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Vibratory onset and offset times in children: A laryngeal imaging study

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Abstract

Objectives—The aim of the study was to evaluate the differences in vibratory onset and offset times across age (adult males, adult females, and children) and waveform types (total glottal area waveform, left glottal area waveform, and right glottal area waveform) using high-speed videoendoscopy.

Methods—In this prospective study, vibratory onset and offset times were evaluated in a total of 86 participants. Forty-three children (23 girls, 18 boys) between 5–11 years and 43 gender matched vocally normal young adults (23 females and 18 males) in the age range (21–45 years) were recruited. Vibratory onset and offset times were calculated in milliseconds from the total, left, and right Glottal Area Waveform (GAW). A two-factor analysis of variance was used to compare the means among the subject groups (children, adult male, and adult female) and waveform type (total GAW, left GAW, right GAW) for onset and offset variables. Post hoc analyses were performed using the Fishers Least Significant Different test with Bonferroni correction for multiple comparisons.

Results—Children exhibited significantly shorter vibratory onset and offset times compared to adult males and females. Differences in vibratory onset and offset times were not statistically significant between adult males and females. Across all waveform types (i.e. total GAW, left GAW, and right GAW), no statistical significance was observed among the subject groups.

Conclusion—This is the first study reporting vibratory onset and offset times in the pediatric population. The study findings lay the foundation for the development of a large age- and gender-based database of the pediatric population to aid the study of the effects of maturation of vocal fold vibration in adulthood. The findings from this study may also provide the basis for evaluating the impact of numerous lesions on tissue pliability, and thereby has potential utility for the clinical differentiation of various lesions.

Keywords

pediatric vibratory onset; pediatric vibratory offset; laryngeal imaging

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Conflict of Interest: None

1. Introduction

Vocal fold vibration is a complex interaction between subglottal pressure and vocal fold tissue properties. The complex interaction between these two factors can be evaluated using vibratory onset and offset times. Vibratory onset time is defined as the time interval between the first instance of vibratory motion to the beginning of the steady-state phonation [1, 2]. Similarly, vibratory offset time is defined as the time interval between the first instance of departure from the steady-state phonation to complete cessation of vibratory motion [2]. Based on the definitions of vibratory onset and offset times, it is evident that these are transitory phenomena, requiring high temporal resolution to capture them. High-speed videoendoscopy [1–5] offers the necessary temporal resolution to capture the transient onset and offset phenomena.

The vibratory onset and offset time can be altered by changes in laryngeal geometry or by vocal fold pathologies [1, 5–7]. Vibratory onset and offset can be affected by unilateral pathologies affecting the vocal folds such as vocal fold cysts, polyp, laryngeal papilloma, unilateral vocal fold paresis/paralysis. Functional voice disorders/muscle tension dysphonia often presents with asymmetries between the right and the left vocal fold onset times. The target pitch, loudness, and the type of phonation (e.g. hard glottal attack, breathy voice, and balanced voice) can also influence the vibratory onset and offset times. In turn, such changes in the vibratory onset and offset time can affect the steady-state vocal fold vibrations and overall voice quality. Evaluation of vibratory onset and offset times could potentially provide insights into the tissue pliability [1, 7] and integrity of the neuromuscular coordination of the vocal system [8, 9]. In recent years, much research has been conducted on differentiating vocal function between children and adults using analysis of sustained phonation. Differences in vocal function between children and adults have been investigated in the literature using acoustic [10–19], aerodynamic [20–24], electroglottographic [25], and laryngeal imaging modalities [26–30]. However, literature on direct measures of vibratory onset and offset times from techniques of laryngeal imaging is scant in adults [2, 5–8, 31–36] and virtually nonexistent in the pediatric population.

To date, studies investigating vibratory onset [2, 6, 7, 31, 32] and offset times [2, 6] in vocally normal adults are on small numbers of participants and have used different types of waveforms, resulting in variable findings. Measurements that quantify vibratory onset and offset times have used two types of waveforms: the total glottal area waveform [2, 36] and individual vocal fold trajectories obtained from various points along the length of the vocal fold [5–7, 31, 32, 34–36]. While the glottal area waveform and the vocal fold trajectories from points along the vocal fold length provide valuable information regarding the change in the glottal area and tissue motion of the selected points, they do not offer insights into the separate behavior of the left and the right vocal folds in their entirety. The intent of analyzing left and right vocal fold motion separately is to evaluate not only the tissue pliability of the entire vocal fold but also the symmetry in the onset and offset gestures between the left and the right vocal folds in the developing larynx. In addition to the known differences in the length of the right and the left recurrent laryngeal nerves, there are differences in the size, [37] myelination, and dendritic and axonal endings in the pediatric

vagus nerve compared to the adults.[38] How these differences affect the vibratory onset and offset times between the left and the right glottal area waveforms has not been systematically investigated in either children or adults.

