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Measurement of glottal cycle characteristics between children and adults: Physiological Variations

Rita R. Patel, Ph.D.^{*}, Denis Dubrovskiy, MS.⁺, and Michael Döllinger, Ph.D.⁺

^{*}Department Speech and Hearing Sciences, College of Arts & Sciences, Indiana University, USA

⁺University Hospital Erlangen, Medical School, Department of Phoniatics and Pediatric Audiology, Erlangen, Germany

Abstract

Objective—The aim of this study is to quantify phases of the vibratory cycle using measurements of glottal cycle quotients and glottal cycle derivatives, in typically developing pre-pubertal children and young adults with use of high speed digital imaging (HSDI).

Method—Vocal fold vibrations were recorded from 27 children (age range 5–9 years) and 35 adults (age range 21–45 years), with HSDI at 4000 frames per second for sustained phonation. Glottal area waveform (GAW) measures of Open Quotient (OQ), Closing Quotient (CQ), Speed Index (SI), Rate Quotient (RQ) and Asymmetry Quotient (AsyQ) were computed. Glottal cycle derivatives of Amplitude Quotient (AQ) and Maximum Area Declination Rate (MADR) were also computed. Group differences (adult females, adult males, and children) were statistically investigated for mean and standard deviation values of the glottal cycle quotients and glottal cycle derivatives.

Results—Children exhibited higher values of Speed Index, Asymmetry Quotient and lower MADR compared to adult males. Children exhibited the highest mean value and lowest variability in Amplitude Quotient compared to adult males and females. Adult males showed lower values of Speed Index, Asymmetry Quotient, Amplitude Quotient and higher values of MADR compared to adult females.

Conclusion—Glottal cycle vibratory motion in children is functionally different compared to adult males and females; suggesting the need for development of children specific norms for both normal and disordered voice qualities.

Keywords

high speed laryngeal imaging; pediatric voice; glottal cycle; vocal fold vibrations; objective voice evaluation

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Correspondence: Rita R. Patel, Ph.D., Indiana University, Department of Speech and Hearing Sciences, 200 S. Jordan Avenue, Rm. # C145, Bloomington, IN 47405-7002, patelrir@indiana.edu, Phone: 812-855-3886, Fax : 812-855-5531.

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INTRODUCTION

Direct assessment of vocal fold vibration is central to appropriate evaluation and treatment of voice disorders regardless of age or pathology because it allows clinicians to make inferences about the movement of the Body (vocalis muscle) and the Cover (epithelium and the lamina propria)¹ of the vocal folds. Routine direct clinical assessment of vocal fold motion is achieved using stroboscopy.² However, there are instances where it is difficult to assess vocal fold vibrations with stroboscopy due to its technological limitations where either it is too slow to capture every vibration or cannot follow severely aperiodic vibrations. Numerous studies recently report the advantage of supplementing clinical assessment of vocal fold motion with high speed digital imaging (HSDI)^{3–7} and/or kymography^{8,9} to improve assessment of vocal fold function. Visual frame-by-frame analysis of HSDI or kymographic analysis is time-consuming as it yields formidable amount of raw visual data for short duration for reliable and valid assessment of vocal fold vibration.¹⁰ For example, 4 seconds of HSDI recorded at 4000 frames per second will require approximately 27 minutes to view the entire recording at 10 frames per seconds. Analysis of vocal fold motion from HSDI and kymography becomes easier when the vibrations are quantified. Since the first high speed film analysis,¹¹ several image processing methods have been proposed recently to quantify vibratory motion from high speed imaging^{12–17} and kymography^{18,19} in adults. There is emerging quantitative normative data^{5,13,20–22} of vibratory motion from HSDI on adults. However, normative data of vibratory motion in the pediatric population is scarce. Clinical assessment and treatment in the pediatric population are exacerbated by the lack of normative data; especially for laryngeal imaging.

