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Laser Projection Imaging for Measurement of Pediatric Voice

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Abstract

Objectives/Hypothesis—The aim of the study was to present the development of a miniature laser projection endoscope and to quantify vocal fold length and vibratory amplitude of the pediatric glottis using high-speed digital imaging coupled with the laser endoscope.

Study Design—For this prospective study, absolute measurement of entire vocal fold length, membranous length of the vocal fold, and vibratory amplitude during phonation were obtained in one child (9 years old), one adult male (36 years old), and one adult female (20 years old) with the use of high-speed digital imaging, coupled with a custom-developed laser projection endoscope.

Methods—The laser projection system consists of a module slip-fit sleeve with two 3-mW 650-nm laser diodes in horizontal orientation separated by a distance of 5 mm. Calibration involved projecting the laser onto grid patterns at depths ranging from 6 to 10 cm and tilt angles of 15 to –5 degrees to obtain pixel-to-millimeter conversion templates. Measurements of vocal fold length and vibratory amplitude were extracted based on methods of image processing.

Results—The system demonstrated a method for estimating vocal fold length and vibratory amplitude with a single laser point with high measurement precision. First measurements of vocal fold length (6.8 mm) and vibratory amplitude (0.25 mm) during phonation in a pediatric participant are reported.

Conclusions—The proposed laser projection system can be used to obtain absolute length and vibratory measurements of the pediatric glottis. The projection system can be used with stroboscopy or high-speed digital imaging systems with a 70-degree rigid endoscope.

Keywords

Laser projection system; high-speed digital imaging; pediatric voice; pediatric vocal fold length

INTRODUCTION

Direct visualization of vocal fold vibratory patterns is fundamental to appropriate diagnosis and treatment of vocal fold pathology. Quantitative assessment of vocal fold vibrations as a function of growth and development in the pediatric population is nonexistent. Clinical practice in pediatric voice disorders has been slow to integrate advances made in the field of quantitative laryngology because of the lack of translational research. Data on vocal fold

motion from adults are valuable but cannot be used for direct interpretation of pediatric phonation because laryngeal anatomy and the vocal fold layered structures in the pediatric population differ considerably from those of the adult.¹⁻⁴ The proposed research is a first step to fill this gap of translational research by developing a miniature laser projection high-speed system for quantitative predictive measurements of vibratory function based on growth and development of the layered structures of the vocal folds.

To aid our understanding of rate of growth and identification of physiologic factors of laryngeal function that underlie the development of mechanically based voice disorders in children, it is important to quantify vocal fold length and vibratory measurements *in vivo*. A critical first step in understanding the development of mechanically based voice disorders in children is determining what constitutes normal pediatric vocal fold vibrations. Children have a shorter membranous portion of the vocal folds^{3,5} and less differentiated vocal ligament^{2,3,6,7} with thicker mucosa until the age of 13² to 16³ years, signifying that the average stress per unit area is large and variable throughout the developmental period. Unfortunately, the application of these laboratory discoveries is lacking in clinical practice owing to the dearth of empirical knowledge of vocal fold vibrations in the constructs of development of pediatric voice and voice disorders.

Quantitative assessment of vocal fold length and vibratory features in absolute scale can be clinically derived if the optical properties of the endoscope and distance of the endoscope from the vocal folds are known. Investigations thus far have been conducted on adults in Europe with the use of two-point laser projection^{8,9} and laser triangulation techniques,^{10,11} coupled with high-speed digital imaging (HSDI). Although useful, the laser projection systems were fitted and calibrated for use with a 90-degree rigid endoscope and have been bulky and large even for use in adults. In the United States, the 70-degree rigid endoscope is used most often. Popolo and Titze⁹ obtained measurements of glottal width and glottal length with the use of a two-point laser coupled with a 70-degree endoscope. These measurements were obtained from simulation of vocal fold vibrations from synthetic vocal folds with the use of videostroboscopy and videokymography. This study reports quantitative measurements of vocal fold length and vibratory amplitude with the use of a two-point laser coupled with a 70-degree endoscope *in vivo* using HSDI.

