The Evolution of Methods for Imaging Vocal Fold Phonatory Function

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Abstract

In this article, we provide a brief summary of the major technological advances that led to current methods for imaging vocal fold vibration during phonation including the development of indirect laryngoscopy, imaging of rapid motion, fiber optics, and digital image capture. We also provide a brief overview of new emerging technologies that could be used in the future for voice research and clinical voice assessment, including advances in laryngeal high-speed videoendoscopy, depth-kymography, and dynamic optical coherence tomography.

In this article, we briefly summarize the evolution of methods for visualizing the phonatory function of human vocal folds in terms of past, present, and future technological developments. We focus primarily on imaging approaches for observing and/or documenting the vibratory behavior of vocal folds during voice production.

The Past to the Present

There have been four major technological developments over the past 150 years that have contributed significantly to the current state of the art in imaging vocal fold phonatory function: indirect laryngoscopy, imaging of rapid motion, fiber optics, and digital image capture.

Indirect Laryngoscopy

Indirect laryngoscopy refers generically to the use of reflected light and images to observe the larynx; this is in contrast to *direct laryngoscopy*, which is performed under general anesthesia in the operating room. In 1807, Phillip Bozzini described the first instrument for looking into accessible orifices of the body (e.g., throat, rectum) that he named the “Lichtleiter” (light conductor) because it used a candle and a reflector to direct light through various sizes of probe tubes or cannulae (Bozzini, 1807). The cannula that he designed for the throat had an additional mirror to enable visualization of the lower pharynx and larynx, thus accomplishing the first indirect (using mirrors) laryngoscopic examination. Following this seminal work, experts began describing other devices for accomplishing mirror laryngoscopy over the first half of the 19th century; however, like Bozzini's earlier work, they did not attract much attention or acceptance by the medical community.

It took the efforts of a prominent singing teacher, Manuel Garcia, to popularize what he referred to as "auto-laryngoscopy" (self-performed mirror laryngoscopy) in a famous publication entitled *Observations on the Human Voice* that was first presented to the Royal Society of London in 1855 (Garcia, 1855). Garcia's astute observations of laryngeal physiology during singing facilitated the subsequent widespread adoption of mirror laryngoscopy by physicians (Clerf, 1956). Turck (1858) and Czermak (1861), two prominent physicians in the 1850s, promoted the clinical use of mirror laryngoscopy in the western world by conducting laryngoscopy clinics/workshops throughout Europe while publically feuding about which of them deserved more credit for pioneering the techniques.

Further advances in the clinical use of indirect mirror laryngoscopy that took place in the mid- to late-19th century came about after the development of instruments and methods for performing transoral laryngeal and airway surgical procedures on awake patients in Europe and post-Civil War United States (Elsberg, 1864; Stoerk, 1859). Although mirror laryngoscopy is still used clinically by some physicians for transoral laryngeal examinations, this approach almost totally has been replaced by more modern rigid endoscopic telescopes that provide magnification in clinics specializing in voice and laryngology.

Imaging of Rapid Motion

During phonation, the vocal folds can open and close over 100 times per second and vibrate at velocities approaching 1 meter per second (Schuster, Lohscheller, Kummer, Eysholdt, & Hoppe, 2005), making it impossible to view dynamic laryngeal motion with the unaided eye during indirect mirror laryngoscopy. *Stroboscopy* is based on creating an optical illusion in which rapid motion appears to be slowed down to a perceivable rate by illuminating it with a light that flashes at an appropriate frequency. Unfortunately, authors of much of the classic voice literature mistakenly have attributed this effect to perceptual properties described by Talbot's law and the persistence of vision. In actuality, the critical visual phenomena are the perception of flicker-free light intensity and the perception of apparent motion from sampled images (Mehta, Deliyski, & Hillman, 2010).

The first strobe-based device designed to observe vocal fold vibration was the *laryngostroboscope*, initially introduced by Oertel in 1878 and subsequently improved upon with the addition of an electric power supply in 1895 (Oertel, 1895). For his laryngostroboscope, Oertel used a perforated pinwheel that he rotated in front of a light source to produce the flashes of light needed for stroboscopic viewing of vocal fold vibration. One major challenge for an expert using the laryngostroboscope was achieving the right relationship between vocal pitch (fundamental frequency) and the speed of pinwheel rotation (rate of light flashes) to get an adequately stable view of vocal fold vibration.