Age-specific normative data of direct vibratory motion are critical for objective measurement of treatment outcomes. Data of vibratory motion from adults, cannot be directly applied to assess children, as there are known differences not only in size,²³ but also functional differences in terms of the underdeveloped layered structure of the vocal folds,^{24–26} higher fundamental frequency,^{27,28} and increased subglottal pressure.²⁹ Limited investigations on direct assessment of vibratory motion in the pediatric population have also revealed functional differences in vibratory motion in children compared to young healthy adults. Through qualitative analysis of glottal cycle montages, generated from high speed digital imaging Patel, Dixon, Richmond, Donohue (2012)³⁰ reported a higher incidence of posterior phonatory gap (girls = 85%, boys = 68%) and a predominantly open phase of the glottal cycle during modal phonation in typically developing 5–11 year old children. Quantitative assessment of vocal fold oscillations in typically developing prepubertal children (5–11 years)^{31,32} revealed both temporal and spatial differences in vibratory motion compared to healthy adults. Children had greater cycle-to-cycle variability during normal phonation compared to adults, especially during the closing phase.³¹ Spatially, the vocal fold oscillations in children were characterized by longer opening phase, increased longitudinal delay for the opening phase and decreased longitudinal delay between the anterior and medio-lateral parts for the closing phase.³¹ However much remains to be investigated in terms of the pattern of change of the glottal area function in children.

The aim of this study is to quantify basic kinematic parameters characterizing the phases of the glottal cycles and glottal cycle derivatives that provide inferences related to the

viscoelastic properties of the vocal folds. Glottal cycle quotients based on the duration of the various glottal cycle phases and the derivatives of the Glottal Area Waveform (GAW) were derived from HSDI in typically developing children. The following glottal quotients: Closing Quotient (CQ), Rate Quotient (RQ), Speed Index (SI), Open Quotient (OQ), Asymmetry Quotients (AsyQ) and glottal cycle derivatives: Amplitude Quotient (AQ) and Mean Area Declination Rate (MADR) were used to characterize vibratory motion differences between typically developing children and adults in modal phonation. The glottal quotients and glottal derivatives were selected to comprehensively capture the relationships between the different phases (opening, closing, and closed phase) of a glottal cycle. To the best of our knowledge there are no studies that have systematically investigated the glottal quotients and its derivatives in children. The specific purpose of this prospective study was to assess the nature of age-related differences in mean and cycle-to-cycle variability (inter cycle variability) in glottal cycle quotients and glottal cycle derivatives between children and adults.

METHODS

Participants

Adult and children participants were recruited from IRB approved advertisements and fliers placed around the University of Kentucky Campus and at University of Kentucky Children's Hospital. A total of 49 children (5–9 years) and 37 adults (21–45 years) participated at the University of Kentucky, Vocal Physiology and Imaging Laboratory after signing appropriate IRB approved informed consent and assent forms. Participants were included in the study if they met the following criteria: had negative histories of vocal pathology, were not professional voice users, and were perceptually judged to have normal voice by a certified speech language pathologist specializing in voice disorders. Children experiencing puberty as identified via case history were excluded from the study, as were adults with a history of smoking. Data from 17 children and 1 adult could not be obtained due to heightened gag reflex. Five children and one adult data could not be included in the study due to lack of the availability of 50 cycles of steady phonation at normal pitch and loudness. Hence data from 27 children and 35 adults was subjected to further analysis. The mean age for adult males was 29 years $\pm$ 8 years and for female participants was 28 years $\pm$ 7 years. For children, the mean age was 7.6 years $\pm$ 1 year.

High Speed Digital Imaging (HSDI)

Sustained phonation on the vowel /i/ was recorded at the participant's typical pitch and loudness. Typical voice production was defined as phonation that is close to the average speaking fundamental frequency and loudness for individual subjects. The examiner judged the level of typical voice production through perceptual judgments of sustained phonation and conversation sample. The recordings were performed by a digital gray scale Pentax Medical high speed system model 9710 with a sampling rate of 4000 frames per second with a spatial resolution of 512 $\times$ 256 pixels for a maximum duration of 4.094 seconds. The camera was coupled to a 70° Pentax Medical endoscope with a xenon light source of 300 watts. Children tolerated the rigid endoscope well, however they required considerable pre-endoscopic preparation, typical of endoscopic examination in routine clinical practice. A

simultaneously recorded acoustic signal, recorded at 50kHz, was used to confirm the presence of steady state phonation and participants' task performance of typical pitch and loudness. Participants performed three practice trials of sustained phonation on the vowel /i/ at typical pitch and loudness, prior to recording with HSDI. After practice, three trials were recorded for each participant. Only one representative sample of typical phonation per participant was analyzed.

