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State of the Art Laryngeal Imaging: Research and Clinical Implications

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Abstract

Purpose of Review—This paper provides a review of the latest advances in videostroboscopy, videokymography and high-speed videoendoscopy, and outlines the development of new laryngeal imaging modalities based on optical coherence tomography, laser depth-kymography, and magnetic resonance imaging, published in the past 2 years.

Videostroboscopy and Videokymography: Image quality has improved and several image processing and measurement techniques have been published.

High-speed videoendoscopy: Significant progress has been made through increased sensitivity and frame rates of the cameras, and the development of facilitative playbacks, phonovibrography and several image segmentation and measurement methods. Clinical evidence was presented through applications in phonosurgery, comparisons with videostroboscopy, normative data, and better understanding of voice production.

Optical coherence tomography: Latest developments allow for the capture of dynamic high resolution cross-sectional images of the vibrating vocal fold mucosa during phonation.

Depth-kymography: New laser technique allowing recording of the vertical movements of the vocal folds during phonation in calibrated spatial values.

Laryngeal magnetic resonance: New methods allow high-resolution imaging of laryngeal tissue microstructure, or measuring of dynamic laryngeal structures during phonation.

Summary—The endoscopic laryngeal imaging techniques have made significant advances increasing their clinical value, while techniques providing new types of potentially clinically-relevant information have emerged.

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Introduction

Visualization of the structure and function of the vocal folds has become an essential component of the clinical voice assessment protocol [1]. The term "laryngeal imaging" typically refers to the endoscopic imaging of vocal fold tissue vibration via videostroboscopy, videokymography (VKG), or high-speed videoendoscopy (HSV). Recent reviews emphasized the need for further technological, methodological and clinical research on laryngeal imaging, including the development of clinical norms and objective image processing and measurement methods [1–4]. A comprehensive overview of the most recent advances in endoscopic laryngeal imaging technology combined with all of the information needed to interpret findings and successfully manage patients with voice disorders can be found in [5**]. This paper provides a review of the latest advances in HSV, VKG and videostroboscopy, and outlines the development of new laryngeal imaging modalities based on optical coherence tomography (OCT), laser depth-kymography, and magnetic resonance imaging (MRI), published in the past 2 years.

Videostroboscopy and Videokymography

Videostroboscopy is the most widely used clinical technique for laryngeal imaging. A well-known drawback of videostroboscopy is the reliance on quasi-periodic voice signals [5**] when producing a real-time slow-motion stroboscopic effect. For dysphonic patients exhibiting increased perturbation in the microphone or electroglottographic tracking signal, which constitute a large percentage of the population with voice disorders, videostroboscopy is not a useful diagnostic tool because it cannot reconstruct a slow motion movie of the intra-glottal cycle. This is the main reason why videostroboscopy requires supplementation by VKG and why it will be eventually supplanted by HSV. Nevertheless, videostroboscopy possesses characteristics that will not be matched easily by other techniques, i.e. real-time visualization with simultaneous audio playback, easily achievable superior image quality, lengthy recordings with established procedures for compression and archiving [6]. The advent of distal-chip nasal laryngoscopy [7] offers superior quality of structural imaging that HSV and VKG will not be able to achieve in the near future, especially with nasal endoscopy. A late publication [8] reported the advent of a full high-definition (1080i) videostroboscopy system. Despite of emerging new techniques, videostroboscopy will continue to offer certain advantages.

VKG is a high-speed imaging modality, which is often supplementing videostroboscopy when viewing irregular vibratory patters by scanning a particular cross-section of the posterior-anterior axis of the vocal folds. Among the recent improvements in VKG, the most noticeable are the new-generation videokymography providing concurrent real-time kymographic and videostroboscopic imaging [9] and the detailed descriptive protocol for visual evaluation of VKG [10]. A noticeable recent trend is the increased effort in the development of automated image segmentation and quantification techniques for VKG [11] and videostroboscopy [12], of a quantitative laryngeal imaging system using videostroboscopy [13], and a method for automatic mucosal wave extraction from VKG [14*]. These automated techniques are essential not only because they offer immediate implementation with the established clinical modalities of videostroboscopy and VKG, but because their principles are fully applicable to HSV, as well.

