

# Chapter 10

## High-speed laryngeal imaging compared to videostroboscopy in the clinical setting

Katherine A. Kendall

### Abstract

Although videostroboscopy is used most commonly in a clinical setting to image the larynx, it has several drawbacks that can be overcome by using high-speed imaging of the larynx. High-Speed Digital Imaging (HSDI) of the larynx has been performed since the 1930's but remained impractical for clinical use until recently because of high cost and cumbersome equipment. The development of commercially available high-speed imaging systems using smaller, more affordable cameras has now made it possible to use this technology in a clinical setting. High-speed imaging has the potential to advance the functional assessment of vocal pathophysiology, ultimately improving the ability to diagnose and manage vocal fold (VF) pathology. Recent advances include color imaging and the ability to accurately synchronize and compare VF vibration and acoustic data. However, several barriers to widespread clinical use of this technology remain. This chapter will review recent advances and ongoing challenges in the clinical use of HSDI compared to videostroboscopy.

**Keywords:** *high speed imaging, laryngoscopy, larynx imaging*

### Introduction

The visual evaluation of VF vibration is an integral part of the work-up and management of patients with voice disorders. Glottal vibratory characteristics have been presumed to be one of the main determinants of voice quality and therefore, their assessment is considered to be integral to both the diagnosis of voice disorders and the determination of treatment outcomes. However, human VF vibrate at a rate of 70 to 1000 times per second and because human visual perception is limited to approximately 15 images per second, the evaluation of VF vibration must rely on technology to “slow down” the rate of vibration and allow the visual analysis of VF vibratory characteristics.

The most common clinical technique currently used to visualize VF vibration is videostroboscopy. Videostroboscopy depends on the measurement of a stable acoustic phonation frequency to determine the rate of strobe flashing and thus, image acquisition. In other words, strobe flash rates depend on the analysis of the acoustic wave form of the patient's phonation. With a maximum recording rate of 30 f/s, the strobe is typically set to flash at a frequency much slower than the frequency of VF vibration and is synchronized so that images are captured from sequential points in the vibratory cycle. As the images thus captured are replayed, they give the impression of a slow-motion movie of the VF in vibration. It is, in reality, a “virtual” movie of VF vibration, made up of images captured at slightly different points from several different vibratory cycles, spliced together to look like sequential vibration.

Although videostroboscopy is the most widely used clinical tool for VF evaluation, it has significant drawbacks. Because it relies on measurement of the acoustic signal

to determine strobe flash frequency, videostroboscopy, cannot be used when a stable vibratory frequency cannot be measured. Laryngeal pathology that results in hoarseness is commonly associated with an unstable frequency of vibration, leading to tracking errors when using videostroboscopy for analysis in these patients. Even small variations in periodicity can affect the strobe sequences and give an erroneous impression of the vibratory characteristics. In a severely disordered voice, fundamental frequency can be impossible to measure. Furthermore, due to a delay in reaching a stable frequency and relaying the information to the strobe, videostroboscopy cannot be used if the patient is unable to phonate for at least 3 seconds or in situations of rapid frequency change such as during the onset or offset of speech. Videostroboscopy samples from approximately every eighth glottal cycle and it is unknown if the information lost from those eight intervening glottal cycles has clinical significance.

The introduction of high-speed imaging of the larynx into clinical practice has expanded the ability to image VF vibration to include situations that cannot be successfully evaluated using videostroboscopy. HSDI of the larynx uses a high-speed camera to capture real-time images at a rate of 2000 to 4000 f/s, independent of the frequency of VF vibration. High-speed imaging of the larynx has the potential to overcome many of the disadvantages of videostroboscopy because image capture rates are independent of the frequency of VF vibration and are significantly higher. The rate of image capture is fast enough to obtain multiple images from a single cycle of vibration and when played back, images can be viewed as an “actual” slow motion movie of VF vibration. Because HSDI does not require the measurement of a stable vibratory frequency to adjust the rate of image acquisition, it can be used successfully in situations where the frequency of vibration is changing rapidly, such as during the onset and offset of voicing and in patients with aperiodic voices, tremor, or laryngeal spasms. Thus, HSDI offers significant potential benefits over standard videostroboscopy in the diagnosis and analysis of patients with irregular VF motion.