It is well accepted that there are structural differences in the laryngeal framework between children and adults; however, there are fine microstructural differences in the vocal fold layers between children and adults. Children have smaller laryngeal cartilages [39–42] and vocal fold length [42–44]. Perpubertal children have an underdeveloped vocal fold ligament and lamina propria that is hypocellular and not fully developed until 13 years of age [43, 45, 46]. There are also differences in the extracellular matrix in terms of the fiber and protein compositions [47], suggesting that the vocal folds in children are more elastic compared to those of adults. These findings suggest that there are differences in the width and the stiffness of the body (muscle) and the cover (epithelium and the lamina propria)[48] in children, thereby altering the geometry and the depth of the vibration of the body and the cover involved in onset and offset. The influence of smaller laryngeal size on the vibratory mechanism of onset and offset has been examined using some models, but not using in vivo studies. Lumped mass models and two-layer body-cover continuum model [49] have shown that the vocal fold vibrations at onset and offset vary depending on the stiffness of the body and the cover [49, 50], subglottal pressure, and glottal area [51–53]. For smaller larynges as in children, findings from lumped mass models of the vocal folds reveal that the vocal fold oscillations and the glottal airflow are reduced due to the smaller size [52]. Based on the above stipulations, we expect children to have shorter vibratory onset and offset times compared to adults. Since in vivo studies are benchmarks for quantifying vibratory onset and offset, we hope to provide empirical data to validate the theoretical models by experimentally evaluating these phenomena. Consequently, our study could help develop theories of vocal fold vibratory motion in children. The aim of the study is to evaluate the differences in vibratory onset and offset between typically developing children and adults across three different waveform types: total, left, and right glottal area waveform.

2. Methods

2.1 Participants

Eighty-six participants were recruited for this study at the Vocal Physiology and Imaging Laboratory, Indiana University, after signing of appropriate Institutional Review Board approved consent and/ assent forms. A total of 43 children (girls = 25, boys = 18) aged 5–11 years (mean = 8.2 years) without any voice disorder were recruited. Gender-matched young adults (21–45 years, mean = 23.6 years) without any voice disorders were recruited for the control group. Children and adults were recruited in the study if their overall voice quality was perceptually rated as normal (Overall Grade = 0) on the GRBAS [48] scale and if they had negative histories of vocal fold pathology. Children undergoing puberty as evident from case history were excluded from the study. Adults with a history of smoking were excluded from the study.

2.2 Data Collection

All recordings were performed in a double-walled, sound-proof room. High-speed videoendoscopic recordings were captured at 4000 frames per second with the spatial resolution of 512×256 pixels (PENTAX digital Model 9710, Montvale, New Jersey) to obtain vibratory onset and offset. The recording duration of 4 seconds was appropriate to capture the short rapid events of vibratory onset and offset. Simultaneous acoustic recordings were captured with high-speed videoendoscopic recordings at a sampling rate of 50kHz with a mouth-to-microphone distance of 5 inches. A minimum of three consecutive repetitions of /hi/ were recorded. Participants were instructed to produce repeated production of /hi.hi.hi/ at self-selected conversational pitch and loudness. Since the consonant /h/ is a voiceless glottal fricative, the combination of a /hi/ was selected because it is produced with a fairly open vocal tract without supraglottal constrictions. The use of /h/ also prevents the occurrence of hard glottal attacks [36], which is critical for obtaining the true vibratory onset and offset time of the vocal folds.

2.3 Data Segmentation and Analysis

When determining the onset and termination of phonation, the middle syllable production of /hi/ was segmented from the high-speed video recordings for all participants in order to eliminate any abrupt vibratory events. The start frame of the segment was selected when the arytenoids were in a fully abducted position prior to the first instance of adductory motion, and the end frame of the segment was selected when the arytenoids were in the fully abducted position immediately after complete cessation of the vocal fold vibratory motion.

Glottal area waveforms (GAW) representing the vibratory onset and offset behavior of the vocal folds were extracted from the high-speed video using the Glottal Analysis tools [54] developed at the Department of Phoniatrics and Pediatric Audiology, Erlangen, Germany. Vibratory onset and offset times were obtained for the total, left, and right glottal area waveform for all participants (Figure 1). The total glottal area waveform represents the area of the entire glottis over time. The left glottal area waveform characterizes the area of the left vocal fold with respect to the central glottal axis over time, whereas the right glottal area waveform represents the area of the right vocal fold from the central glottal axis over time. The amplitudes of all the glottal area waveforms were normalized from 0 to 1, where 0 represents complete vocal fold closure and 1 represents maximum glottal opening during a glottal cycle.