HSDI, unlike stroboscopy, can record actual cycle-to-cycle variations in vibratory motion¹² with superior temporal resolution of up to 8,000 frames per second. This level of detail is especially critical for comprehensive clinical appraisal of children's voice production that has a higher habitual fundamental frequency and shorter phonation duration than typically developing adults. Because of variability in attention span and participation in children, it is often difficult to obtain pediatric phonation samples of greater than 2 to 3 seconds,¹³ resulting in noninterpretable stroboscopic findings. Stroboscopy, although the current gold standard in laryngeal imaging¹⁴ of vocal fold vibration in adults, is limited for studying normal and disordered phonation in the pediatric population because of its limited temporal resolution. With a maximum recording rate of 30 frames per second, stroboscopy is unable to capture vocal fold vibrations of children that are greater than 255 Hz.^{15,16} The proposed research is the first to undertake direct physiologic studies of vocal fold vibrations in children with the use of a custom-built pediatric laser endoscope coupled with HSDI.

The purpose of this paper is to present the development and measurement precision of a miniaturized two-point laser system coupled with a 70-degree rigid endoscope for clinical assessment of pediatric voice. First quantitative measurements of pediatric vibratory motion are presented with the use of the custom-built pediatric laser endoscope coupled with HSDI, in comparison with adult male and female participants.

MATERIALS AND METHODS

Laser Projection System

A prototype miniaturized laser projection system was developed at the University of Kentucky Laryngeal Physiology and Imaging Laboratory in collaboration with the College of Engineering. The laser system projects two horizontal points on the glottal surface. To the best of our knowledge, this is the first clinically feasible laser projection system that has taken into consideration miniaturization and need for disinfecting the endoscope between applications for a 70-degree rigid endoscope. The module designed for this study consists of a slip-fit sleeve that positions the lasers relative to the camera field of view (Fig. 1). The optics for the projection system are separate from the endoscope, as has been used by other investigators^{8–10}; however, they are of small size for use in the pediatric population.

The modular sleeve design is made from stainless steel with 1-mm walls, with the battery compartment and push button switch for operating the lasers, located at the rear of the sleeve, near the scope ocular. The sleeve is held in fixed location over the endoscope by a tight slip-fit mechanical contact with a medical-grade adhesive that is chemically resistant, which allows for disinfecting of the endoscope. The laser assembly is mounted at 8-mm parallel separation and at fixed angular position to a mirror by an integrated mount and cradle (Fig. 2). The upper surface of the mount and cradle has a chamfer to ensure proper orientation along the length of the scope as well as to minimize depth of the laser housing below the existing scope, thus ensuring minimal frontal area of the sleeve. The two lasers internal to the front housing are collocated to project beams, via an internal mirror at a fixed displacement angle, in horizontal orientation to the scope view. The existing scope has a viewing angle of $\alpha = 32.5$ degrees (Fig. 2) for a 70-degree rigid endoscope, which results in a displacement angle for the mirror of $\beta = 50$ degrees from the horizontal. The sleeve is offset behind the scope view port and fiber-optic illumination ends to prevent occlusion by the laser head. The offset of the laser sleeve was minimized to prevent blockage of the beam by the tongue or epiglottis.

The design was tailored to fit the KayPentax 10-mm rigid endoscope, model 9106 (KayPentax, Montvale, NJ). The lasers add only 5 mm of additional width to the endoscope. The current lasers at 3 mW illuminate an area of approximately 2.0 mm² resulting in a 1.5-mW/mm² power density, which is below the 2 mW/mm² density recommended for tissue illumination.

Data Collection

Three volunteer participants were recruited for the study after signing an institutional review board–approved informed consent form. All participants were judged to have normal voice, and their vocal folds were free of lesions. The three participants were composed of one male child (9 years old), one adult male (36 years old), and one adult female (20 years old). Sustained phonation of the vowel /i/ was recorded at participants' self-selected typical conversational pitch and loudness with the use of a custom-built 70-degree laser endoscope coupled with HSDI without the use of topical anesthetic. For the HSDI recordings, a KayPentax high-speed system model 9710 was used. Black-and-white images were recorded for a maximum duration of 4.094 seconds with a spatial resolution of 512 × 256 pixels. A 300-W xenon light source was used.