It is generally believed that enhanced visualization of VF pathophysiology with HSDI will aid in determining both the etiology and treatment of VF disorders. While Satalof's work comparing indirect or flexible laryngeal examination to rigid videostroboscopy demonstrated an improvement of diagnostic capabilities that clearly impacted clinical care, a similar study comparing HSDI to videostroboscopy has yet to be done [1]. It has been shown in up to 62% of patients presenting with a voice complaint that videostroboscopy is unable to be used due to aperiodic vocal frequency causing an inability of the strobe to properly track. However, HSDI can be successfully used in these patients to visualize and analyze VF vibration [2].

Although studies comparing observations of VF vibratory characteristics in normal populations have demonstrated good agreement between HSDI and videostroboscopy, studies comparing the two technologies in patient populations with voice abnormalities have shown significant differences [2-3]. More accurate analysis of VF vibration achieved with HSDI could potentially change the care of the patient. As an example, Mortensen and Woo published a case report in which HSDI was used to diagnose a VF paresis that was not apparent on videostroboscopy [4]. But in order for HSDI to be used routinely as a clinical tool, it must be shown to positively impact clinical decision making and patient outcomes in a wide variety of clinical situations.

### **Current protocols, imaging frame rates, and data acquisition for high-speed laryngeal imaging**

HSDI techniques use conventional rigid endoscopes to record images of the larynx with a full view of the superior laryngeal surface. Patient positioning for high-speed imaging is the same as for videostroboscopy. The focal length of the high speed camera is relatively

narrow and it is helpful to try to pre-focus the camera using a template while positioning the scope end approximately 2 inches from the template. The endoscope, with camera attached, is inserted into the pharynx transorally, in the same manner as is done for videostroboscopy, and the images can be viewed on a monitor. Using a foot pedal control, the examiner can save the last 8 seconds of recording for future playback and analysis.

Due to the amount of data generated from that number of images, recording time is usually limited to 2-8 seconds. However, this is sufficient to evaluate most phonatory behaviors. The recorded images are either color or black and white and can be played back in slow motion for analysis. The playback speed can be adjusted as needed.

Because the rate of image capture with high-speed laryngeal imaging is stable, the number of images captured per vibratory cycle depends on the frequency of VF vibration. More images are captured per cycle at low vibration frequencies and fewer images are captured at higher frequencies of vibration. For example, with an image capture rate of 4000 f/s at the low end of the fundamental frequency range (150 Hz) 26-28 images are captured per vibratory cycle. At the higher end of the range (250 Hz) only 16 images per cycle can be captured. In female singers, the rate of image capture may be insufficient to analyze vocal abnormalities that occur at the high end of their singing register. Delyliski et al. determined that 16 images per cycle are required for adequate analysis of the mucosal wave, which is considered the parameter that best reflects the health of the VF lamina propria [5]. When possible, HSDI frame rates should be adjusted to optimize analysis based on the patient's phonation frequency. Videostroboscopy, on the other hand, is unable to record events that are shorter than 4 to 5 cycles in duration with four to eight cycles occurring between each single image captured.

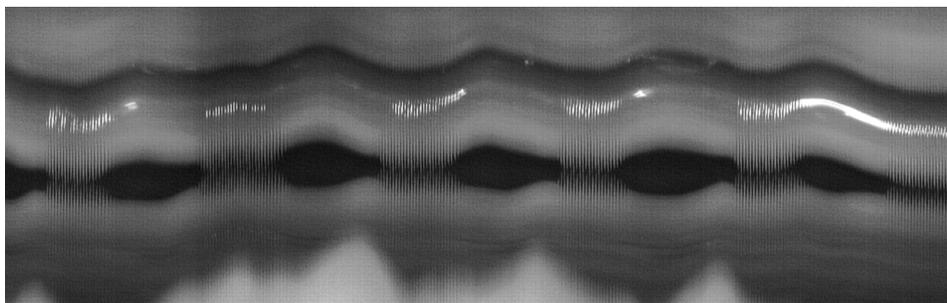
When videostroboscopy is used in the clinical setting for the analysis of VF vibration, study interpretation is done subjectively by the clinician. Although a qualitative method of evaluation, this practice has been helpful in evaluating the overall characteristics of VF behaviors. In an attempt to standardize this type of analysis, assessment forms have been developed and shown to be effective [6]. Because the characteristics of vibration usually assessed with videostroboscopy (amplitude of vibration, mucosal wave, periodicity, phase characteristics, glottic configuration, symmetry, and the presence of adynamic segments) can also be evaluated with HSDI, similar assessment forms have been used in the interpretation of HSDI studies [2-3, 7]. These studies have demonstrated acceptable inter- and intra-rater reliability, similar to those achieved with videostroboscopy [6, 8-10]. However, as with videostroboscopy, there are measurable rater effects on the results, even when each judge has had extensive clinical experience with analysis of laryngeal imaging [2-3].