Data Segmentation and Parameter Extraction

Image segmentation¹⁴ extraction, and computation of parameters were performed by using a custom and in house software application (*Glottal Analysis Tools, GAT*), which was developed at the Department for Phoniatics and Pediatric Audiology, Erlangen - Germany. 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/. From each high speed recording, a sequence of steady state phonation of 50 oscillation cycles (160 ms to 460 ms corresponding to 110 Hz – 310 Hz fundamental frequency) was selected and analyzed. The criterion of a minimum of 50 oscillation cycles of steady phonation was defined empirically and has been used successfully in previous studies.^{31,33} The segmentation of the steady state phonation was guided by inspecting the pitch trace, Root Mean Square (RMS) contour, and wideband spectrogram on TF32³⁴ an acoustic software analysis program. The acoustic tracings were examined both visually and quantitatively for 20Hz shift in 20 millisecond window for steady state phonation.³⁵ The mean fundamental frequency for adult females was 251 Hz ($SD = 31$ Hz), adult males was 145 Hz ($SD = 36$ Hz), male children was 295 Hz ($SD = 31$ Hz), and for female children was 275 Hz ($SD = 31$ Hz).

A Region-Growing approach¹⁴ was used for image segmentation. Seed points were manually set into the open glottis (dark grey values) and all pixels below a defined threshold were considered part of the glottal area. The boundary of the detected glottal area represented the vocal fold edges, and the summation of the considered pixels for each frame over time resulted in the glottal area waveform (GAW). For each period, the video frame with the most open state of the glottis was computed (i.e. maximum of GAW). In these frames, the positions of the dorsal and ventral endings of the glottis were computed. Between these frames, the dorsal and ventral positions were linearly interpolated and the glottal midline was computed between these positions.^{4,14} The glottal cycle quotients of closing quotient, rate quotient, speed index, open quotient, and asymmetry quotient were calculated. Additional glottal cycle derivatives of amplitude quotient and maximum area declination rate were calculated. The mean and standard deviations were computed for every cycle for these parameters, resulting in 50 values for the 50 cycles under investigation. The mean value represents that average for the parameters considered, while the standard deviation represents the variability (periodicity) of the parameter. The mean and standard deviation values over all cycles was used to characterize motion for the steady-state phonation, resulting in a total of 14 parameters.

The definitions and computation of the glottal cycle quotients and glottal cycle derivative parameters used for data analysis are detailed below:

Glottal Cycle Quotients

1) Closing Quotient—Closing quotient³⁶ (CQ) was defined as the duration of the closing phase (not including the closed phased) divided by the duration of the entire cycle (Figure 1).

$$CQ_i = \frac{t_{o \rightarrow c}^i}{T_i}$$

Where: T_i – i^{th} cycle duration, $t_{o \rightarrow c}^i$ – part of i^{th} cycle duration (Figure 1), during which the glottis is closing (open-to-closed). For normal phonation in adults, the values for closing quotient are approximately half of the open quotient, for e.g. 0.26 ± 0.08 .³⁷

2) Rate Quotient—The Rate Quotient (RQ) was defined as the duration of the closed phase plus the duration of the opening phase divided by the duration of the closing phase (Figure 1).³⁸

$$RQ_i = \frac{t_{closed}^i + t_{c \rightarrow o}^i}{t_{o \rightarrow c}^i}$$

Where: t_{closed}^i – part of i^{th} cycle duration during which the glottis is closed (GAW = 0), $t_{o \rightarrow c}^i$ – part of i^{th} cycle duration during which the glottis is closing (open-to-closed), $t_{c \rightarrow o}^i$ – part of i^{th} cycle duration during which the glottis is opening (closed-to-open). Alternatively, rate quotient reflects the duration that the glottis requires to go from zero to maximum change in glottal area divided by the time the glottis takes to go from zero to minimum change in glottal area. Normal value of rate quotient in adult is approximately around 2.8 ± 0.29 .³⁷ High pitch phonation will result in a reduction of the rate quotient due to shortening of the glottal cycle. At high intensity the rate quotient is increased.

3) Speed Index—The Speed Index (SI) describes the symmetry of the opening and closing phases of the glottal cycle (Figure 1). The speed index was defined as the duration of the opening phase minus the duration of the closing phase divided by the duration of the open phase of the glottal cycle:³⁹

$$SI_i = \frac{t_{c \rightarrow o}^i - t_{o \rightarrow c}^i}{t_{open}^i}$$

Where: t_{open}^i – part of i^{th} cycle duration during which the glottis is open (GAW > 0), $t_{o \rightarrow c}^i$ – part of i^{th} cycle duration during which the glottis is closing (open-to-closed), $t_{c \rightarrow o}^i$ – part of i^{th} cycle duration during which the glottis is opening (closed-to-open). For normal phonation the values of the speed index range from –1 to +1.³⁹ The negative value represent that the duration of the opening phase is shorter compared to the duration of the closing phase of the

glottal cycle, whereas a positive speed index indicates that the duration of closing phase is shorter compared to the opening phase of the glottal cycle.