Calibration of the Laser Endoscope Measurements

Vocal fold length and amplitude measurements (in millimeters) were derived from the glottal image using pixel-to-millimeter conversions obtained from matching the distortion of the projected patterns on the glottis to those projected on a set of calibrated grids. The two-

dimensional measurement of the glottal image in millimeters was estimated by point mapping, features of the glottal image to the calibrated grid image corresponding to the best size and shape match of the projected points. A calibration tilt table (Fig. 3) was used to capture changes in the size and shape of the laser points when projected from multiple tilt angles (ranging from -5 to 15 degrees in increments of 5 degrees) at depths of 6 , 7 , 8 , 9 , and 10 cm. These pixel patterns were stored as templates for pattern matching to determine projection angles and depths for the vocal fold images. For the calibration grid images, the laser points were projected onto the grid pattern so that horizontal laser points aligned along the tilt axis. Depth of the projection was recorded as the distance along the laser projection from the endoscope mirror to calibration surface at the tilt table axis. The tilt angles were referenced to 0 degrees when the calibration surface was parallel to the endoscope housing.

The extracted laser patterns from the calibration process were stored in a set of templates for comparison to the laser points projected on the actual glottal image. Figure 4 shows the projected laser points on a grid pattern for a depth of 8 cm and a tilt of 5 degrees. Because the glottal surface is not flat with irregular reflectivity, the edges of the projected laser points will undergo some degree of local distortion not present on the calibrated surface. Therefore, a morphologic image-processing technique was applied to limit these distortions at the edges to result in a more consistent match between the calibrated surface patterns and the patterns of points projected on the glottis. A threshold was applied locally to the gray-scale images to separate the laser projection area with its diffused surroundings from the background. Further processing on the extracted binary image was performed with median filtering.¹⁴ The median root was extracted by repeatedly applying a 3×3 median filter to the binary image until it remained constant. The laser point projection on the left side was used to extract the median root and derive the calibration templates for distances ranging from 6 to 10 cm and tilts of 15 degrees to -5 degrees. The resulting shape was used to find the closest match with the projection onto the vocal fold image (Fig. 5A). The outline of the median root as shown in Figure 5B reveals good match of the laser projection to the existing shape.

Measurement precision for this process is primarily influenced by the variability in matching the glottal image projection pattern to the templates from the calibration grid. The extracted pattern, shape, and size are dependent on the threshold applied to the glottal image. Multiple estimates of glottal length with varying thresholds were made to examine the measurement precision to counter the degree of subjectivity in the thresholding process. The standard deviations of the estimates were computed for varying thresholds over a reasonable range (15 – 30 gray levels) based on human assessment.

Quantitative Measurement of Vocal Fold Length and Vibratory Amplitude

Absolute measurement of vocal fold lengths—Length of the entire vocal fold and membranous vocal fold length during phonation were calculated in millimeters. Both of these lengths were defined anatomically based on Hirano et al.³ Figure 5B shows point G_1 denoting the posterior margin and G_2 denoting the anterior commissure of the vocal folds, which were selected to define the vocal fold length during the maximum open phase of the phonatory cycle, where the vocal folds are in the abducted position. The laser patterns from the vocal fold image projection were correlated with all laser point templates of varying tilts and distances corresponding to the calibrated grid images. The calibration grid with the highest laser pattern correlation coefficient was used as the template to convert the pixels in the vocal fold image to obtain the length in millimeters.

The pixel coordinates from the calibration image denoting the laser pattern projection center P_c were aligned with the vocal fold image center G_c . Subsequently the pixels corresponding to the vocal fold length markers G_1 (posterior glottis) and G_2 (anterior glottis) from the vocal fold image were mapped to the calibration grid image. The distance between these

vocal fold markers G_1 and G_2 (Fig. 4B) was computed from the calibration image points P_1 (posterior glottis) and P_2 (anterior glottis) to obtain the exact pixel per millimeter correlation factor.