The vibratory onset time (milliseconds) was calculated as the time interval between the first visually identifiable vibratory motion and the first instance at which the amplitude periodicity [55] was within two standard deviation of the participants' average steady state phonation value, which was calculated from the center 50% of steady oscillations [56]. Similar to vibratory onset, the vibratory offset time (milliseconds) was calculated from the total, left, and right glottal area waveforms as the time interval between the initial point at which the open quotient [57] or glottal gap index [28, 58] exceeded two standard deviations of the participants' steady state average value and its ending at the peak of the last detectable glottal cycle. The criteria of two standard deviations from the steady state mean value was empirically determined because any value below this threshold would have been less than

5% likely (within the 95th percentile range of expected steady-state value) to have occurred during the steady-state phonation and was therefore considered transient onset/offset behavior. This criterion was empirically defined and was successfully implemented in a previous study [56]. The measure of open quotient was used when complete closure along the length of the vocal folds was observed. In cases of a posterior glottal gap, the glottal gap index was used instead of the open quotient value to determine the departure from the steady state, as in cases of incomplete glottal closure the open quotient will be 1 for the entire sample.

2.4 Reliability

A total of 24 participants (12 children and 12 adults) were selected randomly for analysis of intra-rater reliability. The Pearson product moment correlations for vibratory onset and offset were calculated between the initial and subsequent measurement for total GAW, left GAW, and right GAW. The Pearson product moment correlations for vibratory onset time derived from the total GAW, left GAW, and right GAW were 0.934, 0.958, 0.911 for children and 0.851, 0.844, 0.952 for adults respectively. For the vibratory offset time derived from the total GAW, left GAW, and right GAW the Pearson product moment correlations were 0.972, 0.997, 0.99 for children and 0.951, 0.963, and 0.992 respectively. Results indicate high intra-rater reliability across all the measures.

2.5 Statistical Analysis

A two-sample *t* test was used to compare the mean values between girls (*n* = 25) and boys (*n* = 18). The vibratory onset and vibratory offset times were not statistically different across boys and girls for the total GAW, left GAW, and right GAW (Table 1); hence, for further statistical analysis, data from all children were combined for comparison to adults. A two-factor analysis of variance (ANOVA) was used to compare the means between the subject groups (children, adult male, and adult female) and waveform type (total GAW, left GAW, right GAW) for onset and offset variables. Results were considered significant for *p* < 0.05. Post hoc comparisons of means were performed using the Fisher's Least Significant test. Bonferroni correction for multiple comparisons was applied to the post hoc comparisons. Effect size (ES) was calculated using the partial eta squared method. All analyses were performed using SPSS Statistics software Version 23.0.

3. Results

3.1 Onset

The two-factor ANOVA revealed a significant main effect of group, $F(2,249) = 12.48$, $p < 0.001$; no significant main effect for the waveform type, $F(2,249) = 1.71$, $p = 0.183$; and no significant interaction between group and waveform type, $F(4,249) = 0.43$, $p = 0.788$. Post hoc comparisons using the Fisher's Least Significant Different test with Bonferroni adjustment revealed that children exhibited significantly shorter voice onset time (18.51 ms) compared to adult females (21.30 ms), $t(255) = 2.95$, $p = 0.011$, $ES = 0.438$ and adult males (23.56 ms), $t(255) = 4.78$, $p < 0.0001$, $ES = 0.754$. There was no significant difference between adult males (23.56 ms) and adult females (21.03 ms) for vibratory onset time $t(255) = 1.9429$, $p = 0.159$, $ES = 0.317$.

3.2 Offset

The two-factor ANOVA revealed a significant main effect of group, $F(2,249) = 14.26$, $p < 0.001$; no significant main effect for the waveform type, $F(2,249) = 3.00$, $p = 0.051$; and no significant interaction between group and waveform type, $F(4,249) = 0.21$, $p = 0.934$. Post hoc analysis with the Fisher's Least Significant Difference revealed that children exhibited significantly shorter voice offset time (73.71ms) compared to adult females (83.28 ms), $t(255) = 2.9468$, $p = 0.011$, $ES = 0.448$ and adult males (92.47 ms), $t(255) = 5.1755$, $p < 0.001$, $ES = 0.788$. The vibratory offset was not statistically different between adult males (92.47ms) and adult females (83.28 ms), $t(255) = 2.3027$, $p = 0.066$, $ES = 0.405$.

4. Discussion

The goal of the study was to empirically investigate the vibratory onset and offset time differences between children and adults across. Additionally, the study was intended to evaluate whether or not vibratory onset and offset time varies across the left, right, and the total glottal area waveforms between children and adults.