High-Speed Videoendoscopy

HSV provides reliable functional and structural sampling of the larynx. HSV possesses the clear potential to replace videostroboscopy as the leading endoscopic laryngeal imaging technique. The most significant challenges and advances in the clinical and basic-science implementation of laryngeal HSV have been detailed in [5**,15*].

Advantages of HSV over videostroboscopy and VKG

By default, HSV overcomes the limitations of videostroboscopy, allowing the visualization and objective measurement of the vocal-fold vibratory behavior regardless of whether this behavior is periodic or aperiodic [5**]. HSV records a full image of the vocal folds with high-temporal resolution, a significant advantage over VKG. HSV is a superset of videostroboscopy and VKG, allowing to produce simulated stroboscopy (SSA) and digital kymography (DKG) playbacks [15*]. Videostroboscopy is applicable only with sustained phonation tasks for individuals with stable phonatory characteristics. HSV allows for the accurate and reliable assessment of those tasks in individuals with stable or unstable phonatory characteristics, i.e. pronounced dysphonia. HSV is applicable for evaluating transient vocal-fold vibratory behaviors, such as, phonatory breaks, laryngeal spasms, and the onset and offset of phonation. It can be used for tasks involving vocal attack, coughing, throat clearing, laughing, and other activities involving rapid laryngeal maneuvers. In a recent study [16*], imaging with DKG demonstrated an ability to assign a signal type to various laryngeal vibrations. Braunschweig et al. [17*] used HSV to develop a quantitative parameterization scheme of the phonatory onset, a new approach in developing objective methods for the diagnosis of functional dysphonia. Orlikoff et al. [18*] used HSV to record the phonatory onset at soft, normal and hard glottal attack, in order to validate a vocal attack time measurement, which is further discussed. The current challenges of HSV come from the fact that it is still a work in progress, in which new technologies and methodologies need to follow the clinical needs, while clinical evidence and norms are being established.

Technological breakthroughs

Sensitivity, frame rate, integration time, color, pixel resolution and dynamic range are the most important high-speed camera characteristics relevant to laryngeal HSV [5**,15*]. Today, the most sensitive high-speed cameras have monochrome sensitivity of 7,000 ISO (Vision Research, Inc., Wayne, NJ) and 6,400 ISO (Photron Inc., San Diego, CA), and color sensitivity of 2,100 and 1,600 ISO, respectively. Their characteristics are now sufficient to allow superior image quality with rigid HSV at 8,000 fps in color, and 20,000 fps in monochrome [5**]. A recent study alerted that a typically used frame rate of 2,000 fps is insufficient when evaluating the mucosal wave characteristics [19*]. A report of a low-cost HSV system [20] being commercially available is encouraging for the broad introduction of HSV. However, the system operates at 600–1200 fps, a frame rate likely insufficient for evaluation of many clinical features. More research is necessary to establish the camera characteristics required in a clinical evaluation and how these requirements relate to a specific clinical protocol.

Advances in methodology

HSV contains an enormous amount of biomechanical information about the vocal fold vibration. But this large amount of data is difficult to navigate through. The presentation of the HSV content to the clinician can be made either visually or through measurements. Thus, the methodology for voice evaluation via HSV can be achieved via visual perceptual ratings and measures, and via automatic objective measures, or by combining them in a way intuitive to the clinician. Analytic phase plots [21] have been used to graphically visualize and measure vibratory patterns of the glottal area waveform obtained through HSV.

Facilitative playbacks [15*] have been developed to emphasize particular aspects of the vocal fold vibration, i.e. spatial, temporal, mucosal wave and vertical aspects. Combinations of the DKG playback, mucosal wave (MW) playback, mucosal wave kymography (MKG) playback, three-dimensional (3D) playback, and objective measurements have been used to provide normative information about vibratory features typically evaluated through the voice assessment protocol, such as periodicity [22*], symmetry [23], mucosal wave [19*], open quotient, glottal closure and mucus aggregation [24].