The vocal fold length was computed by projecting the closest neighboring grid crossing points D_1 and D_2 (shown in Fig. 4B) onto the line between P_1 and P_2 . Because the length between D_1 and D_2 is known from the calibration grid, its projection on the glottal line is computed directly. The remaining lengths between the projection points and the glottal line endpoints are computed through interpolation from the surrounding grid crossing points. The resulting vocal fold length in millimeters was computed as follows:

$$d_G = d_1 + d_{12} + d_2 \quad (1)$$

where d_{12} is the length of the projected calibration grid points (D_1 and D_2) onto the medial vocal fold line, and d_1 and d_2 are the distances between the projected points on the center vocal fold line and end points P_1 (posterior glottis) and P_2 (anterior glottis).

Absolute measurement of vibratory amplitude—The maximum horizontal excursion of the vocal fold from the medial glottal line along the midmembranous section of the vocal fold was defined as the vibratory amplitude. The vocal fold length was used to estimate vibratory amplitude from the medial glottis line. A pixel-to-millimeter conversion factor for the vibratory amplitude was obtained by dividing the estimated vocal fold length by the pixel distance between the two end points demarcated by the anterior-most and posterior-most parts of the vocal folds. Vocal fold margins were detected by applying a threshold to the pixels along the vocal fold edges to separate the illuminated fold area from the dark background between the folds.¹⁰ The thresholds were set interactively by a human observer to ensure the detected edges agreed with those observed in the images. The two points (P_1 and P_2) that determined the vocal fold length measurement were selected with the same criteria³ and tracked every cycle to compensate camera and tissue motion. The amplitude of the left and right fold was measured independently, in pixels along a line perpendicular to the medial line in the midmembranous portion of the vocal fold, where the displacement would be at a maximum. Given that p_A is the pixel distance between the medial line and a vocal fold edge and p_G is the vocal fold pixel length in the current frame, the vibratory amplitude (d_A) in mm was computed as follows:

$$d_A = p_A \frac{d_G}{p_G} \quad (2)$$

To ensure consistency in the pixel structures when matching with a correlation measure to compute the change from cycle to cycle during sustained phonation, the vocal fold points of posterior commissure (G_1) and the anterior margin (G_2) were updated for each vibratory cycle at the maximal glottal openings. The accuracy of this tracking was verified through direct human observation of these points relative to the actual images. The mean amplitude in millimeters was computed independently for the right and left vocal fold.

RESULTS

Membranous vocal fold length, entire vocal fold length, and midmembranous vibratory amplitude for self-selected habitual pitch with constant loudness were calculated for the three participants. The estimated vocal fold length during phonation for the adult male was 17.62 mm, for the adult female was 12.69 mm, and for the male child was 6.84 mm (Table I). The membranous length of the vocal fold as expected was smaller than the length of the

entire vocal fold during phonation (Table II). Table I shows the camera distance and tilt angle obtained through a bilinear interpolation of the highest match scores made with the neighboring templates and the laser projection pattern on the glottis image.

Bounds on the precision of estimating vocal fold length owing to the sensitivity of camera motion were obtained from the maximum and minimum glottal length estimates made from the neighboring template. In all cases the endoscope was between 7 and 8 cm from the field of view. For the adult male and female, the tilt angle was between 10 and 15 degrees, and for the child it was between -5 and 0 degrees. A 5.4% (± 0.95 mm) variation exists in the estimates of vocal fold length for the adult male, 3.4% (± 0.43 mm) for the adult female, and 3.3% (± 0.27 mm) for the child. Motion of the camera inherent during endoscopy resulted in less than 5% variability in estimating the vocal fold length. The measurement precision, evident from the estimates of standard deviation (Table I and Table II) of this custom-built laser endoscope, is well below the pixel resolution of the images, which is approximately 0.2 mm per pixel, indicative of high measurement repeatability. The standard deviations were computed over estimates of length and amplitude, resulting from threshold variations used to extract the pattern shape from the glottal image. The results show almost negligible measurement variation.

