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Pediatric high speed digital imaging of vocal fold vibration: A normative pilot study of glottal closure and phase closure characteristics

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Abstract

Objective—The aim of the study is to characterize normal vibratory patterns of both glottal closure and phase closure in the pediatric population with the use of high speed digital imaging.

Methods—For this prospective study a total of 56 pre-pubertal children, 5–11 years (boys = 28, girls = 28) and 56 adults, 21–45 years (males = 28, females = 28) without known voice problems were examined with the use of a new technology of high speed digital imaging. Recordings were captured at 4000 frames per second for duration of 4.094 seconds at participants' typical phonation. With semi-automated software, montage analysis of glottal cycles was performed. Three trained experienced raters, rated features of glottal configuration and phase closure from glottal cycle montages.

Results—Posterior glottal gap was the predominant glottal closure configuration in children (girls = 85%, boys = 68%) with normal voice. Other glottal configurations observed were: anterior gap (girls = 3.6%, boys = 0%), complete closure (girls = 7%, boys = 10%), hour glass (girls = 0%, boys = 11%). Adults with normal voice also demonstrated predominantly higher percentage of posterior glottal gap configuration (females = 75% male = 54%) compared to the configurations of anterior gap (females = 0% male = 7%), complete closure (females = 2% male = 39%), hour glass (females = 3.6% male = 3.6%). A predominantly open phase (51–70% of the glottal cycle) was observed in 86% girls and 71% boys. Compared to children, adult females showed a predominantly balance phased closure 46%, followed by open phase (39%) and predominantly closed phase (14%). Adult males showed a predominantly closed phase (43%), followed by predominantly open phase (39%), followed by a balanced phase (18%).

Conclusions—This is a first study investigating characteristics of normal vibratory motion in children with high speed digital imaging. Glottal configuration and phase closure for children with normal voices are distinctly different compared to adults. The results suggest that posterior glottal gap and a predominantly open phase of the glottal cycle should be considered as normal glottal configuration in children during modal pitch and loudness. This study provides preliminary information on the vibratory characteristics of children with normal voice. The data presented here

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may provide the bases for differentiating normal vibratory characteristics from the disordered in the pediatric population.

Keywords

high speed digital imaging; pediatric voice; pediatric vocal fold motion; pediatric vibratory characteristics

INTRODUCTION

Accurate imaging procedures are an essential tool for clinical management of vocal fold pathologies in the pediatric population.¹ It has been documented that stroboscopy with distal chip tip flexible endoscopy¹ and with rigid endoscopy are feasible^{2,3} and particularly valuable in pediatric patients with a history of prolonged dysphonia, for whom initial treatment has failed. Superior accuracy in laryngeal imaging has been demonstrated in adults with high speed imaging compared to stroboscopy.^{4,5} However, similar high speed imaging studies have not been completed in the pediatric population. Moreover, the diagnostic value of pediatric videostroboscopy and its abilities to differentiate between different phonatory mechanism and voice pathologies are limited as there is insufficient information in the literature on what constitutes normal vibratory motion in the pediatric population.

Although stroboscopy is the preferred¹ assessment tool for clinically evaluating vibratory properties of the vocal fold; it appears to be limited for studying vibration patterns of normal and disordered pediatric phonation, because of its limited temporal resolution and requirement of fairly regular vibratory patterns for at least 3–4 seconds before the strobe light can track phonation. Due to variability in attention span and cooperation in children, it is often difficult to obtain pediatric phonation samples of greater than 2–3 seconds,² often resulting in non-interpretable stroboscopic findings. With maximum frame rate of 30 frames per second, stroboscopy is often insufficient for examining voice disorders in children, who have a fundamental frequency of greater than 255 Hz, due to lack of an adequate amount of frames per second that can be captured from children.^{6,7}