4) Open Quotient—The Open Quotient (OQ) was defined as the duration of the cycle during which the vocal folds remain open (opening plus closing phase) divided by the duration of the entire cycle.^{11,40}

$$OQ_i = \frac{t_{open}^i}{T_i}$$

Where: T_i – i^{th} cycle duration, t_{open}^i – part of i^{th} cycle duration during which the glottis is open ($GAW > 0$). Normal range for adults ($n = 2$, male subjects) from high speed film studies was reported to be 0.64–0.88.¹¹ Normal range for adults ($n = 52$ with 24 male and 28 female) from digital kymographs generated from HSDI was reported to be 0.498 ± 0.134 .⁵

5) Asymmetry Quotient—The Asymmetry Quotient (AsyQ) was defined as the ratio of the duration of the opening phase divided by the duration of the open phase.⁴¹

$$AsyQ_i = \frac{t_{c \rightarrow o}^i}{t_{open}^i}$$

Where: t_{open}^i – part of i^{th} cycle duration during which the glottis is open ($GAW > 0$), $t_{c \rightarrow o}^i$ – part of i^{th} cycle duration during which the glottis is opening (closed-to-open). For normal adult phonation the asymmetry quotient is approximately 0.52.⁴² A skewed waveform to the right will have an asymmetry quotient that is greater than 0.5, indicating that the duration of the opening phase is greater, compared to the closing phase. An asymmetry quotient of less than 0.5 will be represented by a waveform that is skewed to the left, indicating that the duration of the closing phase is greater than the duration of the opening phase of the glottal cycle.

Glottal Cycle Derivative Features

1) Amplitude Quotient—Amplitude Quotient (AQ) was defined as following:⁴³

$$AQ^i(Sample) = \frac{A_i}{MADR^i} \quad 1Sample = \frac{1}{\text{Sampling Rate(Hz)}} s;$$

Where: A_i (**Pixel**) – amplitude of i^{th} cycle; $MADR^i \left(\frac{\text{Pixel}}{\text{sample}} \right)$ – MADR for i^{th} cycle. The absolute value of amplitude quotient can be viewed as an indirect measure reflecting the viscoelastic property/stiffness of the vocal folds that is determined by the shape and amplitude of the GAW. Amplitude quotient for normal phonation in adult females was reported to be -3.86 ± 1.17 .⁴²

2) Maximum Area Declination Rate—Maximum area declination rate (MADR) was defined as the maximum amplitude of the negative peak of the first derivative of the glottal area waveform. This measure represents the maximum velocity during the closing phase of the glottal cycle, however differs from velocity by its sign. It is analogous to the maximum flow declination rate derived from the glottal flow signal,³⁶ however here it is derived from the glottal area waveform signal.

Statistical Analysis

Initially, statistical analysis was performed to examine if children less than or equal to 8 years were different compared to children greater than 8 years. Shapiro-Wilk test of normality was performed to test for normality of the 14 dependent variables (mean of 7 variables and standard deviations of 7 variables). Results from the Shapiro-Wilk test revealed that the mean values of the following 6 parameters (CQ, RQ, SI, AsyQ, AQ, and MADR) were normally distributed. A two sample t-test was used to compare mean values and the mean standard deviation between children < 8 years for parameters with normal distribution and Mann-Whitney U-Test was used for non-normal distribution.

Group differences between the three groups (adult females vs. adult males, females vs. children, and male vs. children) were analyzed for all 14 parameters. Shapiro-Wilk test of normality was used to examine the distribution for all 14 parameters. The mean values of the following five parameters (CQ, RQ, SI, AsyQ, MADR) were normally distributed, whereas 9 parameters showed a non-normal distribution. For the normally distributed parameters, ANOVA was performed. For non-normal distributed parameters, Kruskal-Wallis tests were performed with Bonferroni correction ($p < .05/9 = .0055$). For normally distributed parameters, post-hoc test was performed using the Least-Square Difference (LSD) tests. Post-hoc tests for non-normal distributed parameters were performed using Mann-Whitney U tests with significant level of $p = .05$, since Bonferroni correction was already performed before. Post-hoc tests were performed only if the ANOVA or the Kruskal-Wallis tests showed significance. Results were considered significant for $p = .05$, if not Bonferroni corrected. Statistical analysis was performed using IBM SPSS Statistics 19.0.