4.1 Vibratory onset/offset time differences between children and adults

The current study demonstrates that the mean vibratory onset time in children is significantly shorter compared to the vibratory onset time of adult males and adult females respectively. This finding is not surprising, since prior studies using excised larynx and/or biomechanical modeling techniques have reported that the phonation threshold pressure and the onset time has been reported to be lower due to reduced size [51], increased subglottal pressure [59–61], decreased prephonatory glottal width[61], and reduced stiffness in a two mass model of the vocal folds [52]. The findings from this study provide empirical evidence of reduced vibratory onset time from in vivo measurement of vocal fold vibratory motion in children. Children before puberty not only have smaller vocal tracts [41], laryngeal structures [39, 40], and vocal folds [27, 44, 62], but have an immature lamina propria structure, especially in terms of elastin and collagen fibers [42, 43, 45, 47, 63]. These circumstances suggest that in addition to being smaller in size, the vocal folds of children are less stiff compared to those of adults. The more elastic vocal folds of the children achieve a steady state faster than adult vocal folds that have well-developed vocal ligaments and muscles. Since children have smaller vocal folds and under-developed vocal fold ligaments and muscles, structures that constitute the body of the vocal fold, it can be safely hypothesized that the shorter vibratory onset times observed in this study may be attributed to the reduced stiffness of the vocal folds and shorter length of the vocal folds in children. Additionally, in the literature, high subglottal pressures (estimated tracheal pressures) have been reported in children [23, 64], indicating that the floppy fold will be set into oscillation faster due to the increased pressure; the result is reduced vibratory onset time. Future studies that simultaneously record the subglottal pressure and vibratory onset time are required to determine the relationship between vibratory onset time and subglottal pressure in children.

Similar to the findings from the vibratory onset time, the vibratory offset time was significantly shorter in children compared to adult males and adult females respectively. The shorter vibratory offset time in children could be linked to the smaller vocal tract and

underdeveloped layered structures of the vocal folds, which thereby restrict the oscillations of the vocal folds [52]. It may be that vibratory offset and vibratory onset follow a developmental course inverse to that of the fundamental frequency [11, 12]. That is, with increasing age the vibratory onset and offset time may show a trend of linear increase until target adult values are achieved. Compared to onset, vibratory offset has been reported to be achieved by reducing subglottal pressure, thereby increasing the postphonatory glottal width using a two mass model of the vocal folds [52]. Future research investigating the relationship between subglottal pressure and glottal width during offset, with simultaneous measure of vibratory offset time, will not only provide insights into the physiological mechanism of offset in children, but will also further elucidate the relationship between vibratory onset and offset and its use as a diagnostic parameter.

Overall, vibratory offset time was longer across all the participants compared to the vibratory onset time, however was not subjected to statistical analysis. This finding is consistent with previous findings of decreased phonatory threshold flow for offset, increased hysteresis, and reduced subglottal pressure at offset when compared to onset [52, 53, 65, 66]. Determining the relationship between the vibratory offset and onset is important to developing theories of voice production in children.

The relationship between fundamental frequency and vibratory onset/offset time is not straightforward and has not been systematically and comparatively investigated in children and adults. The mean fundamental frequency for children was 299.14Hz (SD = 44.78Hz, Range = 255.92 – 396.65Hz). For adult females the average fundamental frequency was 276.52Hz (SD = 34.51Hz, Range = 234.66 – 380.12Hz). The average fundamental frequency for males was 155.14Hz (SD = 30.39, Range = 111.97 – 206.18 Hz). To what extent the differences in onset/offset reflect the variations in fundamental frequency among the three groups in this study is a question for future research.

4.2 Vibratory onset/offset time between adult males and adult females

Overall the vibratory onset and offset times in females were shorter than those in adult males; however the findings did not achieve statistical significance. The lack of statistical significance could be due to the small sample size (female = 25, male = 18). However, this is the first large scale study comparing vibratory onset and offset times between adult males and females. Prior studies of onset and offset times often reported these measures on single female subject [2, 32, 67].

4.3 Vibratory onset/offset time between total, left, and right glottal area waveforms

As expected, vibratory onset and offset times were similar among the three waveforms: total glottal area waveform, left glottal area waveform, and right glottal area waveform for both children and adults. The vibratory onset and offset times were generally a bit longer for the total glottal area waveform compared to the left and the right glottal area waveforms. However, the difference was not statistically significant. To the best of our knowledge, investigations into vibratory differences among left, right, and total glottal area waveform are lacking in children and adults. The study findings suggest that in typical voice the findings from the total glottal area waveform, or either the left or the right glottal area

waveform can be used. The findings also suggests the pre-pubertal children exhibit symmetry in adductory and abductory gesture between the left and the right vocal folds for the onset and the offset behaviors respectively like adults.