Another significant development in HSV methodology was the advent of phonovibrography (PVG), a method for mapping HSV movies of vocal fold vibrations into 2-dimensional diagrams for visualizing and analyzing the underlying laryngeal dynamics [25,26*]. A preliminary study [27] and a follow-up investigation [28*] found that continuous voice use (vocal loading) during the workday stresses the vocal folds in healthy subjects and can be detected by applying the PVG technique.

Image segmentation is an important process for detecting and extracting the features of interest that are later subjected to measurement. In HSV, there are three types of segmentation: temporal, spatial and spatiotemporal segmentation. Temporal segmentation, which helps identify the time periods of interest in an HSV recording was presented in [15*]. HSV spatial segmentation was reported using region growing [29], thresholding [21,30**] or level set [31] algorithms. Spatiotemporal segmentation based on paired active contours was recently developed [32] into a fast, reliable and accurate algorithm.

Comparison to videostroboscopy, HSV normative data

Several late studies from different teams compared directly videostroboscopy to HSV when evaluating a very similar range of clinical vibratory features: cycle and width periodicity [22*]; phase asymmetry [23]; mucosal wave [19*]; mucus aggregation [24]; glottal configuration, phase closure, symmetry, mucosal wave, amplitude, and periodicity [33*]; and vocal fold edge, glottal closure, phase closure, vertical level, amplitude, mucosal wave, phase symmetry, tissue pliability, and periodicity [34*]. Although interpretation of the data varied among teams, the data were actually very similar. One thing in common between those studies was the finding that HSV norms are very different from videostroboscopic. These studies contributed significantly by providing preliminary HSV norms.

HSV in phonosurgery

Recently, HSV was used to gain better insights into the voice production mechanisms of patients who have undergone endoscopic phonosurgical treatment of early glottic cancer [30**] that cannot be obtained with videostroboscopy. The use of HSV with time-synchronized acoustic voice signal enabled direct correlations between acoustic parameters and measures of glottal closure and vibratory symmetry extracted from HSV. This information should substantially assist surgeons in identifying biomechanical phonatory mucosal deficits and the effectiveness of implant reconstruction efforts.

HSV as a tool in basic voice science

Above the potential of HSV as a clinical tool is the role of HSV as a powerful technique for refining our understanding of voice production. HSV is a great tool in investigating the interrelations between the biomechanical aspects of vocal-fold vibration, i.e. the vocal-fold physiology, and other biofeedback signals that have been traditionally used for the evaluation of vocal function. HSV was successfully used in the experimental validation of a non-invasive measure of vocal attack time during the onset of phonation through measuring the time lag between the rise of the acoustic and electroglottographic signals [18*]. The relationship between the glottal area waveform as computed through HSV and the glottal flow waveforms obtained by inverse-filtering the acoustic signal was studied in [35]. A direct linkage of measures of vocal-fold contact obtained through electroglottography to visual physiologic measures of vocal-fold contact through HSV allowed to cross-validate several electroglottographic features [36]. Automated image and signal processing methods were used to reveal relationships between vocal-fold vibratory function and the resulting acoustic characteristics of the voice [21,30**].

Another area of basic research is the use of HSV in improving the theoretical models of voice production. HSV recordings were taken as a basis to simulate the five common glottis closure types during normal phonation in [37]. Schwarz et al. [29] utilized HSV to obtain a parametric description of the spatio-temporal characteristics of the vocal fold oscillations. Murugappan et al. [38*] used HSV to determine the effect of higher subglottal pressures on higher harmonics and loudness when unilateral vocal fold scarring is present. The influence of asymmetric vocal fold stiffness on voice production was evaluated using HSV on life-sized, self-oscillating vocal-fold fabricated physical models [39].