The pitch-matching problem was not effectively addressed until the 1950s when experts began to develop systems that automatically synchronized the flash rates of the light source with estimates of fundamental frequency to produce stroboscopic images of vocal fold vibration (von Leden, 1961; von Leden, Moore, & Timcke, 1960). Bless, Hirano, and Feder (1987) facilitated the adoption of laryngeal stroboscopy into routine clinical voice practice in the United States when they published *Videostroboscopic Evaluation of the Larynx*.

Even though laryngeal stroboscopy is currently the gold standard in clinical voice assessment, it has inherent limitations. First, the strobe effect only can be produced if the motion being observed is adequately periodic; thus, stroboscopy is typically incapable of revealing vocal fold vibratory patterns once dysphonia (aperiodicity) exceeds a moderate level (Patel, Dailey, & Bless, 2008). Second, even when successful, stroboscopy provides a global visualization of periodic motion that is not sensitive enough to capture cycle-to-cycle variations in vocal fold vibration (Hillman & Mehta, 2010). Clinicians overcome these limitations by using high-speed imaging because they can record at rates that are much higher than, and not dependent on, a speaker's fundamental frequency.

In the late 1930s, Farnsworth conducted the first documented investigations of *slow-motion capture* of the vocal folds using a high-speed motion picture camera (Farnsworth, 1940; Herriott & Farnsworth, 1938). The setup, devised at Bell Laboratories, included two mirrors and an incandescent lamp and achieved a sampling rate of 4,000 pictures per second. Others advanced the Bell Labs equipment, adding color photography and xenon light for illumination (Moore, White, & Von Leden, 1962), as well as noise reduction methods and insulation material to permit high-quality recording of the acoustics. Researchers in additional studies introduced important refinements to the endoscopic methodology, light illumination, and sensitivity of the analog motion picture camera for use in viewing the laryngeal anatomy and vocal fold motion (Brubaker & Holinger, 1947; Gould, Jako, & Tanabe, 1974; Le Cover & Rubin, 1960; Metz, Whitehead, & Peterson, 1980; Moore et al., 1962; Tribe & Shelton, 1957). Notably, the cumbersome nature of manual frame-by-frame analysis of massive reels of cinematic film restricted the early use of high-speed filming to research applications.

Švec and Schutte developed the alternative high-speed imaging technique of *videokymography* when they modified standard video camera technology to capture cycle-to-cycle-based estimates of vocal fold vibratory behavior (Švec & Schutte, 1996). In this technique, the camera only scans one line in the field of view instead of the entire laryngeal image. With the reduction in image density, the camera's hardware resources can be reappropriated to increase the line scan rate to approximately 8,000 line scans per second. Thus, clinicians using videokymography took advantage of high-speed frame rates by trading off spatial information to compactly represent left-to-right vocal fold motion at one location along the anterior-posterior glottal axis. This approach has gained more popularity in Europe than in the United States.

Fiber Optics

In the early 1950s, Hopkins and colleagues were among the first to begin experimenting with passing the light from an illuminated image through a bundle of coherent glass fibers with the goal of using this technology for endoscopic examination of accessible body cavities (Hopkins & Kapany, 1954). Glass proved to exhibit ideal properties for passing light in a bendable medium, acting as an optical waveguide that took advantage of the physics of total internal reflection to replace the prior use of multiple lenses in rigid endoscopes. The tensile strength, transparency, and homogeneity of glass made it an excellent material with which to construct long, flexible fibers. Hirschowitz and his collaborators pushed the endoscopic application of fiber optic technology forward in the late 1950s to produce the first fiber-optic gastroscope (Hirschowitz, Curtis, & Peters, 1958).

Sawashima and colleagues (Sawashima & Hirose, 1968) reported the first laryngeal images captured with transnasal flexible fiberscopes. The availability of flexible fiberoptic laryngoscopy had a significant clinical impact, making it possible to perform laryngeal examinations on most individuals who could not tolerate transoral endoscopy, which was particularly applicable to pediatric patients. Transnasal endoscopy also provided a means to observe more natural laryngeal function during a wider range of speech and non-speech tasks compared to transoral endoscopy, which limits the speaker to sustained vowel phonation and involves procedures that influence how the larynx functions (e.g., holding the extended tongue outside of the mouth).