The mean peak midmembranous vibratory amplitude for the child (0.25 mm) was smallest (Table III and Table IV) compared to the adult female (0.84) and adult male (0.93). The standard deviations of the peak amplitudes normalized by their mean showed greatest variability for the child (30%) compared to 7% for adult female and 5% for adult male. Asymmetric displacement about the midline was observed for the child and adult male, and the adult female showed a symmetric behavior (Fig. 6). In addition, the male participant exhibited a consistent nonsymmetry between the opening and closing dynamics.

DISCUSSION

The proposed laser projection system along with HSDI shows feasibility for obtaining quantitative measurements of vocal function in the pediatric population. The position of the endoscope relative to the glottal image plane can be determined with appropriate calibration, as long as the projected pattern changes uniquely with depth and tilt. This alleviates the precision required to construct and mount lasers to provide parallel projection with a constant distance in the projection plane.^{10,11} It also allows for more freedom of motion for the clinician in that the laser points do not have to be projected onto a regular surface of the vocal folds that will not distort the projected dots with a fixed distance. This is especially critical in the pediatric population, when endoscopy sometimes could be challenging. A disadvantage of this method is that it requires a calibration process of creating templates to match the pattern distortion. However, the calibration process is only required one time for the device. Templates for the pattern changes can be stored in the software along with the corresponding pixel-to-millimeter conversion images.

A critical aspect of the system related to performance was matching the extracted laser points to those of the calibrated image. Movement error on the order of 1 cm can result in up to a 5% error. Similarly, a matching error resulting in the wrong template could also result in a similar level of error. Matching errors can result from significant distortions for patterns and irregularities due to diffraction and tissue specularly and absorption. Some of these distortions due to diffraction and tissue properties were inherent in this experiment. However, the robustness of the resulting measurements was enhanced by taking the median root to smooth out small structural irregularities on edges from diffusion and diffraction. Correlation of the binary images is an inherently robust operation. The thresholding process that focused on shape of the pattern rather than grey levels also reduced the variability in the

match. Although the thresholding at different gray levels can change the shape and size of the pattern, results showed that this threshold when selected over a wide range of values (25 gray levels) resulted in negligible variation. This is in part due to the high contrast of the projected pattern used.

Although this system projected two laser points, the second point was never used in any significant capacity. It did help with the horizontal alignment on the images. Because this single projection method showed high-precision measurements, future devices would only need a single laser and could be made smaller or more easily embedded in the endoscope itself. The result of further miniaturization of the laser endoscopic device could make it feasible to obtain quantitative measurements of the pediatric glottis in children as young as 3 years. One major improvement to this system would be to distribute many smaller patterns over the imaging plane and use local correlation, using concepts of structured light. This way the critical patterns would distribute over the image and fall naturally on the flatter surfaces of the fold, and the clinician would not have to be concerned with positioning the scope to place the pattern on a specific position. The principles of the device and measurement systems using calibration grids and pattern templates could be directly applied.

Quantitative measurements of vocal fold lengths and vibratory amplitudes during phonation for adults were similar to those reported in the literature.^{8–10} We report first in vivo quantitative measurements of vocal fold length and vibratory amplitude for a 9-year-old child. As expected, the child showed shorter vocal fold length, reduced vibratory amplitude, and greater peak-to-peak variation in the midmembranous vibratory amplitude compared to the adults. Overall for all participants, the length of the vocal fold during phonation is smaller than the measurements of vocal fold lengths reported during abduction. The study findings lend preliminary evidence to the amount of shortening of the vocal fold length during phonation, due to rotation and translation motion of the vocal process.¹⁷ Future studies on measurement of vibratory length in vivo may lead to development of age-specific biomechanical models, critical for understanding of vocal fold tension and dynamic strain, which are factors related to high-impact stress in children and the assessment of treatment outcomes by providing measurement of lesion size before and after treatment in children.