Optical Coherence Tomography

Traditionally, imaging of the vocal folds has been primarily limited to endoscopic viewing of the mucosal surfaces, in the form of static pictures to document the presence or absence of pathology, or via video recordings utilizing stroboscopic, high-speed, and/or kymographic techniques to capture the motion of the mucosal surfaces (vocal fold vibration) during phonation. Since 1997, there have been numerous papers published that describe the use of OCT to acquire static cross-sectional images of the layered microstructure of vocal fold mucosa; which in a normal vocal fold would include the epithelium and the different levels of the lamina propria [40–42]. OCT uses interferometry of backscattered near-infrared light to image cross-sections of tissue down to a depth of approximately 2 mm with a resolution of about 10 μm. In vocal folds this offers the possibility for assessing histopathology (optical biopsy) or surgically-induced alterations to the mucosa that can not be obtained with traditional surface imaging. More recent technological advances in OCT have resulted in much faster image acquisition rates than were originally possible. One leading version of this newer technology, optical frequency domain imaging (OFDI), has already been used to produce dynamic cross-sectional imaging/movies of vocal fold mucosa during a sub-epithelial injection [43] and during phonation at frame rates that were still too slow to track true vibratory activity [44]. However, this second publication is one example of a study that demonstrated the potential to employ non-contact OCT through a transoral endoscope in an awake patient. Efforts are already underway to couple the faster sampling of newer OCT technology with stroboscopic-like triggering to allow the capture of high resolution cross-sectional images (3D volumes) of the vibrating vocal fold mucosa during phonation [45**]. This could provide the unprecedented capability to more directly relate quantitative measures of tissue biomechanics to normal and pathological states of the vocal fold layered microstructure, within the ~2 mm limit in tissue penetration of OCT and for voices that are periodic enough for stroboscopic sampling.

Depth-Kymography

Traditionally, the visualization of the surface of the vocal folds via laryngoscopy provides a two-dimensional image in a horizontal plane, which is not calibrated in size. Precise knowledge of the absolute dimensions of human vocal folds and their vertical vibration parameters has significant importance in clinical diagnosis and intervention. Depth-kymography is a novel laser line-triangulation laryngoscopic technique for the quantitative visualization of the vertical (upward-downward) movements of the vocal folds during phonation, allowing for in-vivo recording of the third dimension of the tissue surface movements in absolute values [46]. The vibration profiles in both horizontal and vertical directions are calibrated and measured in absolute units with a resolution of ±50 μm. The same team employed depth-kymography in studying the generation and propagation of mucosal waves by locating the position of their maximum vertical position and the propagation velocity [47*]. In a follow-up study, direct quantitative comparisons between 3D profiling measurements and simulations of human vocal fold vibrations were reported [48] validating the technique. Depth-kymography has the potential to become an important addition to the voice assessment protocol.

Magnetic Resonance Imaging

High-resolution MRI had been used to construct a three-dimensional anatomical model of the cartilages of the human larynx [49], providing an anatomical framework for registering different larynges to the same coordinate space. Lately, a three-dimensional educational computer model of the larynx was developed from MRI scans [50]. Two recent studies opened new directions for applying MRI for laryngeal imaging: MR microimaging of excised larynges confirmed valid high-resolution imaging of laryngeal tissue microstructure [51*], and dynamic MRI of laryngeal and vocal fold vibrations was realized for the first time for measuring of laryngeal structures and glottal parameters in dynamic function [52*].

Conclusion

Within the last 2 years, there have been published reports of new developments in endoscopic imaging, where the biggest advance was marked in the development of new methods for and the clinical validation of high-speed videoendoscopy. New laryngeal imaging modalities based on optical coherence tomography, depth-kymography and magnetic resonance imaging carry significant clinical appeal, especially the optical coherence tomography.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

** of outstanding interest

1. Mehta DD, Hillman RE. Voice assessment: Updates on perceptual, acoustic, aerodynamic, and endoscopic imaging methods. Current Opinion in Otolaryngology and Head and Neck Surgery 2008;16 (3):211–215. [PubMed: 18475073]

2. Deliyski DD. Clinical Feasibility of High-Speed Videoendoscopy. Perspectives on Voice and Voice Disorders 2007;17(1):12–16.

3. Doellinger M. The next step in voice assessment: High-speed digital endoscopy and objective evaluation. Current Bioinformatics 2009;4(2):101–111.