High Speed Digital Imaging (HSDI), unlike stroboscopy, can record *actual* cycle-to-cycle variations in vibratory motion⁴ with superior temporal resolution of up to 8,000 frames per second. In a two second segment, for phonation of 250 Hz, HSDI recorded at 4000 frames per second can record approximately 130 times more vibrations compared to digital stroboscopy. A comparison of vibratory motion observed on stroboscopy and HSDI is illustrated in Figure 1. In this example, the HSDI at 4000 fps, for a pitch of 250 Hz results in capturing 16 frames per glottal cycle. For stroboscopy operating at 30 frames per second only 0.12 frames per glottal cycle are captured. The first flash of stroboscopic light would be triggered after 8.33 glottal cycles or 133.28 frames. Hence, with stroboscopy considerable information is lost regarding successive glottal cycles. The detailed temporal resolution afforded by HSDI appears to be ideal for comprehensive clinical appraisal of vibratory motion children's voice quality that is characterized by higher habitual fundamental frequency and short phonation duration. To our knowledge the present study is the first to undertake direct study of vocal fold vibrations with HSDI in children.

Identification of glottal closure configuration and phase closure, through direct visualization of vibratory patterns is fundamental to appropriate diagnosis and treatment of vocal pathology. Vocal fold closure configuration during normal phonation has been shown to change with age in adults due to the anatomical changes in the larynx as part of the aging process, with young women predominantly demonstrating a posterior gap and incomplete closure configuration, whereas the elderly women demonstrated higher incidence of anterior

gap and spindle shaped glottal configuration.⁸ However, experimental investigations of vocal fold vibratory changes associated with growth and development in children are lacking, despite the recognition that the pediatric larynx is not merely a miniature version of the adult larynx. It has been well documented that children have voices that are different from adults. Empirical evidence thus far from measurement of aerodynamic characteristics,^{9–12} vocal fold histology,^{13–18} laryngeal framework,^{14,16} acoustic,^{19–22} and electroglottographic²³ assessments of vocal function, have all demonstrated differences between the pediatric and adult voices. The acoustic, aerodynamic, and electroglottographic changes in voice are thought to be due to the anatomical age-related changes in the size of the larynx and the layered structures of the vocal folds.

Data on vocal fold motion from adults²⁴ is valuable, but cannot be used for direct interpretation of pediatric phonation as laryngeal anatomy and the vocal fold layered structures in the pediatric population differ considerably when compared to adults. Children have shorter membranous portion of the vocal folds^{14,25} and less differentiated vocal ligament with thicker mucosa.^{9, 11} How these structural differences of the pediatric glottis translate into unique vibratory motion characteristics is not known. The goal of the present study is to evaluate if age and gender related differences in glottal closure configuration and phase closure exists, in typically developing children (5–11 years) compared to young adults (21–45 years) for modal (typical) phonation with the use of HSDI.

METHODS

Participants

A total of 131 participants; 75 children, age range (5–11 years) and 56 adults (21–45 years) were recruited through the University of Kentucky Vocal Physiology and Imaging Laboratory via IRB approved advertisements and fliers placed around the University of Kentucky campus and the University of Kentucky Children's Hospital. Data from 11 children could not be obtained due to heightened gag reflex. All participants or their proxies completed appropriate IRB approved informed consent and assent forms. Participants were included in the study if they met the following criterion: had negative histories of vocal pathology, were not professional voice users, perceptually judged to have normal voice by a certified speech language pathologist specializing in voice disorders. Participants going through puberty as identified via case history and parental interview were excluded. Selection criteria for adult participants were similar to those of pediatric group, except that the adult participants had a negative history of smoking.

Data Collection/Instrumentation

High speed recordings were performed with KayPentax, model 9710 at 4000 frames per second for a maximum duration of 4.094 seconds (limited by the duration of the available instrument) with spatial resolution of 512×256 pixels. Simultaneous acoustic signal was sampled at 50 kHz. Acoustic recording was used to confirm the presence of steady state phonation and participants' task performance of typical pitch and loudness. All participants performed three trials of typical phonation before recording with HSDI. The participants were asked to sustain typical phonation on the vowel /i/ that was ± 10 Hz of their speaking fundamental frequency as determined by the multidimensional voice profile module of the KayPentax Computerized Speech Lab Model No. 4500. A xenon light source of 300 watts was used. Participants were seated in a comfortable exam chair. A 70° rigid endoscope was used for visualization during phonation of the vowel /i/ at typical pitch and loudness.