Greater variability in peak-to-peak vibratory amplitude in children could be attributed to variability in aerodynamic power or could be a result of the immature vocal fold ligament and the layered structure of the vocal folds.^{2,3,6,7} For all participants, mean amplitude differences between left and right vocal fold were observed, indicative of asymmetric peak excursion between the two vocal folds. Group studies quantifying the vibratory features as a function of growth and development with the use of laser projection with HSDI are warranted. Future studies on quantitative measurements of such vibratory features may lead to the development of empirically based age-appropriate paradigms for early identification and therapeutic management of pediatric dysphonia.

CONCLUSION

The custom-built laser device and the calibration procedure resulted in quantitative measurements of vocal fold length and vibratory amplitude with low standard deviations, suggestive of high measurement repeatability. The device was used to successfully extract measurements from a child. The unique aspect of this system is that it uses only one laser dot pattern for greater potential for miniaturization. The calibration method introduced in this paper determines the depth and angle of the camera relative to the glottal plane and can be applied to various projection patterns. The important characteristics for the projected pattern are shape and size sensitivity to changes in camera position, robust shape extraction

from the clinical image, and pattern location on the vocal fold regions for natural camera positions in imaging the glottal region.

Clinical Applicability

Further research is required for the clinical applicability of HSDI and the laser-point endoscope in a typical pediatric clinic. Currently the technologic limitations related to data storage and camera light prevent high-speed imaging to replace standard stroboscopy, especially in a busy clinical practice. Also, the current commercially available high-speed systems do not have the option of coupling a projection system to a flexible endoscope. Clearly, in its current state, HSDI can be viewed as an augmentation instead of replacement, especially in cases with stroboscopy tracking errors.¹² The addition of laser endoscopy, although useful, will require further studies to determine whether the slip-fit attachment withstands repeated insertion of the endoscope in Cidex® (Civco Medical Solutions, Kalina, IA) for disinfection. Future devices can include projection pattern inside the endoscope (similar to the optics for the illumination), with laser patterns extended over the field of view for ease of projection of laser patterns in the field of interest. Finally, the acceptable intensity levels and frequency for projected laser patterns need to be studied further and alternatives explored if the projected pattern is not visible in the illuminating light required to capture vocal fold vibrations at capture rates of 5,000 frames per second. These issues are being explored in future implementations to make this practical for use in a busy clinic.

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BIBLIOGRAPHY

1. 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; 115:784–788. [PubMed: 17076102]
2. Hartnick CJ, Rehbar R, Prasad V. Development and maturation of the pediatric human vocal fold lamina propria. *Laryngoscope*. 2005; 115:4–15. [PubMed: 15630357]
3. Hirano, M.; Kurita, S.; Nakashima, T. Growth, development, and aging of human vocal fold. In: Bless, DM.; Abbs, JH., editors. *Vocal Fold Physiology: Contemporary Research and Clinical Issues*. San Diego, CA: College-Hill Press; 1983. p. 22-43.
4. Kahane JC. A morphological study of the human prepubertal and pubertal larynx. *Am J Anat*. 1978; 151:11–19. [PubMed: 623031]
5. Kahane JC. Growth of the human prepubertal and pubertal larynx. *J Speech Hear Res*. 1982; 25:446–455. [PubMed: 7176619]
6. Sato K, Hirano M, Nakashima T. Fine structure of the human newborn and infant vocal fold mucosae. *Ann Otol Rhinol Laryngol*. 2001; 110:417–424. [PubMed: 11372924]
7. 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*. 1999; 108:232–238. [PubMed: 10086614]
8. Schuberth S, Hoppe U, Dollinger M, Lohscheller J, Eysholdt U. High-precision measurement of the vocal fold length and vibratory amplitudes. *Laryngoscope*. 2002; 112:1043–1049. [PubMed: 12160271]
9. Popolo PS, Titze IR. Qualification of a quantitative laryngeal imaging system using videostroboscopy and videokymography. *Ann Otol Rhinol Laryngol*. 2008; 117:404–412. [PubMed: 18646436]
10. Larsson H, Hertegard S. Calibration of high-speed imaging by laser triangulation. *Logoped Phoniatr Vocol*. 2004; 29:154–161. [PubMed: 15764209]