4. Verikas A, Uloza V, Bacauskiene M, Gelzinis A, Kelertas E. Advances in laryngeal imaging. European Archives of Oto-Rhino-Laryngology 2009;266(10):1509–1520. [PubMed: 19618198]

5**. Kendall, KA.; Leonard, R., editors. Laryngeal evaluation: Indirect laryngoscopy to high-speed digital imaging. New York, NY: Thieme Medical Publishers, Inc; 2010. (This comprehensive, full-color reference provides a thorough overview of the most recent advances in endoscopic laryngeal imaging technology combined with the information needed to interpret findings and successfully manage patients with voice disorders.)

6. Crump JM, Deutsch T. Exchanging digital video of laryngeal examinations. J Voice 2004;18(1):13–23. [PubMed: 15070220]
7. Kawaida M, Fukuda H, Kohno N. Electronic videoendoscopic laryngostroboscopy. ORL J Otorhinolaryngol Relat Spec 2004;66(5):267–274. [PubMed: 15583441]
8. Tsunoda A, Hatanaka A, Tsunoda R, Kishimoto S, Tsunoda K. A full digital, high definition video system (1080i) for laryngoscopy and stroboscopy. J Laryngol Otol 2008;122(1):78–81. [PubMed: 17623492]
9. Qiu Q, Schutte HK. Real-time kymographic imaging for visualizing human vocal-fold vibratory function. Rev Sci Instrum 2007;78(2):024302. [PubMed: 17578128]
10. Švec JG, Šram F, Schutte HK. Videokymography in voice disorders: what to look for? Ann Otol Rhinol Laryngol 2007;116(3):172–180. [PubMed: 17419520]
11. Manfredi C, Bocchi L, Bianchi S, Migali N, Cantarella G. Objetive vocal fold vibration assessment from videokymographic images. Biomedical Signal Processing and Control 2006;1(2):129–136.
12. Osma-Ruiz V, Godino-Llorente JI, Sáenz-Lechón N, Fraile R. Segmentation of the glottal space from laryngeal images using the watershed transform. Comput Med Imaging Graphics 2008;32(3):193–201.
13. Popolo PS, Titze IR. Qualification of a quantitative laryngeal imaging system using videostroboscopy and videokymography. Ann Otol Rhinol Laryngol 2008;117(6):404–412. [PubMed: 18646436]
14*. Jiang JJ, Zhang Y, Kelly MP, Bieging ET, Hoffman MR. An automatic method to quantify mucosal waves via videokymography. Laryngoscope 2008;118(8):1504–1510. (This study proposed a least squares method to quantify the vibratory properties of each of the four vocal fold lips via VKG. The method allows for easy determination of the four sets of vibratory parameters, and examination of the effect of biomechanical parameters on vocal fold vibrations.). [PubMed: 18545215]
15*. Deliyski DD, Petrushev PP, Bonilha HS, Gerlach TT, Martin-Harris B, Hillman RE. Clinical implementation of laryngeal high-speed videoendoscopy: Challenges and evolution. Folia Phoniatrica et Logopaedica 2008;60(1):33–44. (This paper summarizes the practical, technological and methodological challenges and advances in HSV, and shares the authors' vision of the necessary steps towards developing HSV into a robust clinical tool for laryngeal evaluation.). [PubMed: 18057909]
16*. Zhang Y, Krausert CR, Kelly MP, Jiang JJ. Typing vocal fold vibratory patterns in excised larynx experiments via digital kymography. Ann Otol Rhinol Laryngol 2009;118(8):598–605. (In this study, imaging with digital kymography demonstrated an ability to assign a signal type to various laryngeal vibrations. Signal typing techniques utilizing direct observation of the vocal folds could be useful in determining valid methods for the analysis of vocal fold vibrations.). [PubMed: 19746760]
17*. Braunschweig T, Flaschka J, Schelhorn-Neise P, Döllinger M. High-speed video analysis of the phonation onset, with an application to the diagnosis of functional dysphonias. Medical Engineering and Physics 2008;30(1):59–66. (This paper presents a method in which HSV was used to record the phonation onset process at different sound pressure levels allowing for a quantitative parameterization of the phonatory onset, a new approach in developing an objective method for the diagnosis of functional dysphonia.). [PubMed: 17317268]
18*. Orlikoff RF, Deliyski DD, Baken RJ, Watson BC. Validation of a glottographic measure of vocal attack. Journal of Voice 2009;23(2):164–168. (This study used HSV to validate a new non-invasive vocal attack time measurement, which is the time lag between the rise of the sound pressure and electroglottographic signals. Manual measures of HSV recordings of the phonatory onset at soft, normal and hard glottal attack had strong correlations with the new acoustic-glottographic measure.). [PubMed: 18083343]
19*. Shaw HS, Deliyski DD. Mucosal wave: A normophonic study across visualization techniques. Journal of Voice 2008;22(1):23–33. (This study compared visual evaluations of the mucosal wave using videostroboscopy, HSV and HSV-based facilitative playbacks. Results demonstrated prevalence of atypical mucosal wave by normophonic persons, differences across imaging techniques, and a relationship between visual judgments and fundamental frequency. A major