Data Segmentation

Prior to data segmentation of the high speed videos, the data from all participants were verified for task performance, based on acoustic analysis of sustained phonation on the vowel /i/. Data from 6 children were excluded as their fundamental frequency and loudness were outside of their speaking frequency and loudness range. The mean fundamental frequency for boys was 260.41 Hz (SD = 30.01) and girls was 270.67 Hz (SD = 29.5), for females was 210 Hz (SD = 19.32 Hz), and for males was 141 Hz (SD = 18.51) with loudness of 80.62 dBSPL (SD = 2.21 dB) for the four groups. After task verification, a steady state segment of phonation of 3 seconds was identified on the high speed video recording based on the short-term frequency analysis of the acoustic signal. Image processing software in Matlab (version 7.10, MathWorks) was used to develop the custom segmentation tool for this study. Glottal cycle montages were generated for five consecutive cycles, based on the steady state acoustic signal with a relatively centered video segment with minimal hand motion for each participant and stored as an image file. An image consisting of series of frames representing the different phases of a glottal cycle (opening phase, open phase, closing phase, and a closed phase) is defined as a glottal cycle montage (Figure 2).

Data Analysis

Three masked trained raters with a minimum of 3 years of experience in treating voice disorders, rated glottal closure configuration and phase closure for a total of 112 participants (children n = 56, adult n = 56) from the glottal cycle montage images. Glottal closure configuration and phase closure were rated for all five consecutive cycles. High speed glottal cycle montages from two female children could not be rated for glottal configuration due to the view of the posterior glottis being hidden by the arytenoids. Glottal closure was defined as the configuration in which the vocal folds approximate each other during the closed phase (point of maximal closure) of the vibratory cycle. Closure was rated as 'complete' if no glottal gap was evident on maximal closure; 'posterior gap' if the closure is accomplished along the membranous portion of the glottis with a gap in the posterior glottis; 'anterior gap' if the closure was accomplished in the posterior part of the larynx, but a gap remained at some point in the anterior thirds of the vocal folds; and 'hour glass' configuration when the closure was accomplished along the mid-membranous portion of the vocal fold edges, but the gaps remain in both the anterior and posterior to the point of closure.²⁶ (Figure 2) Phase closure was defined as the time ratio of the open to closed phases that best describes the vibratory pattern. The open phase of the glottal cycle is the amount of time the vocal folds are open (opening + closing). The closed phase is the amount of time the vocal folds remain closed. The ratio of open to closed phases was divided into three categories: 1) 50%–50%, 2) greater than 50%, and 3) less than 50%. Phase closure of 50% open versus 50% closed indicates a balanced phase, i.e. equal % of open phase and closed phase. Phase closure of less than 50% open phase, is indicative of greater closed phase of the vibratory cycle; and phase closure of greater than 50% open phase, is indicative of a greater open phase compared to the closed phase of the glottal cycle.²⁶ (Figure 3).

STATISTICAL ANALYSIS

Age (children versus adults) and gender group differences and the interactions between age and gender (male children versus male adults; female children versus female adults; male children versus female children; male adults versus female adults) for glottal closure configuration and phase closure, were evaluated by comparing proportions using chi-square statistics. Results were considered significant for $p < 0.01$ due to testing multiple hypotheses for a given endpoint (adult versus children, males versus females, and the interaction

between these two factors). All analyses were performed using PC-SAS statistical software version, 9.2 (SAS Institute Inc, Cary, NC).

Reliability of Measurement

Approximately 15% (children = 10, adults = 10) of the data set was re-analyzed to determine interrater reliability. Pearson product moment correlations between initial and subsequent measurements for each of the indices were calculated. Because analysis was performed using glottal cycle montage images, its reproducibility was high. Interrater reliability as determined by the Pearson product moment correlations for glottal cycle configurations and phase closures ranged from $r = 0.99$ to 0.98 .

