
<td>2.81 ± 1.16</td>
<td>2.59 ± 1.12</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>CV of PTP</td>
<td>0.19 ± 0.11</td>
<td>0.24 ± 0.16</td>
<td>0.20 ± 0.10</td>
<td>.554</td>
</tr>
<tr>
<td>Mean Ps</td>
<td>7.72 ± 1.94</td>
<td>6.61 ± 1.62</td>
<td>6.14 ± 1.83</td>
<td>.005</td>
</tr>
<tr>
<td>CV of Ps</td>
<td>0.13 ± 0.06</td>
<td>0.12 ± 0.04</td>
<td>0.11 ± 0.05</td>
<td>.305</td>
</tr>
</tbody>
</table>

For labial interruption, trials for Ps were performed at comfortable amplitude, and trials for PTP were performed at softest possible amplitude. Values are presented as mean ± standard deviation. P values represent results of repeated measures analysis of variance testing. CV = coefficient of variation; Ps = subglottal pressure at comfortable amplitude; PTP = phonation threshold pressure.
This is the first study applying mechanical interruption for measurement of PTP in children and the first comparing measurement reliability of PTP for labial and mechanical interruption methods in children. As predicted, mean PTP was different for labial interruption versus mechanical interruption. This is likely due to differences in task and timing of measurement. For labial interruption, subjects phonate as quietly as possible, and PTP is estimated as the P骨骼 at that amplitude. This has the advantage of not requiring additional computations other than those usually used for P骨骼. It has disadvantages of requiring separate trials for estimation of PTP and P骨骼 at comfortable amplitude and also relying on subjects to phonate consistently at their truly softest amplitude, which was difficult for younger subjects. In this study, we ensured subjects achieved lowest possible phonation both subjectively, by monitoring volume during and across trials and instructing the subject to lower amplitude as much as possible, and quantitatively, by ensuring that the minimum sound pressure level was maintained across trials. However, difficulty achieving or maintaining that lowest possible amplitude is an inherent limitation of the labial interruption technique.

Measurement of PTP via labial interruption represents an onset PTP. As has been demonstrated in theoretical, physical, and excised larynx models, PTP exhibits a hysteresis effect, where higher pressure is required to initiate phonation than to sustain it. There has been one study examining this phenomenon in human subjects. Five healthy volunteers underwent direct measurement of P骨骼 via cricothyroid membrane puncture. Two subjects exhibited a significant hysteresis effect, whereas two were equivocal, and one showed higher offset than onset pressure. Of note, there were difficulties in the experiment with needle plugging, limiting data collection. Considering the strong theoretical basis as well as the data from well-controlled excised larynx experimentation, the hysteresis phenomenon appears real and certainly could have contributed to at least part of the disparity in PTP values observed in this study.

Additional factors that may contribute to lower observed mean PTP for mechanical interruption are increased subject effort or air leak during an interruption. Estimation of PTP via mechanical interruption requires identification of phonation offset within the interruption. Increased subject effort at interruption onset could result in delayed phonation offset and thus a lower estimation of PTP. Evaluation of auditory traces for a steady decrease helped mitigate this potential issue. Determination of phonation offset using electroglottography will be explored in the future.

Interestingly, mean P骨骼 at comfortable amplitude was also different between labial and mechanical interruption. Each approach has previously been shown to be accurate via simultaneous indirect and direct P骨骼 measurement. The difference is likely related to the difference in task, with increased pressure created with lip closure required for /p/ compared to the open mouth required for /d/. Alternative explanations include differences in sound pressure level, though this was kept consistent across methods within each subject. The 150-ms time constant used in P骨骼 estimation for mechanical interruption could potentially be too short; however, this has been demonstrated previously in mathematical and physical models as well as human subjects to be appropriate. As P骨骼 was measured at 150 ms, the use of a 250 ms instead of the usual 500 ms interruption during mechanical interruption should not affect measurement; future studies will focus on optimizing interruption duration.

Overall, intrasubject variability for each method was relatively low, approximately 10% to 13% of the mean for P骨骼, and 19% to 24% for PTP. Evaluating mechanical interruption alone, variability tended to be higher for trials with a mask than a mouthpiece. Obtaining a perfect seal for labial interruption is not as essential due to use of the intraoral pressure tube; it is also easier as the subject is controlling the interruption. For mechanical interruption,
obtaining a perfect seal is more challenging (due to the external, device-controlled interruption) and more important to its success (as the subject produces the sustained vowel with an open mouth, and thus, no introral pressure tube is used). Though different sized masks were available, air leak occurred in a minority of trials, more commonly in younger subjects. If an air leak is present, the phonation offset will either be unclear or not occur. Using a mouthpiece can circumvent this issue. Application of cheek restraints (constant pressure applied to the subject’s cheeks to prevent expansion during the interruption and possible leak around the mask or mouthpiece) could also be evaluated.

Interestingly, a correlation between age and coefficient of variation for PTP measurement was only observed with mechanical interruption using a mask. This is likely related to the aforementioned issues with mask seal and air leak. The lack of a relationship with age for labial interruption and mechanical interruption using a mouthpiece, coupled with the overall reasonable intrasubject variability, suggest that routine clinical measurement of PTP in children is feasible and reliable. PTP is a sensitive indicator of laryngeal biomechanics and the ability of the larynx to function as an energy transducer to produce voice. This study demonstrates that it can be measured in children as young as 4 years with acceptable measurement precision, which is clinically valuable.

Limitations in this study include a low number of subjects at each specific age; this limits our ability to draw strong conclusions on effects of age and intrasubject variability. A prior study by Weinrich et al.34 presenting normative data for the Phonatory Aerodynamic System used labial interruption to measure mean Ps in 30 male and 30 female pediatric subjects. This demonstrated a trend for decreasing mean Ps with increasing age, though this was not statistically significant. In our study, we did not identify a relationship between mean PTP and age. As vocal fold thickness increases during puberty in males secondary to a relationship between mean PTP and age. As vocal fold thickness increases during puberty in males secondary to a relationship between mean PTP and age. As vocal fold thickness increases during puberty in males secondary to a relationship between mean PTP and age. As vocal fold thickness increases during puberty in males secondary to a relationship between mean PTP and age.

PTP and Ps can be measured reliably in pediatric subjects using either mechanical or labial interruption. If mechanical interruption is used, it is preferable to use a mouthpiece rather than a mask. Documenting the method used for data collection is important, as mean values differ for techniques based on voice task and whether onset versus offset threshold pressure is measured. Clinical measurement of PTP is feasible and may offer valuable quantitative insight into laryngeal function.

CONCLUSION

PTP and Ps can be measured reliably in pediatric subjects using either mechanical or labial interruption. If