High-speed laryngeal imaging has also made use of fiberoptic technology to capture phonatory function during the production of different vowels (Maurer, Hess, & Gross, 1996). Unfortunately, the optical resolution and illumination provided by flexible fiberscopes is inferior to that of rigid telescopes. Thus, clinicians prefer a transoral procedure using a rigid endoscope over flexible fiberscopes for better image quality and endoscope stability, which are especially critical for slow-motion capture.

Digital Image Capture

Since the 1930s the development of image capture devices have been driven by industries as diverse as the military, medicine, and television broadcasting (Weimer, 1976). Early devices converted optical information to electrical signals using various forms of photo-conductive tubes, such as RCA's "vidicon" vacuum tube. Subsequent advances in photosensitive detectors led Boyle and Smith (1970) to conceive of the charge-coupled device (CCD) at Bell Laboratories . Their colleagues obtained the first empirical results using CCDs (Amelio, Tompsett, & Smith, 1970). For their development of the CCD, Boyle and Smith shared the Nobel Prize in Physics in 2009.

Following the development of CCD technology, researchers began investigating ways to miniaturize the digital image capture electronics while maintaining or improving image quality. It was not until Japanese imaging laboratories began researching active pixel sensor (APS) research, which was further developed by researchers at the Jet Propulsion Laboratory, that large-scale, miniature camera-on-chip technology was made available (Fossum, 1993). APS devices are popularly known as CMOS (complementary metal-oxide semiconductor) sensors, so named after their typical manufacturing process. Placing miniature imaging chips on the distal end of flexible endoscopes has greatly improved the image quality that can be obtained during a transnasal laryngeal examination as compared to using the older fiberoptic imaging technology.

Digital image capture refers to the ultimate conversion of electrical signals to a sequence of ones and zeros that can be understood by a computer. The brightness of several parts of an image are thus encoded and stored in binary format within a specified dynamic range. Color, temporal resolution, and dynamic range are limited by the sensitivity of the camera sensor. New ultra-high-speed digital video processors, made possible because of the increased light sensitivity of image sensors, recently have become available in systems designed for clinical use (Deliyski et al., 2008).