conclusion was that the frame rate of 2000 fps appears insufficient for most female habitual phonations.). [PubMed: 17014988]

20. Sekimoto S, Tsunoda K, Kaga K, Makiyama K, Tsunoda A, Kondo K, Yamasoba T. Commercially available high-speed system for recording and monitoring vocal fold vibrations. Acta Otolaryngol 2009;129(12):1524–1526. [PubMed: 19922108]
21. Yan Y, Damrose E, Bless D. Functional analysis of voice using simultaneous high-speed imaging and acoustic recordings. J Voice 2007;21(5):604–16. [PubMed: 16968665]
22*. Bonilha HS, Deliyski DD. Period and glottal width irregularities in vocally normal speakers. Journal of Voice 2008;22(6):699–708. (This study compared visual evaluations of the periodicity of the glottal cycle and width using videostroboscopy, HSV and HSV-based facilitative playbacks. The results suggested that period irregularities are less frequent in normophonic speakers than glottal width irregularities, findings questioning the physiological source of acoustic jitter. There was a lack of confidence in rating aperiodicities through stroboscopy.). [PubMed: 18031989]
23. Bonilha HS, Deliyski DD, Gerlach TT. Phase asymmetries in normophonic speakers: Visual judgments and objective findings. American Journal of Speech-Language Pathology 2008;17(4): 367–376. [PubMed: 18840697]
24. Bonilha HS, Aikman A, Hines K, Deliyski DD. Vocal fold mucus aggregation in vocally normal speakers. Logopedics Phoniatrics Vocology 2008;33(3):136–142.
25. Lohscheller J, Eysholdt U, Toy H, Dollinger M. Phonovibrography: mapping high-speed movies of vocal fold vibrations into 2-D diagrams for visualizing and analyzing the underlying laryngeal dynamics. IEEE Trans Med Imaging 2008;27(3):300–309. [PubMed: 18334426]
26*. Lohscheller J, Eysholdt U. Phonovibrogram visualization of entire vocal fold dynamics. Laryngoscope 2008;118(4):753–758. (This is a presentation of a visualization procedure that extracts vocal fold vibrations from HSV and transfers the motion information into a set of three phonovibrogram (PVG) images that make visual vocal fold displacements, velocities, and accelerations. The PVG approach makes visual the entire range of motion of vibrating vocal fold edges.). [PubMed: 18216742]
27. Lohscheller J, Doellinger M, McWhorter AJ, Kunduk M. Preliminary study on the quantitative analysis of vocal loading effects on vocal fold dynamics using phonovibrograms. Ann Otol Rhinol Laryngol 2008;117(7):484–493. [PubMed: 18700422]
28*. Doellinger M, Lohscheller J, McWhorter A, Kunduk M. Variability of normal vocal fold dynamics for different vocal loading in one healthy subject investigated by phonovibrograms. J Voice 2009;23 (2):175–181. (This is an investigation of the potential of HSV and the phonovibrogram (PVG) analysis to document the effects of continuous voice use (vocal loading) during the workday in normal vocal fold dynamics. Constant voice usage stresses the vocal folds in healthy subjects and can be detected by applying the PVG technique.). [PubMed: 18313896]
29. Schwarz R, Döllinger M, Wurzbacher T, Eysholdt U, Lohscheller J. Spatio-temporal quantification of vocal fold vibrations using high-speed videoendoscopy and a biomechanical model. J Acoust Soc Am 2008;123(5):2717–2732. [PubMed: 18529190]
30**. Mehta DD, Deliyski DD, Zeitels SM, Quatieri TF, Hillman RE. Voice production mechanisms following phonosurgical treatment of early glottic cancer. Ann Otol Rhinol Laryngol 2010;119(1): 1–9. (This study provided the first insight into postoperative voice production mechanisms following phonosurgical treatment of early glottic cancer that cannot be obtained with videostroboscopic assessment. The use of simultaneous, time-synchronized HSV and acoustic recordings can help better understand and further optimize phonosurgical interventions.). [PubMed: 20128179]
31. Skalski, A.; Zieliński, T.; Deliyski, D. Proceedings of the International Conference on Signals and Electronic Systems ICSES 2008. Kraków, Poland: AGH University of Science and Technology Press; Analysis of vocal folds movement in high speed videoendoscopy based on level set segmentation and image registration; p. 223-226.
32. Moukalled, HJ.; Deliyski, DD.; Schwarz, RR.; Wang, S. Segmentation of Laryngeal High Speed Videoendoscopy in Temporal Domain using Paired Active Contours. In: Manfredi, C., editor. Proceedings of the 6th International Workshop on Models and Analysis of Vocal Emissions for Biomedical Applications MAVEBA. Firenze. Italy: Firenze University Press; 2009. p. 137-140.