RESULTS

Fifty-six children (5–11 years) and 56 adults (21–45 years) served as participants for this study. Glottal closure and phase closure were rated on glottal cycle montages obtained from HSDI on modal phonation.

Glottal Closure

Table 1 summarizes the incidence of the occurrence of the different glottal configurations in children and adults. Overall, the percentage of participants with complete glottal configuration did not differ by age when subjected to the Chi-square statistics. Children exhibited a variety of glottal configurations (posterior glottal gap, 78.57%; complete closure, 14.29%; hourglass closure, 5.36%; and anterior gap, 1.79%). Similarly, adults also showed a variety of glottal closure configurations (posterior gap, 64.29; complete closure, 30.36, and both, anterior gap and hourglass closure gaps, 3.57%. Compared to children (14.29%), adults showed higher incidence of complete glottal closure (30.36) and slightly reduced incidence of posterior glottal gap. However, these differences proved to be statistically insignificant when subjected to chi-square testing.

Gender differences in the occurrence of glottal closure configuration were observed between adults and children are displayed in Table 3. Adult males and females had higher incidence of complete closure configuration and lower incidence of posterior gap compared to boys and girls respectively (Table 3). Adult males showed higher incidence of anterior glottal gap (7.14%) compared to boys (0%). Contrary to this, girls showed higher incidence of anterior glottal gap (3.57%) compared to adult females (0%). Boys showed higher incidence (10.71%) of hour glass closure configuration compared to adult males (3.57%). Whereas, adult females showed higher incidence of an hour glass closure (3.57) compared to girls.

At modal pitch and loudness, gender differences in the occurrence of glottal closure configuration were observed between boys and girls (Table 3). Girls had higher number of occurrence of posterior phonatory gap (89.28%) compared to boys (67.86%) and reduced number of complete closure (7.14%) configuration compared to boys (21.43%). Interestingly none of the girls in the study exhibited an hour-glass closure configuration; whereas 11% of the boys exhibited an hour glass closure configuration. Anterior glottal gap was not observed in boys, but was observed in approximately 4% of the girls.

As seen in Table 3, gender differences in the occurrence of complete closure, posterior gap, and anterior gap glottal closure configurations were observed among adult male and female. Male participants had higher incidence of complete closure (39.29%) compared to females (21.43%) and lower incidence of posterior glottal gap (53.57%) compared to females (75%). Adult males had higher incidence of an anterior gap (7.14%) compared to female (0%); whereas the incidence for an hour glass closure configuration was similar for both adult male and female (3.57%).

Phase Closure

Group differences in phase closure were observed in children and adults. The proportion of participants with a greater open phase (greater than 50%) configuration is significantly higher (Table 2) in children (80.36%) compared to adults (39.29%) ($p < 0.0001$). The adult participants had significantly higher (28.57%) proportion of closed phase (less than 50%) configuration compared to children (0%), ($p < 0.0001$).

This increase in open phase configuration in children is consistent across gender (Table 4). Boys have significantly greater proportion ($p = 0.0069$) of open phase configuration (75%) compared to adult male (39.29%). Girls had significantly greater ($p = 0.0003$) open phase configuration (85.71%) compared to adult females (39.29%). Further gender analysis of increase closed phase configuration revealed that adult males (42.86%) had significantly higher proportion ($p < 0.0001$) of closed phased compared to boys. The 50–50 phase closure rate is significantly higher ($p = 0.0095$) in adult females (46.43%) compared to girls (14.29%).

Phase closure differences between boys and girls were observed, but were not statistically significant when subjected to chi-square testing (Table 4). Boys had higher incidence (25%) of balanced closure compared to girls (14.29%); whereas girls showed higher incidence (85.71%) of predominantly open phase compared to the boys (75%). None of the children in the study showed a predominance of closed phase.