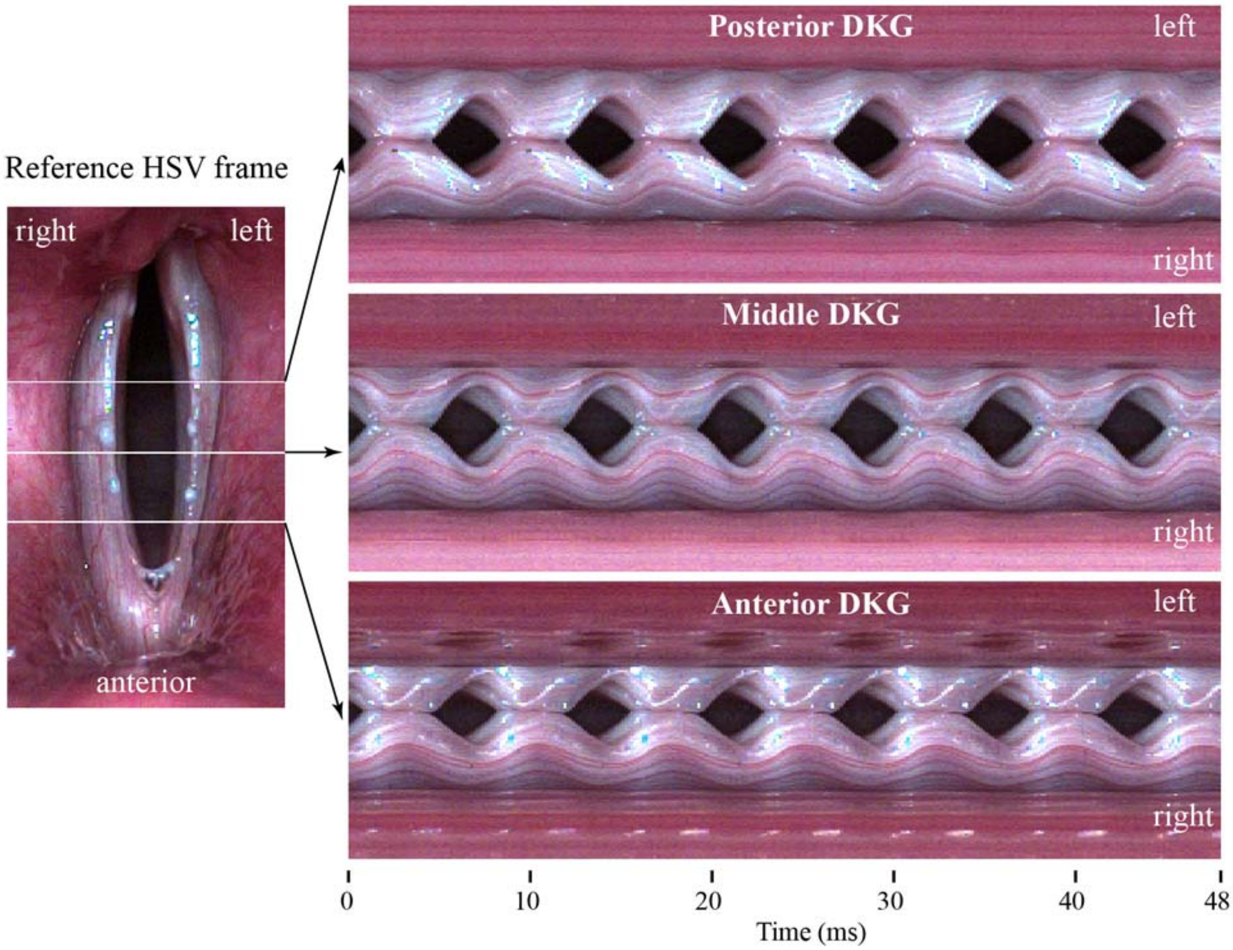
The Future of Laryngeal Imaging

Laryngeal High-Speed Videoendoscopy

Researchers have accomplished major advances in high-speed imaging technology in recent years in order to couple rigid and flexible endoscopes with sensitive solid-state image sensors to accomplish high-quality *laryngeal high-speed videoendoscopy* (HSV). Recently, Vision Research integrated a new self-resetting CMOS sensor with custom features to obtain excellent imaging characteristics. Equipped with a 70° rigid endoscope and a 300-watt constant Xenon light source, the camera enables typical laryngeal HSV with 24-bit RGB color, 10,000 frames per second, spatial resolution up to 800x600 pixels, sample duration up to 32 s, and viewing angle as in stroboscopy (Deliyski & Hillman, 2010). Advances in laryngeal HSV are making it possible for researchers to investigate critical relationships between vocal fold physiology and acoustic voice production in human subjects. For example, researchers are developing HSV systems with synchronous acquisition of acoustics, electroglottography, neck skin acceleration, and, in the most comprehensive setup, airflow and intraoral pressure (Mehta, Zañartu, Quatieri, Deliyski, & Hillman, 2011).

It is almost as important for researchers to determine how to process the massive amount of data generated by HSV imaging as it is to collect the data in the first place. HSV-based signal processing approaches include spectral techniques (Granqvist & Lindestad, 2001), spatio-temporal analysis (Lohscheller, Eysholdt, Toy, & Döllinger, 2008; Neubauer, Mergell, Eysholdt, & Herzel, 2001), and Nyquist analysis of the time-varying glottal area (Yan, Damrose, & Bless, 2007). Other processing approaches seek to preserve and facilitate/enhance the visualizations of HSV images by deriving additional video playbacks (as opposed to difficult-to-interpret contours and measures), including simulated stroboscopy, digital kymography, mucosal wave playback and kymography, and three-dimensional reconstruction (Deliyski et al., 2008). In Figure 1, we display an example of digital kymography (DKG) performed on the color HSV recording of a vocally normal adult male producing a sustaining vowel(6,250 frames per second). The validity, practicality, and clinical relevance of high-speed technology continue to be studied to understand its role clinical voice assessment.