RESULTS

Similar to the Phonovibrogram analysis,³¹ none of the parameter means or standard deviations were significant between children less than or greater than 8 years, hence they were pooled into one group of children.

Group comparisons across the means of glottal quotients and derivatives

The average speed index ($M = .25$, $SD = .15$) ($p = .000$) and asymmetry quotient ($M = .63$, $SD = .07$) ($p = .000$) were significantly larger in children compared to adult male where the speed index was ($M = -.03$, $SD = .12$) and asymmetry quotient was ($M = .48$, $SD = .06$). This suggests that children consistently had a greater duration for the opening phase of the glottal cycle compared to the closing phase, whereas adult males had a greater duration for the closing phase compared to the opening phase. The maximum velocity during the closing phase as represented by the maximum area declination rate was reduced in children ($M =$

–1168, $SD = 307$) compared to adult males ($M = -695$, $SD = 155$) ($p = .000$). The average speed index ($p = .065$), asymmetry quotient ($p = .065$), and maximum area declination rate ($p = .057$) were not statistically significant between adult female and children (Table 1). The amplitude quotient was largest in typically developing children ($M = -2.75$, $SD = .82$) compared to adult female ($M = -3.33$, $SD = .73$) ($p = .019$) and adult male ($M = -6.51$, $SD = 2.10$) ($p = .000$) (Figure 2).

Adult males have significantly lower values of speed index ($p = .000$), asymmetry quotient ($p = .000$), and amplitude quotient ($p = .000$), and high values of maximum area declination rate ($p = .001$) compared to adult females. The vibratory cycle for adult females had a speed index of ($M = .18$, $SD = .78$), asymmetry quotient ($M = .59$, $SD = .05$), and maximum area declination rate ($M = -1011$, $SD = 290$).

The closing quotient, rate quotient, and the open quotient were similar across the three groups (Figure 1). The average closing quotient values for children was ($M = .32$, $SD = .07$), adult females was ($M = .35$, $SD = .08$), and adult males was ($M = .38$, $SD = .11$). The average rate quotient values for children was ($M = 2.37$, $SD = .84$), adult females was ($M = 2.04$, $SD = .78$), and adult males was ($M = 1.85$, $SD = .74$). The average open quotient values for children was ($M = .87$, $SD = .15$), adult females was ($M = .86$, $SD = .17$), and adult males was ($M = .74$, $SD = .19$).

Group comparisons across the standard deviations of glottal quotients and derivatives

Due to the stringent alpha error, only one of the 7 parameters was significant (Figure 3). Children ($M = .25$, $SD = .12$) ($p = .000$) and females ($M = .25$, $SD = .19$) ($p = .000$) had reduced variability in the amplitude quotient compared to adult males ($M = .66$, $SD = .41$) (Table 2).

DISCUSSION

Glottal cycle quotients (closing quotient, rate quotient, speed index, open quotient, asymmetry quotient) are important basic parameters that characterize the phases of a glottal cycle, and glottal cycle derivatives (amplitude quotient, mean area declination rate) are parameters that provide indirect insights into the viscoelastic properties of vocal folds (e.g. peak closing velocity and stiffness). Data on norms and normal variations of these kinematic features in typically developing children are critical for identification of abnormal vocal fold motion in children with voice disorders and for understanding the development of vibratory motion in children. The results support the hypothesis that there are functional differences in vocal fold oscillation in children compared to adults.

Evidence of functional differences in vibratory motion in developmentally normal children

The study revealed that typically developing children have longer opening phase relative to the closing phase compared to the adult males, as indicated by larger speed index and skewed asymmetry quotient to the right. This finding of a long opening phase, correlates with our previous study that investigated spatiotemporal differences between children and adults with the use of Phonovibrograms.³¹ Vocal fold motion in children revealed greater duration of the opening phase compared to the closing phase on Phonovibrogram analysis,