33*. Kendall KA. High-speed laryngeal imaging compared with videostroboscopy in healthy subjects. Archives of Otolaryngology - Head and Neck Surgery 2009;135(3):274–281. (This preliminary study describes a range of normal values for vocal fold vibratory characteristics as recorded with laryngeal HSV, providing a basis for comparison of studies in patients with voice problems.). [PubMed: 19289706]

34*. 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(6):413–424. (This study investigated the clinical value of HSV compared to that of videostroboscopy across three voice disorder groups classified as epithelial, subepithelial, and neurologic disorders. HSV may aid in clinical decision-making for cases of severe dysphonia when patients exhibit values exceeding 0.87% jitter, 4.4% shimmer, and a signal-to-noise ratio of less than 15.4 dB.). [PubMed: 18646437]

35. Schwarz RR, Deliyski DD. Experimental analysis of the relationship between the glottal flow and glottal area waveforms. J Acoust Soc Am 2008;123(5;2):3740.

36. Golla, ME.; Deliyski, DD.; Orlikoff, RF.; Moukalled, HJ. Objective Comparison of the Electroglottogram to Synchronous High-Speed Images of Vocal-Fold Contact During Vibration. In: Manfredi, C., editor. Proceedings of the 6th International Workshop on Models and Analysis of Vocal Emissions for Biomedical Applications MAVEBA. Firenze, Italy: Firenze University Press; 2009. p. 141-144.

37. Yang A, Lohscheller J, Berry DA, Becker S, Eysholdt U, Voigt D, Döllinger M. Biomechanical modeling of the three-dimensional aspects of human vocal fold dynamics. J Acoust Soc Am 2010;127 (2):1014–1031. [PubMed: 20136223]

38*. Murugappan S, Khosla S, Casper K, Oren L, Gutmark E. Flow fields and acoustics in a unilateral scarred vocal fold model. Ann Otol Rhinol Laryngol 2009;118(1):44–50. (This study used HSV on a unilateral scarred excised canine larynx model and determined that higher subglottal pressures may excite higher harmonics and improve loudness for patients with unilateral vocal fold scarring. This finding implies that therapies that raise the subglottal pressure may be helpful in improving voice quality.). [PubMed: 19244963]

39. Pickup BA, Thomson SL. Influence of asymmetric stiffness on the structural and aerodynamic response of synthetic vocal fold models. J Biomech 2009;42(14):2219–2225. [PubMed: 19664777]