In adults, the findings from this study reflects previous findings where no significant differences were reported for left and right vocal folds among hypofunctional, normal, and hyperfunctional subjects in a study by Braunschweig et al (2008) [7], where the participants had normal or light functional dysphonia. However the measurements obtained in Braunschweig et al (2008) [7] were from the mid-membranous points of the vocal folds, whereas the measurements reported here are from the entire left and right vocal folds. Moreover, Braunschweig et al (2008) [7] examined only female participants in their study. The current study examined both males and females. Like children, the lack of statistical difference among the three waveforms in adults suggests symmetry in the adductory/abductory gesture and the onset/offset of airflow for starting and stopping the vibratory motion. This finding of symmetry between the left and right vocal folds in the vibratory onset and offset time is a valuable finding, for evaluating vibratory onset and offset time for various voice disorders in children and adults. Often voice disorders like vocal fold paresis/paralysis, cysts, sulcus vocalis, present unilaterally, where vibratory onset and offset time of the affected vocal fold would be impaired compared to the unaffected vocal fold. The findings from this study provide preliminary normative references for potential early identification of voice disorders and differentiating mass lesions along the membranous vocal folds through analysis of vibratory onset and offset in children and adults. The emerging normative references provided in this study can also be useful for evaluating subtle disturbances in vibratory behavior following endocrine changes related to pre- and post-menopause, and superficial and/or systemic dehydration [56] in adults.

4.4 Methodological considerations

The target fundamental frequency, intensity, and syllable duration are all factors that could influence onset and offset durations. The participants in this study were instructed to phonate /hi.hi. hi/ at habitual pitch and loudness, resulting in a range of produced frequencies and intensities. Eliciting the onset task at a predefined pitch and loudness, could minimize the influence of variable pitch and loudness. The rate of /hi/ production could be an additional factor influencing the onset and offset durations. One way to obtain comparable duration of /hi/ across subjects is to elicit /hi/ at target syllable per second rate with the help of a metronome [56] at a predefined syllable per second rate.

5. Conclusions

The purpose of this study was to determine whether differences in vibratory onset and offset times are apparent between children and adults across different types of waveforms. In an effort to move the findings towards generalizable norms, the study presents a more robust data set for future large-scale studies. Children demonstrated shorter vibratory onset and offset times compared to adult males and females. When compared between children and adults, the vibratory onset and offset times did not differ across left, right, and total glottal area waveforms. The established symmetry in left/right vibratory onset and offset lays the

foundation for studies investigating asymmetries in disordered populations. The study findings provide preliminary data for developing empirical, data-driven theories of voice production in children.

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References

1. Patel, et al. A Case Report in Changes in Phonatory Physiology Following Voice Therapy: Application of High-Speed Imaging. *J Voice*. 2012
2. Kunduk, et al. Investigation of voice initiation and voice offset characteristics with high-speed digital imaging. *Logoped Phoniatr Vocol*. 2006; 31(3):139–44. [PubMed: 16966156]
3. Patel, Dailey S, Bless D. Comparison of high-speed digital imaging with stroboscopy for laryngeal imaging of glottal disorders. *Ann Otol Rhinol Laryngol*. 2008; 117(6):413–24. [PubMed: 18646437]
4. Deliyski DD, Hillman RE. State of the art laryngeal imaging: research and clinical implications. *Curr Opin Otolaryngol Head Neck Surg*. 2010; 18(3):147–52. [PubMed: 20463479]
5. Eysholdt U, et al. Direct evaluation of high-speed recordings of vocal fold vibrations. *Folia Phoniatr Logop*. 1996; 48(4):163–70. [PubMed: 8823984]
6. Ikuma T, et al. A Spatiotemporal Approach to the Objective Analysis of Initiation and Termination of Vocal-fold Oscillation With High-speed Videoendoscopy. *J Voice*. 2015
7. Braunschweig T, et al. High-speed video analysis of the phonation onset, with an application to the diagnosis of functional dysphonias. *Medical Engineering & Physics*. 2008; 30(1):59–66. [PubMed: 17317268]
8. Cooke A, et al. Characteristics of vocal fold adduction related to voice onset. *J Voice*. 1997; 11(1): 12–22. [PubMed: 9075172]
9. Chhetri DK, Neubauer J, Berry DA. Neuromuscular control of fundamental frequency and glottal posture at phonation onset. *J Acoust Soc Am*. 2012; 131(2):1401–12. [PubMed: 22352513]
10. Huber JE, et al. Formants of children, women, and men: the effects of vocal intensity variation. *J Acoust Soc Am*. 1999; 106(3 Pt 1):1532–42. [PubMed: 10489709]
11. Kent RD. Anatomical and neuromuscular maturation of the speech mechanism: evidence from acoustic studies. *J Speech Hear Res*. 1976; 19(3):421–47. [PubMed: 979206]
12. Maturo S, et al. Establishment of a Normative Pediatric Acoustic Database. *Arch Otolaryngol Head Neck Surg*. 2012 Oct; 138(10):956–961. [PubMed: 22986573]
13. Hill CA, et al. Consistency of voice frequency and perturbation measures in children. *Otolaryngol Head Neck Surg*. 2013; 148(4):637–41. [PubMed: 23396592]
14. Diercks GR, et al. Consistency of voice frequency and perturbation measures in children using cepstral analyses: a movement toward increased recording stability. *JAMA Otolaryngol Head Neck Surg*. 2013; 139(8):811–6. [PubMed: 23949356]
15. Glaze LE, Bless DM, Susser RD. Acoustic Analysis of Vowel and Loudness Differences in Children's Voice. *J Voice*. 1990; 4(1):37–44.
16. Meredith ML, et al. Describing pediatric dysphonia with nonlinear dynamic parameters. *International Journal of Pediatric Otorhinolaryngology*. 2008; 72(12):1829–1836. [PubMed: 18947887]
17. Robb MP, Saxman JH. Developmental trends in vocal fundamental frequency of young children. *J Speech Hear Res*. 1985; 28(3):421–7. [PubMed: 2981049]
18. Baker S, et al. The effect of task type on fundamental frequency in children. *Int J Pediatr Otorhinolaryngol*. 2008; 72(6):885–9. [PubMed: 18395803]