which uses the degree of angle to indicate the time-dependent course of the vocal fold opening and closing.³¹ However, unlike Phonovibrogram analysis, the glottal waveform analysis provides quantitative information of the glottal area as is typically observed from visual analysis of stroboscopic imaging in the clinic. The waveform shapes resulting from the glottal waveform analysis are more intuitive regarding the glottal area function compared to the Phonovibrograms, which are static images generated from HSDI based on splitting the glottal midline to pictorially represent the motion of the right vocal fold below the left vocal fold. Both, speed index and asymmetry quotient, are similar to the well-known speed quotient, which is defined as the ratio of the duration of the opening phase to the duration of the closing phase.¹¹ However, unlike speed quotient, the asymmetry quotient and speed index are conceptually simpler to understand as the values range from 0 to 1 and from -1 to 1, respectively, whereas for the speed quotient that values can range from 0 to ∞ .⁴¹ Furthermore, unlike the speed quotient, the speed index and the asymmetry quotient are normalized by the duration of the open phase, thereby jointly provide more substantial details about the duration of the opening and closing phases relative to the duration of the open phase of the glottal cycle compared to the speed quotient.

The large opening phase could hypothetically be linked to large subglottal pressure⁴⁴ and floppy layered structure^{25,45} of the vocal folds. During the pre-pubertal period the vocal folds are composed predominantly of the epithelium and an immature ligament compared with the fully developed tri-laminar layered structure of the adult vocal folds that consists of the epithelium, lamina propria, and the deep layers.^{25,45}

Another unique finding of the study is that typically developing children have greater peak closing velocity as is indicated by the smaller values of the maximum area declination rate in children ($M = -1168$) compared with the adults males ($M = -694$). Smaller values of the maximum area declination rate in children indicate bigger changes in glottal area during the closing phase of the glottal cycle, which is equivalent to larger peak closing velocity (i.e. larger absolute value of MADR). However, the parameter of maximum area declination rate only provides indirect estimates of the peak velocity during the closing phase. Further investigations with the use of laser projection systems coupled with imaging systems need to be conducted to investigate if indeed the peak closing velocity calculated in metric units is larger in typically developing children compared to adults.^{32,46}

Children demonstrated larger amplitude quotient compared to adult males and females, but smaller cycle-to-cycle variability in amplitude quotient. Assuming that the observed participant groups had approximately equal distance between the endoscope and the vocal folds during the recordings, smaller absolute values of amplitude quotient can be interpreted as reduced stiffness of vocal folds in children. The immature floppy vocal folds^{24,26} of children would be more difficult to control and therefore could result in greater cycle-to-cycle instability compared to adults.

Kinematic features of speed index, asymmetry quotient, and maximum area declination rate were similar between children and adult females, suggesting that glottal cycle oscillations in children in terms of these kinematic features are similar to those of female vocal fold

oscillations. This in part could be related to the small, relatively comparable magnitude of the vocal fold oscillations and the approximately equal fundamental frequency.

Statistical results did not reveal significance between the closing quotient, rate quotient, and open quotient across the three groups for modal phonation. However, all three groups exhibited an indirect proportional dependency between the mean value of the closing quotient and the speed index, suggesting that the larger the value of the closing time (i.e. the closing quotient), the smaller the value of the speed index (Figure 4, upper graph). The variability of the speed index and the closing quotient as represented by the values of the standard deviation (Figure 4, lower graph), correlate almost linearly. The closing quotient for children was $.323 \pm .074$, adult female was $.352 \pm .081$, and adult male was $.379 \pm .108$, indicating that the duration of the closing phase is similar across the three groups. These are the first findings of closing phase in children's phonation. The findings of closing phase from adult female phonation are slightly smaller than the values reported by Bohr et al (2013).⁴² The mean closing quotient for healthy females ($n = 77$) was $.45 \pm .07$ in the Bohr et al study (2013).⁴² The normal subjects in the Bohr et al study (2013)⁴² were recruited during routine clinical examination with unremarkable findings of vocal fold lesions, indicating that they may not have lesions, but could still have a voice disorder, accounting for the larger values of the closing quotient. The mean closing quotient in Mehta et al (2011)³⁷ was $.26 \pm .08$, which is smaller than the findings of closed quotient in this study. The smaller closing quotient in Mehta et al (2011)³⁷ could be due to the small number of subjects ($n = 7$) and could also be due to the fact that the value of the closed quotient was averaged across both males and females. The rate quotient for children was $2.372 \pm .842$, adult female was $2.038 \pm .781$, and adult male was $1.851 \pm .744$. The rate quotient was highest in children followed by adult females and males; however these findings did not achieve statistical significance. The open quotient for children was $.868 \pm .151$ (295Hz), adult female was $.859 \pm .169$ (251 Hz), and adult male was $.736 \pm .186$ (145Hz). Visual analysis of glottal cycle montage generated from high speed imaging of 56 children revealed that children had greater open phase of glottal cycle compared to the closed phase for phonation at typical pitch and loudness.³⁰ The values of open quotient for adult subjects are within the normal ranges of the values for open quotient reported by Timcke et al (1958)¹¹ from high speed films of .64 to .88 for weak to medium intensities. The findings of open quotient from this study also correlate with the frequency dependent value of open quotient reported by Sonesson (1960)⁴⁷. For a pitch of 175Hz the mean open quotient reported by Sonesson (1960)⁴⁷ was .68, for 275Hz the open quotient was .80, and for 325Hz, the open quotient was .82. The adult values for open quotient are larger than the values reported by Mehta et al (2010)⁵ $.498 \pm .134$ and Lohscheller et al (2012),⁴⁸ where the open quotient in female was $.66 \pm .14$ and for male was $.56 \pm .10$ for the mid membranous region of the vocal fold. The open quotient from Mehta et al (2010)⁵ was derived from digital kymographs generated from HSDI recorded at 2000 frames per second,²¹ whereas in Lohscheller et al (2012)⁴⁸ the open quotient was calculated from HSDI captured at 4000 frames per second. Digital kymographs though useful only provide information from a selected horizontal segment along the length of the vocal fold. The current findings are from the glottal area waveform that tracks the entire glottal area compared to the mid membranous portion from the digital kymographs as in Mehta et al (2010)⁵ and Lohscheller et al (2012).⁴⁸ Moreover, the high-speed videos in this