Adults, both male and female showed differences in phase closure, however like children; these were not statistically significant (Table 4). Adult females showed higher incidence (46.43%) of a balanced phase compared to males (17.86%), where as adult males showed a higher incidence of closed phase (42.86%) compared to females (14.29%). The incidence of predominantly open phase was similar in both males and females (39.29%).

DISCUSSION

The goal of the present study was to describe normative data on glottal closure configuration and phase closure, with the use of HSDI in typically developing children (5–11 years) compared to young adults (21–45 years) for modal (typical) phonation. High speed laryngeal imaging analysis completed on 112 participants on vibratory parameters of glottal closure configuration and phase closure yielded a pediatric voice profile, distinct from young adults, characterized by increased incidence of posterior phonatory gap and greater than 50% open phase duration during normal pitch and loudness. The study also revealed that rigid transoral endoscopy with regular 8mm endoscope could be performed in approximately 88% of cases (5–11 years) without the use of topical anesthesia. This is in contrast to the previous study where stroboscopy with a rigid endoscope could not be performed on 26%.² Differences in endoscopic techniques also could account for the percentage differences.

Glottal Closure and Phase Closure in Children

Young children demonstrated posterior gap more frequently (79%) compared to complete closure, hourglass closure, and anterior gap. McAllister et al²⁷ reported posterior gaps in 23% of 10 year old children. In their study, stroboscopy was feasible only in 32 out of 60 children. It is unclear if the above percentage McAllister et al²⁷ study is obtained from stroboscopy alone or stroboscopy and indirect microlaryngoscopy. The preponderance of posterior glottal gap in both boys and girls could be due to the age related anatomical changes of larger cartilaginous (posterior) glottis compared to the membranous portion of the vocal fold.²⁵ Though the posterior glottis is of adult proportion (30% to 45%) by 5 years of age,¹⁶ the membranous portion of the vocal fold length is not fully developed until after puberty.²⁵ Lack of statistical significance in the occurrences of posterior phonatory gap

between children and adults, could be due to the small sample size, as adults in this study also showed a higher occurrence of posterior phonatory gap.

Overall girls demonstrated a higher incidence of posterior glottal gap. This data lends indirect evidence of possible gender differences/ sexual dimorphism in the rate of growth of the membranous portion of the vocal folds between boys and girls from 5–11 years, given that the posterior glottis is of the adult dimension by 5 years of age.¹⁶ Indirect evidence of sexual dimorphism in the development of membranous vocal fold length is further apparent from the finding that boys had a higher incidence of complete glottal closure compared to girls. The finding that only boys demonstrated an hour glass closure configuration was interesting, given the higher incidence of vocal nodules in boys compared to girls.^{28,29} The presence of an hourglass closure configuration in the absence of vocal fold lesions could be indicative of higher impact stress. The differences could also be attributed to changes in vocal intensity and the immature layered vocal fold structure and its viscoelasticity, resulting in different vibratory configurations of glottal closure.¹⁵ Quantitative analyses of large number of glottal cycles need to be performed to further investigate the variations in glottal closure as a function of loudness changes.

Children had a greater incidence of an increased open phase compared to closed phase, indicating that the vocal folds remain open for a longer duration during a glottal cycle in children compared to adults. The increase in open phase is evidence from direct assessment of the finding of a higher open quotient-20% (vocal fold open time/period) quantified from the indirect assessment of the aerodynamic waveform in children.⁹ Though not statistically significant, there appears to be gender differences in the incidence of balance and increased open phase between boys and girls, indicating sexual dimorphism. Besides the apparent size differences, the novel finding of increased open phase in children could be attributed to known differences in the layered structures^{17,18} and the viscoelastic properties¹⁴ of the vocal folds. Other vibratory factors that are thought to influence the open phase of the glottal cycle are the shape of the medial margin of the vocal folds, contact area of the waveform, or the convergent/divergent vibratory patterns,³⁰ which could not be determined from visual imaging of the superior view of the vocal folds. Quantification of the unique spatiotemporal vibratory characteristics in the pediatric population with HSDI may elucidate on the actual mechanism and on the unique immature body-cover^{18,25} relationship of the pediatric glottis. Interestingly, none of the children in the study exhibited a pattern where the vocal folds remained closed for longer than 50% of the time. The lack of a predominantly closed phase in the pediatric population could be due to the inherent high modal pitch in children. It would be interesting to study the variations in phase closure and glottal configuration as a function of loudness and pitch changes in typically developing children. Further empirical investigations quantifying the relationship between the unique multilayered structure of the pediatric vocal folds and the resulting spatiotemporal features from HSDI could serve as a basis for clinical differentiation of normal from disordered pediatric vocal function. These investigations are currently underway in our lab.