11. George NA, de Mul FF, Qiu Q, Rakhorst G, Schutte HK. New laryngoscope for quantitative high-speed imaging of human vocal folds vibration in the horizontal and vertical direction. *J Biomed Opt.* 2008; 13:064024. [PubMed: 19123670]
12. Patel R, Dailey S, Bless D. Comparison of high-speed digital imaging with stroboscopy for laryngeal imaging of glottal disorders. *Ann Otol Rhinol Laryngol.* 2008; 117:413–424. [PubMed: 18646437]
13. Wolf M, Primov-Fever A, Amir O, Jedwab D. The feasibility of rigid stroboscopy in children. *Int J Pediatr Otorhinolaryngol.* 2005; 69:1077–1079. [PubMed: 16005350]
14. Hartnick CJ, Zeitels SM. Pediatric video laryngostroboscopy. *Int J Pediatr Otorhinolaryngol.* 2005; 69:215–219. [PubMed: 15656955]
15. Hertegard S. What have we learned about laryngeal physiology from high-speed digital videoendoscopy? *Curr Opin Otolaryngol Head Neck Surg.* 2005; 13:152–156. [PubMed: 15908812]
16. Wittenberg T, Moser M, Tigges N, Eysholdt U. Recording, processing, and analysis of digital high-speed sequences in glottography. *Mach Vis Appl.* 1995; 8:399–404.
17. Titze I. Physiological and acoustic differences between male and female voices. *J Acoust Soc Am.* 1999; 85:1699–1707. [PubMed: 2708686]

Fig. 1. Pediatric two-point laser projection endoscope. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Fig. 2. Relations of laser assembly and laser beam path for the two-point laser projection system with a 70-degree endoscope. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Fig. 3. Setup for creating calibration grid images, where d is the depth of the image field and θ is the tilt angle.

Fig. 4.

(A) Endoscope image with laser projection on calibrated grid. Line crossings correspond to 5.08 mm in x and y directions. (B) Outline of template dot at P_c . Positions of glottal points superimposed with X markers at P_1 and P_2 . The grid crossing points involved in distance measurements are denoted with circular markers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Fig. 5.

(A) Endoscope image with laser projection on vocal fold. (B) Outline of projected dot at Gc with positions for glottal length measurement denoted with X markers at G₁ and G₂. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Fig. 6. Left and right vocal fold displacements from glottal line based on the pixel-to-millimeter conversion from the glottal length points: (a) male child, (b) adult female, and (c) adult male. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE I

Vocal Fold Lengths Using Interpolated Template Estimates of the Nearest Neighboring Templates.

Subject	Interpolated Vocal Fold Length, mm	Standard Deviation	Template Angle, degrees	Template Depth, cm
Adult male	17.62	0.003	12.31	7.46
Adult female	12.69	0.002	12.36	7.47
Child	6.84	0.0002	-3.12	7.37

TABLE II

Membranous Length Using Interpolated Template Estimates of the Nearest Neighboring Templates.

Subject	Interpolated Membranous Length, mm	Standard Deviation	Template Angle, degrees	Template Depth, cm
Adult male	12.62	0.002	12.31	7.46
Adult female	9.96	0.002	12.36	7.47
Child	3.66	0.0004	-3.12	7.37

TABLE III

Amplitude Estimates Over 0.5 Seconds Phonation Segment for Left Vocal Fold.

Subject	Mean, mm	Standard Deviation, mm	Pitch, Hz
Adult male	1.09	0.03	155.6
Adult female	0.88	0.04	239.0
Child	0.22	0.07	261.9

TABLE IV

Amplitude Estimates Over 0.5 Seconds Phonation Segment for Right Vocal Fold.

Subject	Mean, mm	Standard Deviation, mm	Pitch, Hz
Adult male	0.88	0.03	155.6
Adult female	0.80	0.04	239.0
Child	0.29	0.06	261.9