40. Burns JA, Zeitels SM, Anderson RR, Kobler JB, Pierce MC, de Boer JF. Imaging the mucosa of the human vocal fold with optical coherence tomography. Ann Otol Rhinol Laryngol 2005;114(9):671–676. [PubMed: 16240928]

41. Klein AM, Pierce MC, Zeitels SM, Anderson RR, Kobler JB, Shishkov M, de Boer JF. Imaging the human vocal folds in vivo with optical coherence tomography: a preliminary experience. Ann Otol Rhinol Laryngol 2006;115(4):277–284. [PubMed: 16676824]

42. Vokes DE, Jackson R, Guo S, Perez JA, Su J, Ridgway JM, Armstrong WB, Chen Z, Wong BJ. Optical coherence tomography-enhanced microlaryngoscopy: preliminary report of a noncontact optical coherence tomography system integrated with a surgical microscope. Ann Otol Rhinol Laryngol 2008;117(7):538–547. [PubMed: 18700431]

43. Burns JA, Kim KH, Kobler JB, deBoer JF, Lopez-Guerra G, Zeitels SM. Real-time tracking of vocal fold injections with optical coherence tomography. Laryngoscope 2009;119(11):2182–2186. [PubMed: 19676103]

44. Yu L, Liu G, Rubinstein M, Saidi A, Wong BJ, Chen Z. Office-based dynamic imaging of vocal cords in awake patients with swept-source optical coherence tomography. J Biomed Opt 2009;14(6): 064020. [PubMed: 20059258]

45**. Kobler JB, Chang EW, Zeitels SM, Yun S. Dynamic imaging of vocal fold oscillation with 4D optical coherence tomography. Laryngoscope. in press. (This is the first report of triggering optical coherence tomography in a manner similar to laryngeal videostroboscopy to provide a dynamic 3-dimensional view of the layered microstructure of the vocal folds during phonatory vibration.).

46. 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(6):064024. [PubMed: 19123670]

47*. George NA, de Mul FF, Qiu Q, Rakhorst G, Schutte HK. Depth-kymography: high-speed calibrated 3D imaging of human vocal fold vibration dynamics. Phys Med Biol 2008;53(10):2667–2675. (Depth-kymography is a novel laser line-triangulation laryngoscopic technique for visualization of the vertical movements of the vocal folds during phonation. This study investigated the generation and propagation of mucosal waves by locating the position of their maximum vertical position and the propagation velocity.). [PubMed: 18443389]

48. de Mul FF, George NA, Qiu Q, Rakhorst G, Schutte HK. Depth-kymography of vocal fold vibrations: part II. Simulations and direct comparisons with 3D profile measurements. Phys Med Biol 2009;54 (13):3955–3977. [PubMed: 19494425]
49. Selbie WS, Gewalt SL, Ludlow CL. Developing an anatomical model of the human laryngeal cartilages from magnetic resonance imaging. J Acoust Soc Am 2002;112(3 Pt 1):1077–1090. [PubMed: 12243156]
50. Hu A, Wilson T, Ladak H, Haase P, Fung K. Three-dimensional educational computer model of the larynx: voicing a new direction. Arch Otolaryngol Head Neck Surg 2009;135(7):677–681. [PubMed: 19620589]

51*. Herrera VL, Viereck JC, Lopez-Guerra G, Kumai Y, Kobler J, Karajanagi S, Park H, Hillman R, Zeitels SM. 11.7 Tesla magnetic resonance microimaging of laryngeal tissue architecture. Laryngoscope 2009;119(11):2187–2194. (This study utilized MR microimaging of excised larynges allowing high-resolution imaging of laryngeal tissue microstructure. Histology confirmed the utility of MR microimaging of modeled scar, implant residence time, and tissue responses.). [PubMed: 19824052]

52*. Ahmad M, Dargaud J, Morin A, Cotton F. Dynamic MRI of larynx and vocal fold vibrations in normal phonation. Journal of Voice 2009;23(2):235–239. (This study used dynamic MRI of the larynx and vocal folds during phonation for measuring the vertical laryngeal movements and the glottal angle of the vocal folds opening and closing in dynamic phase.). [PubMed: 18082366]