study were recorded at 4000 frames per second for improved temporal resolution, resulting in higher accuracy of the measurements. The reduced size of the segment analyzed (less than 30 cycles) in Mehta et al (2010)⁵ and Lohscheller et al (2012)⁴⁸ compared to the 50 cycles analyzed in this study, may also have an influence on the kinematic features extracted. It needs to be determined how variations in size of the token used for analysis influences the kinematic features.

Children and female subjects had lower variability in amplitude quotient compared to the adults. Statistical significance was not observed for any of the variability measures indicating that the inter-cycle variability was similar across the three groups for the glottal cycle quotients and derivatives.

Kinematic differences in typically developing adults

Adult males have lower values of speed index, asymmetry quotient, amplitude quotient, and higher values of maximum area declination rate compared to adult females. The negative value of speed index in males ($-.03 \pm .12$) and the lower asymmetry quotient ($0.48 \pm .06$) compared to female participants speed index ($.18 \pm .78$) and asymmetry quotient ($.59 \pm .05$) indicates that the opening phase of the glottal cycle is smaller in males compared to the females. The asymmetry quotient for the females in this study is somewhat similar to the asymmetry quotient of 0.52 ± 0.06 , obtained from large number of participants ($n = 77$) in Bohr et al (2013) study.⁴² The lower amplitude quotient in male participants (-6.51 ± 2.10) compared to female participants (-3.33 ± 0.73) suggests that the GAW has larger amplitudes, assuming that the endoscope is at a similar distance. The value of the amplitude quotient for female participants in this study is similar to the value of -3.86 ± 1.17 found in a large scale study ($n = 77$) by Bohr et al (2013).⁴² Adult males have smaller changes in the glottal area during the closing phase as signified by the large values of maximum area declination rate (-694 ± 155) compared to females (-1011 ± 290). The small changes in glottal area during the closing phase in male indicate that male participants have reduced peak closing velocity compared to adult female participants. It needs to be determined how the values of the maximum area declination rate would change as a function of varying pitch and loudness levels.

Methodological Considerations

The values in this study are based on modal phonation. It will need to be determined how these vary with pitch and loudness modulation in children. Other limiting factors of the study are the recording duration of 4000 frames per second, spatial resolution of 512×256 pixels, and calculation of glottal cycle derivatives in pixels rather than in metric units.