Glottal Closure and Phase Closure in Adults

Overall posterior glottal gap was the highest occurring closure configuration in adults, followed by complete closure, and anterior & hourglass configuration. Like prior investigations^{8,31,32} with stroboscopy, females in this study demonstrated a higher incidence of a posterior gap compared to male. To the best of our knowledge this is the largest study, investigating the gender differences with the use of HSDI. None of the females in the study showed an anterior phonatory gap. In terms of phase closure, adults exhibited all three types of phase closure. A novel finding of this investigation is that females tended to exhibit a 50–50% (balanced) phase closure, where as males tended to exhibit a phase closure with increased closed phase during modal phonation. The gender difference between the phase

closure could be attributed to the inherent differences in vocal registers between male and female modal phonation. It is possible that some of the differences observed could be due to the use of high vowel /i/, head extension, and measurements performed with HSDI. However, the effects of modification of the oral cavity for endoscopic visualization and the instrumentation were present for both adult and children in this study. It is unlikely that the differences are related to the effects from visualization via rigid endoscope. In addition of the differential muscle activation patterns the vibratory differences could also be due to the fine micro viscoelastic differences in the layered structures of the adult male and female. Further investigations clinically quantifying spatiotemporal features resulting from the unique multilayered structure of the vocal folds, could serve as indirect indicator of viscoelastic properties of the vocal folds in clinical examination, both for adults and the pediatric population.

CONCLUSIONS

The physiologic signs of vocal maturation of posterior phonatory gap and increased open phase should not be misinterpreted as signs of vocal pathology. The present data represents preliminary normative data of differential glottal closure and phase closure in typically developing children compared to adults. Clinical implications of these data underscore the importance of establishing a normative database from which clinical interpretations of pathological conditions can be made for either stroboscopy or high speed imaging.

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References

1. Hartnick CJ, Zeitels SM. Pediatric video laryngo-stroboscopy. *Int J Pediatr Otorhinolaryngol*. Feb; 2005 69(2):215–219. [PubMed: 15656955]
2. Wolf M, Primov-Fever A, Amir O, Jedwab D. The feasibility of rigid stroboscopy in children. *Int J Pediatr Otorhinolaryngol*. Aug; 2005 69(8):1077–1079. [PubMed: 16005350]
3. Jensen SB, Pedersen AM, Vissink A, et al. A systematic review of salivary gland hypofunction and xerostomia induced by cancer therapies: prevalence, severity and impact on quality of life. *Support Care Cancer*. Aug; 2010 18(8):1039–1060. [PubMed: 20237805]
4. Patel R, Dailey S, Bless D. Comparison of high-speed digital imaging with stroboscopy for laryngeal imaging of glottal disorders. *Ann Otol Rhinol Laryngol*. Jun; 2008 117(6):413–424. [PubMed: 18646437]
5. Olthoff A, Woywod C, Kruse E. Stroboscopy versus high-speed glottography: A comparative study. *Laryngoscope*. Jun; 2007 117(6):1123–1126. [PubMed: 17545874]
6. Hertegard S. What have we learned about laryngeal physiology from high-speed digital videoendoscopy? *Curr Opin Otolaryngol Head Neck Surg*. Jun; 2005 13(3):152–156. [PubMed: 15908812]
7. Wittenberg T, Moser M, Tigges M, Eysholdt U. Recording, processing, and analysis of digital high-speed sequences in glottography. *Machine Vision and Applications*. 1995; 8:399–404.
8. Linville SE. Glottal gap configurations in two age groups of women. *J Speech Hear Res*. Dec; 1992 35(6):1209–1215. [PubMed: 1494266]
9. Stathopoulos ET, Sapienza C. Respiratory and laryngeal measures of children during vocal intensity variation. *J Acoust Soc Am*. Nov; 1993 94(5):2531–2543. [PubMed: 8270731]