19. Hacki T, Heitmüller S. Development of the child's voice: premutation, mutation. *Int J Pediatr Otorhinolaryngol*. 1999; 49(Suppl 1):S141–4. [PubMed: 10577793]
20. Sapienza CM, Stathopoulos ET. Respiratory and laryngeal measures of children and women with bilateral vocal fold nodules. *J Speech Hear Res*. 1994; 37(6):1229–43. [PubMed: 7877283]
21. Sapienza CM, Stathopoulos ET. Comparison of maximum flow declination rate: children versus adults. *J Voice*. 1994; 8(3):240–7. [PubMed: 7987426]
22. Stathopoulos ET, Sapienza C. Respiratory and laryngeal measures of children during vocal intensity variation. *J Acoust Soc Am*. 1993; 94(5):2531–43. [PubMed: 8270731]
23. Stathopoulos ET, Sapienza CM. Developmental changes in laryngeal and respiratory function with variations in sound pressure level. *J Speech Lang Hear Res*. 1997; 40(3):595–614. [PubMed: 9210117]
24. Boliek CA, et al. Refinement of speech breathing in healthy 4- to 6-year-old children. *J Speech Lang Hear Res*. 2009; 52(4):990–1007. [PubMed: 19641078]
25. Cheyne HA, Nuss RC, Hillman RE. Electrolaryngography in the pediatric population. *Arch Otolaryngol Head Neck Surg*. 1999; 125(10):1105–8. [PubMed: 10522502]
26. Patel, et al. Pediatric high speed digital imaging of vocal fold vibration: A normative pilot study of glottal closure and phase closure characteristics. *Int J Pediatr Otorhinolaryngol*. 2012; 76:954–959. [PubMed: 22445799]
27. Patel, et al. Laser projection imaging for measurement of pediatric voice. *The Laryngoscope*. 2011; 121(11):2411–7. [PubMed: 21993904]
28. Patel, Dubrovskiy D, Dollinger M. Characterizing vibratory kinematics in children and adults with high-speed digital imaging. *J Speech Lang Hear Res*. 2014; 57:S674–S686. [PubMed: 24686982]
29. Patel R, et al. Kinematic measurements of the vocal-fold displacement waveform in typical children and adult populations: quantification of high-speed endoscopic videos. *J Speech Lang Hear Res*. 2015; 58(2):227–40. [PubMed: 25652615]
30. Döllinger M, Dubrovskiy D, Patel R. Spatiotemporal analysis of vocal fold vibrations between children and adults. *Laryngoscope*. 2012; 122(11):2511–8. [PubMed: 22965771]
31. Freeman E, et al. A comparison of sung and spoken phonation onset gestures using high-speed digital imaging. *J Voice*. 2012; 26(2):226–38. [PubMed: 21256709]
32. Mergell P, et al. Phonation onset: vocal fold modeling and high-speed glottography. *J Acoust Soc Am*. 1998; 104(1):464–70. [PubMed: 9670538]
33. McDonnell M, et al. Vocal fold vibration and phonation start in aspirated, unaspirated, and staccato onset. *J Voice*. 2011; 25(5):526–31. [PubMed: 20951547]
34. Tigges M, et al. Imaging of vocal fold vibration by digital multi-plane kymography. *Comput Med Imaging Graph*. 1999; 23(6):323–30. [PubMed: 10634144]
35. Wittenberg T, et al. Recording, processing, and analysis of digital high-speed sequences in glottography. *Machine Vision and Applications*. 1995; 8:399–404.
36. Koster O, et al. Qualitative and quantitative analysis of voice onset by means of a multidimensional voice analysis system (MVAS) using high-speed imaging. *J Voice*. 1999; 13(3):355–74. [PubMed: 10498052]
37. Jotz GP, et al. Histological asymmetry of the human recurrent laryngeal nerve. *J Voice*. 2011; 25(1):8–14. [PubMed: 20083375]
38. de Graaf-Peters VB, Hadders-Algra M. Ontogeny of the human central nervous system: what is happening when? *Early Hum Dev*. 2006; 82(4):257–66. [PubMed: 16360292]
39. Kahane JC. A morphological study of the human prepubertal and pubertal larynx. *Am J Anat*. 1978; 151(1):11–9. [PubMed: 623031]
40. Kahane JC. Growth of the human prepubertal and pubertal larynx. *J Speech Hear Res*. 1982; 25(3):446–55. [PubMed: 7176619]
41. Vorperian HK, et al. Developmental sexual dimorphism of the oral and pharyngeal portions of the vocal tract: an imaging study. *J Speech Lang Hear Res*. 2011; 54(4):995–1010. [PubMed: 21106698]
42. Eckel HE, et al. Morphology of the human larynx during the first five years of life studied on whole organ serial sections. *Ann Otol Rhinol Laryngol*. 1999; 108(3):232–8. [PubMed: 10086614]