Summary and Conclusions

Automated, quantitative analysis of vocal fold motion obtained from high speed digital imaging, revealed differences in glottal cycle quotients and glottal cycle derivatives in typically developing pre-pubertal children compared to adults. These are the first findings that provide evidence for functional differences in the shape of the glottal area waveform in children. New findings are presented in terms of longer duration of the opening phase, increased relative peak closing velocity, and reduced absolute value of amplitude quotient

compared to adult males. Vocal fold vibration in children are similar to adult females in terms of increased opening phase, increased relative peak closing velocity, and reduced absolute value of amplitude quotient, but different compared to adult males, suggesting that vocal fold vibration in children are more similar to those of adult females, compared to adult males. Only one glottal cycle derivative feature of amplitude quotient was different between adult males and adult females. The glottal area waveform in children and adults are similar in terms of closing quotient, rate quotient, and open quotient. The findings here further substantiate the need to study the vibratory characteristics in pre-pubertal children using large scale study. With further large scale studies in children the findings here may provide a physiological framework of vibratory features, from which vocal fold pathologies could be differentiated in children.

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Figure 1.

Visualization of the Glottal Area Waveform (GAW) and its derivative: Closing Quotient, Open Quotient, Speed Index, Asymmetry Quotient, Rate Quotient, Maximum Area

Declination Rate (MADR), and Amplitude Quotient. T_i = cycle duration, $t^i_{O \rightarrow C}$ – part of i^{th} cycle duration, during which the glottis is closing (open-to-closed).

Figure 2.

Mean (M) values of the parameters representing the phases of the glottal cycle across children ($n = 27$), adult female ($n = 19$), and adult male ($n = 16$). CQ = Closing Quotient, RQ = Rate Quotient, SI = Speed Index, OQ = Open Quotient, Amplitude Quotient (AQ), Maximum Area Declination Rate (MADR), and AsyQ = Asymmetry Quotient.

Figure 3.

Standard Deviation (*SD*) values of the parameters representing the phases of the glottal cycle across children ($n = 27$), adult female ($n = 19$), and adult male ($n = 16$). CQ = Closing Quotient, RQ = Rate Quotient, SI = Speed Index, OQ = Open Quotient, Amplitude Quotient (AQ), Maximum Area Declination Rate (MADR), and AsyQ = Asymmetry Quotient

Figure 4.

Correlations between the mean and standard deviation values of speed index and closing quotient across the three groups (children, adult males, and adult females). Correlation coefficients r as well as the linear regression lines are depicted.

Table 1

Summary of ANOVA statistics and post-hoc test for normally distributed parameters. The *p* values highlighted in bold are statistically significant. Degrees of freedom is represented by 'df', and effect size is represented by ' η^2 '. MADR = Mean Area Declination Rate, SD = Standard Deviation.

Parameter	Female (n=19) vs. Male (n=16)	Female (n=19) vs. Children (n=27)	Male (n=16) vs. Children (n=27)	ANOVA (<i>p</i> < 0.05)		
				<i>p</i> value	F value	df / η^2
Closing Quotient_Mean	-	-	-	0.116	2.233	2 / 0.070
Rate Quotient_Mean	-	-	-	0.106	2.335	2 / 0.073
Speed Index_Mean	0.000	0.065	0.000	0.000	25.027	2 / 0.458
Asymmetry Quotient_Mean	0.000	0.065	0.000	0.000	25.025	2 / 0.458
MADR_Mean	0.001	0.057	0.000	0.000	15.384	2 / 0.342

Table 2

Summary of Kruskal-Wallis statistics and post-hoc test for non-normally distributed parameters. The *p* values highlighted in bold are statistically significant. Degrees of freedom is represented by 'df', and effect size is represented by ' η^2 '. MADR = Mean Area Declination Rate, SD = Standard Deviation.

Parameter	Female (n=19) vs. Male (n=16)	Female (n=19) vs. Children (n=27)	Male (n=16) vs. Children (n=27)	Kruskal-Wallis (<i>p</i> < 0.0055)		
				<i>p</i> value	H value	df / η^2
Closing Quotient_SD	-	-	-	0.048	6.054	2 / 0.099
Rate Quotient_SD	-	-	-	0.021	7.736	2 / 0.126
Speed Index_SD	-	-	-	0.78	5.101	2 / 0.083
Open Quotient_Mean	-	-	-	0.032	6.877	2 / 0.112
Open Quotient_SD	-	-	-	0.233	2.914	2 / 0.048
Asymmetry Quotient_SD	-	-	-	0.084	4.944	2 / 0.081
Asymmetry Quotient_Mean	0.000 / 10	0.019 / 151	0.000 / 5	0.000	35.540	2 / 0.582
Amplitude Quotient_SD	0.000 / 30	0.680 / 238	0.000 / 42	0.000	22.767	2 / 0.373
MADR_SD	-	-	-	0.159	3.684	2 / 0.060