10. Sapienza CM, Stathopoulos ET. Comparison of maximum flow declination rate: children versus adults. *J Voice*. Sep; 1994 8(3):240–247. [PubMed: 7987426]
11. Stathopoulos ET, Duchan JF, Sonnenmeier RM, Bruce NV. Intonation and pausing in deaf speech. *Folia Phoniatr (Basel)*. 1986; 38(1):1–12. [PubMed: 3710326]
12. Hoit JD, Hixon TJ, Watson PJ, Morgan WJ. Speech breathing in children and adolescents. *J Speech Hear Res*. Mar; 1990 33(1):51–69. [PubMed: 2314085]
13. Hirano, M.; Kiyokawa, K.; Kurita, S.; Fujimura, O., editors. *Laryngeal muscles and glottic shaping*. New York: Raven press ltd; 1988. *Vocal physiology: voice production, mechanisms and functions*
14. Kahane JC. Growth of the human prepubertal and pubertal larynx. *J Speech Hear Res*. Sep; 1982 25(3):446–455. [PubMed: 7176619]
15. Sato K, Hirano M, Nakashima T. Fine structure of the human newborn and infant vocal fold mucosae. *Ann Otol Rhinol Laryngol*. May; 2001 110(5 Pt 1):417–424. [PubMed: 11372924]
16. Eckel HE, Koebke J, Sittel C, Sprinzl GM, Pototschnig C, Stennert E. Morphology of the human larynx during the first five years of life studied on whole organ serial sections. *Ann Otol Rhinol Laryngol*. Mar; 1999 108(3):232–238. [PubMed: 10086614]
17. 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*. Oct; 2006 115(10):784–788. [PubMed: 17076102]
18. Hartnick CJ, Rehbar R, Prasad V. Development and maturation of the pediatric human vocal fold lamina propria. *Laryngoscope*. Jan; 2005 115(1):4–15. [PubMed: 15630357]
19. Sussman JE, Sapienza C. Articulatory, developmental, and gender effects on measures of fundamental frequency and jitter. *J Voice*. Jun; 1994 8(2):145–156. [PubMed: 8061770]
20. Campisi P, Tewfik TL, Manoukian JJ, Schloss MD, Pelland-Blais E, Sadeghi N. Computer-assisted voice analysis: establishing a pediatric database. *Arch Otolaryngol Head Neck Surg*. Feb; 2002 128(2):156–160. [PubMed: 11843724]
21. Glaze LE, Bless DM, Susser RD. Acoustic Analysis of Vowel and Loudness Differences in Children's Voice. *J Voice*. 1990; 4(1):37–44.
22. Kent RD. Anatomical and neuromuscular maturation of the speech mechanism: evidence from acoustic studies. *J Speech Hear Res*. Sep; 1976 19(3):421–447. [PubMed: 979206]
23. Cheyne HA, Nuss RC, Hillman RE. Electrolaryngography in the pediatric population. *Arch Otolaryngol Head Neck Surg*. Oct; 1999 125(10):1105–1108. [PubMed: 10522502]
24. Von Leden H, Moore P, Timcke R. Laryngeal Vibrations: Measurements of the Glottic Wave: Part III. The Pathologic Larynx. *AMA Arch Otolaryngol*. 1960; 71(1):16–35.
25. 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*. 1983. p. 22–43.
26. Bless DM, Hirano M, Feder RJ. Videostroboscopic evaluation of the larynx. *Ear Nose Throat J*. Jul; 1987 66(7):289–296. [PubMed: 3622324]
27. McAllister A, Sederholm E, Ternstrom S, Sundberg J. Perturbation and hoarseness: a pilot study of six children's voices. *J Voice*. Sep; 1996 10(3):252–261. [PubMed: 8865096]
28. Dobres R, Lee L, Stemple JC, Kummer AW, Kretschmer LW. Description of laryngeal pathologies in children evaluated by otolaryngologists. *J Speech Hear Disord*. Aug; 1990 55(3):526–532. [PubMed: 2199731]
29. Sederholm E, McAllister A, Dalkvist J, Sundberg J. Aetiologic factors associated with hoarseness in ten-year-old children. *Folia Phoniatr Logop*. 1995; 47(5):262–278. [PubMed: 8563778]
30. Titze IR. Physiologic and acoustic differences between male and female voices. *J Acoust Soc Am*. Apr; 1989 85(4):1699–1707. [PubMed: 2708686]
31. Biever DM, Bless D. Vibratory characteristics of the vocal folds in young adult and geriatric women. *Journal of Voice*. 1989; 3(2):120–131.
32. Murry T, Xu JJ, Woodson GE. Glottal configuration associated with fundamental frequency and vocal register. *J Voice*. Mar; 1998 12(1):44–49. [PubMed: 9619978]