43. Hirano, M.; Kurita, S.; Nakashima, T. Growth, Development, and Aging of Human Vocal Fold. In: Bless, DM.; Abbs, JH., editors. *Vocal Physiology contemporary research and clinical issues*. College-Hill Press; San Diego, California: 1983. p. 22-43.
44. Rogers DJ, et al. Evaluation of true vocal fold growth as a function of age. *Otolaryngol Head Neck Surg*. 2014; 151(4):681–6. [PubMed: 25171926]
45. Hartnick CJ, Rehbar R, Prasad V. Development and maturation of the pediatric human vocal fold lamina propria. *Laryngoscope*. 2005; 115(1):4–15. [PubMed: 15630357]
46. Boseley ME, Hartnick CJ. Development of the human true vocal fold: depth of cell layers and quantifying cell types within the lamina propria. *Ann Otol Rhinol Laryngol*. 2006; 115(10):784–8. [PubMed: 17076102]
47. Sato K, Hirano M, Nakashima T. Fine structure of the human newborn and infant vocal fold mucosae. *Ann Otol Rhinol Laryngol*. 2001; 110(5 Pt 1):417–24. [PubMed: 11372924]
48. Hirano, M., editor. *Clinical examination of voice*. Springer-Verlag; New-York: 1981.
49. Zhang Z. Characteristics of phonation onset in a two-layer vocal fold model. *J Acoust Soc Am*. 2009; 125(2):1091–102. [PubMed: 19206884]
50. Story BH, Titze IR. Voice simulation with a body-cover model of the vocal folds. *J Acoust Soc Am*. 1995; 97(2):1249–60. [PubMed: 7876446]
51. Lucero JC, Koenig LL. Simulations of temporal patterns of oral airflow in men and women using a two-mass model of the vocal folds under dynamic control. *J Acoust Soc Am*. 2005; 117(3 Pt 1):1362–72. [PubMed: 15807024]
52. Lucero JC, Koenig LL. Phonation thresholds as a function of laryngeal size in a two-mass model of the vocal folds. *J Acoust Soc Am*. 2005; 118(5):2798–801. [PubMed: 16334896]
53. Lucero JC. A theoretical study of the hysteresis phenomenon at vocal fold oscillation onset-offset. *J Acoust Soc Am*. 1999; 105(1):423–31. [PubMed: 9921668]
54. Lohscheller J, et al. Clinically evaluated procedure for the reconstruction of vocal fold vibrations from endoscopic digital high-speed videos. *Medical image analysis*. 2007; 11(4):400–13. [PubMed: 17544839]
55. Qiu Q, et al. An automatic method to quantify the vibration properties of human vocal folds via videokymography. *Folia Phoniatr Logop*. 2003; 55(3):128–36. [PubMed: 12771464]
56. Patel, Walker R, Sivasankar M. Spatiotemporal quantification of vocal fold vibration following exposure to superficial laryngeal dehydration: A preliminary study. *Journal of voice*. In press.
57. Timcke R, Von Leden H, Moore P. Laryngeal vibrations: measurements of the glottic wave. I. The normal vibratory cycle. *AMA Arch Otolaryngol*. 1958; 68(1):1–19. [PubMed: 13544677]
58. Kunduk, et al. Assessment of the variability of vocal fold dynamics within and between recordings with high-speed imaging and by phonovibrogram. *Laryngoscope*. 2010; 120(5):981–7. [PubMed: 20422695]
59. Plant RL, Freed GL, Plant RE. Direct measurement of onset and offset phonation threshold pressure in normal subjects. *J Acoust Soc Am*. 2004; 116(6):3640–6. [PubMed: 15658714]
60. Plant RL, Younger RM. The interrelationship of subglottic air pressure, fundamental frequency, and vocal intensity during speech. *J Voice*. 2000; 14(2):170–7. [PubMed: 10875568]
61. Lucero JC. Optimal glottal configuration for ease of phonation. *J Voice*. 1998; 12(2):151–8. [PubMed: 9649070]
62. Patel, et al. In vivo measurement of pediatric vocal fold motion using structured light laser projection. *Journal of Voice*. 2013; 27(4):463–472. [PubMed: 23809569]
63. Ishii K, et al. Age-related development of the arrangement of connective tissue fibers in the lamina propria of the human vocal fold. *Ann Otol Rhinol Laryngol*. 2000; 109(11):1055–64. [PubMed: 11089998]
64. Stathopoulos ET, Weismer G. Oral airflow and air pressure during speech production: a comparative study of children, youths and adults. *Folia Phoniatr (Basel)*. 1985; 37(3–4):152–9. [PubMed: 4054770]
65. Berry DA, et al. Bifurcations in excised larynx experiments. *J Voice*. 1996; 10(2):129–38. [PubMed: 8734387]