Figure 1: Illustration of DKG From the Posterior, Middle, and Anterior Positions Along the Glottal Axis.



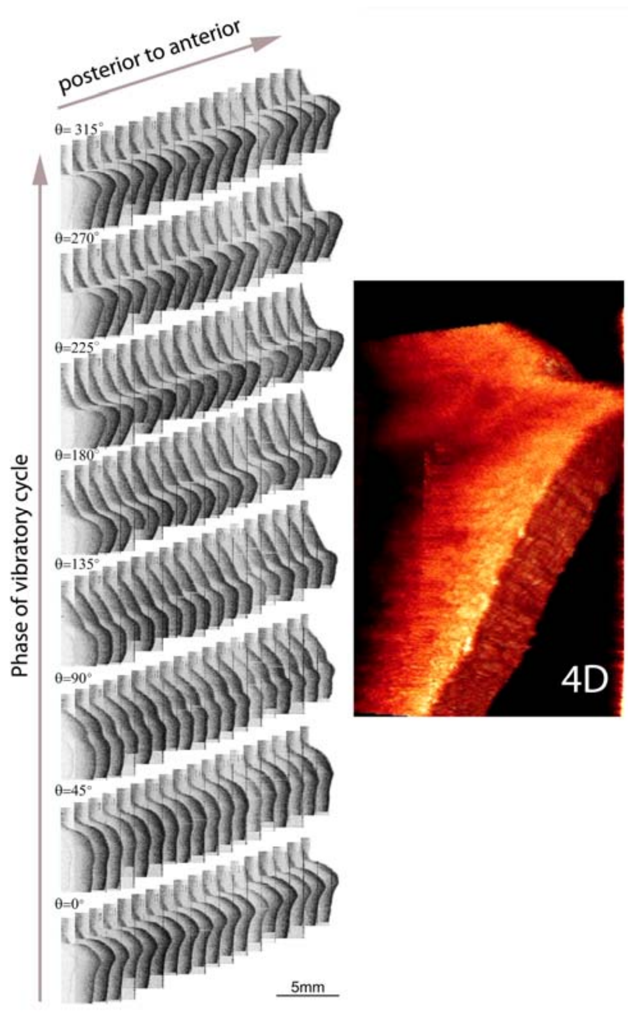
Depth-Kymography

Traditionally, clinicians visualizing the surface of the vocal folds via laryngoscopy see a two-dimensional image in a horizontal plane. Depth-kymography is a novel laryngoscopic technique that uses laser line triangulation to track the vertical movements of the larynx during phonation (George, de Mul, Qiu, Rakhorst, & Schutte, 2008). Researchers using this method obtain in vivo recordings of the third (superior-inferior) dimension that is missing in traditional endoscopic images. With a better understanding of the vibration profiles output (they are still kymographic line scans instead of full-frame images), depth-kymography has the potential to become an important addition to the voice assessment protocol.

Dynamic Optical Coherence Tomography

Clinicians using traditional endoscopic methods are limited to surface visualizations of the vocal fold mucosa. Some have attempted to extract information regarding the layered microstructure of the vocal folds using optical coherence tomography (OCT), in which they acquire cross-sectional images of the vocal fold epithelium and different levels of the lamina propria (Burns et al., 2005). Enhanced imaging of these tissue layers provides critical information related to mucosal wave generation. Yu and colleagues demonstrated the potential of non-contact OCT through a transoral endoscope in an awake patient, although at frame rates much too low for capturing vocal fold phonatory function (Yu et al., 2009). In Figure 2, we illustrate an effort underway to couple the faster sampling of newer OCT technology with stroboscopic-like triggering to allow the capture of high-resolution cross-sectional images of the vibrating vocal fold mucosa during phonation (Kobler, Chang, Zeitels, & Yun, 2010). We display stroboscopic OCT images of 18 coronal planes along the anterior-posterior glottal axis for 8 different phases within the vocal fold vibratory cycle of a calf excised hemilarynx.

Figure 2. Stroboscopic OCT Images. In the Image on the Right, Experts Use a Single Frame From a Four-Dimensional OCT Movie To Visualize Motion Across the Vocal Fold Surface and the Full Depth of the Mucosal Wave.



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