Figure 1.

Comparison of glottal cycles obtained from High Speed Digital Imaging (HSDI) and stroboscopy. The glottal cycle montage is generated from a 9 year old female during production of sustained /i/ at normal pitch and loudness with a fundamental frequency of 250 Hz. The red box represents one glottal cycle. On HSDI 16 frames (red box) can be captured for one cycle, however the first stroboscopy flash light (yellow box) is triggered only after ~8 glottal cycles, indicating missing information from each subsequent 8 glottal cycles or 133.28 frames

Figure 2. Schematic diagram and glottal cycle montage from high speed digital imaging indicating open phase and closed phase of one glottal cycle

Figure 3.
Glottal closure configurations in children, 5–11 years of age

Table 1

Frequency of occurrence of glottal closure configuration in children (n = 56) compared to young adults (n = 56)

	Age Group			
	Children		Adult	
Configuration	Incidence	%	Incidence	%
Complete Closure	8/56	14.29	17/56	30.36
Posterior Gap	44/56	78.57	36/56	64.29
Anterior Gap	1/56	1.79	2/56	3.57
Hourglass Closure	3/56	5.36	2/56	3.57

Table 2

Frequency of occurrence of phase closure configuration in children (n = 56) compared to young adults (n = 56)

	Age Group			
	Children		Adult	
Phase Closure	Incidence	%	Incidence	%
50%–50%	11/56	19.64	18/56	32.12
Greater than 50%	45/56	80.36	22/56	39.29
Less than 50% (more closed)	0/56	0%	16/56	28.57

Table 3

Gender differences in the frequency of occurrence of glottal closure in children and adults

	Gender			
	Male		Female	
Configuration	Incidence	%	Incidence	%
Complete Closure				
Children	6/28	21.43	2/28	7.14
Adults	11/28	39.29	6/28	21.43
Posterior Gap				
Children	19/28	67.86	25/28	89.28
Adults	15/28	53.57	21/28	75
Anterior Gap				
Children	0/28	0	1/28	3.57
Adults	2/28	7.14	0/28	0
Hourglass Closure				
Children	3/28	10.71	0/28	0
Adults	1/28	3.57	1/28	3.57

Table 4

Gender differences in the frequency of occurrence of phase closure in children and adults

	Gender			
	Male		Female	
Phase Closure	Incidence	%	Incidence	%
50%–50%				
Children	7/28	25	4/28	14.29
Adults	5/28	17.86	13/28	46.43
Greater than 50%				
Children	21/28	75	24/28	85.71
Adults	11/28	39.29	11/28	39.29
Less than 50%				
Children	0/28	0	0/28	0
Adults	12/28	42.86	4/28	14.29