66. Regner MF, et al. Onset and offset phonation threshold flow in excised canine larynges. *Laryngoscope*. 2008; 118(7):1313–7. [PubMed: 18401267]
67. Ikuma T, Kunduk M, McWhorter AJ. Advanced waveform decomposition for high-speed videoendoscopy analysis. *J Voice*. 2013; 27(3):369–75. [PubMed: 23490133]

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Figure 1.
Example of different types of glottal area waveforms in a 5-year-old female child

Table 1

Comparison of vibratory onset and offset times across boys and girls using t-test

Dependent Variable	Boys (n = 18) Mean (SD)	Girls (n = 25) Mean (SD)	t- value	df	p-Value
Vibratory onset time (ms)					
Total GAW	19.44 (6.08)	19.89 (6.27)	0.23	41	0.817
Left GAW	19.90 (6.97)	16.33 (5.08)	-1.95	41	0.059
Right GAW	17.93 (4.96)	18.06 (5.68)	0.08	41	0.939
Vibratory offset time (ms)					
Total GAW	76.54 (25.97)	78.48 (21.64)	0.27	41	0.791
Left GAW	69.99 (21.06)	70.67 (20.20)	0.11	41	0.915
Right GAW	70.75 (23.97)	74.75 (22.06)	0.54	41	0.592

GAW = Glottal Area Waveform; *df* = degrees of freedom; *SD* = Standard Deviation

Table 2

Summary statistics of vibratory onset time (milliseconds)

Group/Subgroup	Number	Mean (SD)	Median	95% Confidence Interval	25th Percentile	75th Percentile
Children						
Total GAW	43	19.70 (6.12)	18.25	17.82 to 21.59	14.50	24.75
Left GAW		17.83 (6.13)	16.25	15.94 to 19.71	12.50	21.00
Right GAW		18.01 (5.33)	17.00	16.37 to 19.65	14.50	21.50
Adult Females						
Total GAW	25	21.38 (6.99)	20.25	18.50 to 24.26	16.25	26.00
Left GAW		21.66 (7.37)	19.75	18.62 to 24.70	17.00	28.50
Right GAW		20.87 (6.33)	19.50	18.26 to 23.48	16.50	26.00
Adult Males						
Total GAW	18	25.57 (7.99)	25.25	21.59 to 29.54	19.25	31.00
Left GAW		23.03 (7.89)	23.00	19.11 to 26.95	17.00	27.75
Right GAW		22.10 (6.27)	24.75	18.98 to 25.22	19.25	26.50

SD = Standard Deviation

Table 3

Summary statistics of vibratory offset time (milliseconds)

Group/Subgroup	Number	Mean (SD)	Median	95% Confidence Interval	25th Percentile	75th Percentile
Children						
Total GAW	43	77.67 (23.27)	75	70.51 to 84.83	60.25	98.75
Left GAW		70.38 (20.32)	69.25	64.13 to 76.64	55.75	89.25
Right GAW		73.08 (23.77)	70.50	65.76 to 80.39	56.75	96.50
Adult Females						
Total GAW	25	87.53 (22.49)	90.00	78.25 to 96.81	77.75	94.00
Left GAW		76.86 (16.96)	81.25	69.86 to 83.86	65.75	88.00
Right GAW		85.45 (19.72)	85.50	77.31 to 93.59	75.00	97.00
Adult Males						
Total GAW	18	97.92 (25.50)	104.63	85.23 to 110.60	79.50	117.75
Left GAW		89.17 (23.40)	89.38	77.53 to 100.80	76.25	105.25
Right GAW		90.33 (26.58)	92.00	77.11 to 103.55	69.00	103.00

SD = Standard Deviation