In general, the development of an examination protocol for use with HSDI is recommended. This ensures that the final recording is optimal for a full evaluation of all vibratory parameters. Because the onset and offset of voicing is one parameter that can only be evaluated with high-speed laryngeal imaging, it should be included in the examination protocol. An attempt should be made to record voicing at or near the patient's fundamental frequency, however this is not always an easy task. Often, in order to bring the larynx into view for recording, the patient is asked to voice at a frequency above the fundamental, effectively elevating the larynx for viewing. It is therefore important to establish the fundamental frequency prior to the onset of recording and then to attempt viewing of the larynx at that frequency. In general, a range of 20 Hz above or below the average fundamental frequency is accepted as representative of the fundamental frequency. Because some vibratory abnormalities occur only at certain frequencies and because vibratory characteristics are affected by the frequency of vibration, it is important that recording at a high pitch and then at a lower pitch also be performed. The remainder of the examination can be tailored to the patient specific complaints.

### Data analysis

In developing the imaging protocol, it must be kept in mind that with HSDI, 2000-4000 frames are recorded for each second of vibration and review of the images is usually done at a rate of 9-10 f/s. Therefore, a minimum of 3.7 minutes are needed to review one second of voicing and up to 60 minutes is needed to review the entire 8 seconds of voicing recorded in the study. Most clinicians don't have 60 minutes to review each study and most often will look at much smaller segments of the study to make assessments, which may limit the ability to recognize clinically relevant findings. When clinicians are free to make assessments from any part of the study, there may be differences in interpretation based on variables including loudness, pitch, effort level, and modal register of the subject [11-12]. Furthermore, changes in frequency of vibration may not be as easily identified with HSDI as they are with videostroboscopy because the observed difference from cycle to cycle may be subtle and requires the examiner to review many cycles to assess.

One feature of most clinically available HSDI systems that can help overcome the difficulties of cycle to cycle analysis is the digital kymography function [13]. The kymograph displays the movement of the VF edges at a point along the anterior-posterior axis of the VF. The point can be chosen by the examiner. The computer then creates a vertical display of the movement at that point over time so that several cycles of vibration can be seen simultaneously and changes in vibration frequency can be easily identified (Figure 1). The kymograph function is also helpful with the evaluation of symmetry of vibration between the two VF and it can also be used to evaluate the mucosal wave. Further analysis can be done to create sine waves describing VF motion in terms of mucosal wave amplitude, phase difference and frequency of vibration [14-16]. Although the use of kymography is very helpful, this technique is still significantly limited by the fact that only one point along the A-P axis of the glottic opening can be analyzed at a time, precluding the detection of A-P asymmetries of vibration. Furthermore, as the analysis relies on the manual reviewing of the image, only a relatively small number of images can be viewed at a time. Ultimately, the effective analysis of the large amounts of data collected with HSDI will depend on the development of software that allows rapid interpretation and synthesis of the data. This transition from a "qualitative" videostroboscopic analysis to a "quantitative" HSDI analysis, however, has the potential to significantly increase the accuracy of image interpretation.



**Figure 1.** Computer-generated kymograph.

Real-time processing of thousands of high-speed image frames requires an image detection method that is automatic, highly accurate, and efficient in extracting VF vibratory patterns. Several software programs for HSDI analysis have been developed recently. Similar to the information obtained with digital kymography, but analyzing the entire superior view of the VF simultaneously, the analysis of the glottal area wave form (GAW) has been proposed as a mechanism to help integrate the large amount of data obtained

from high-speed studies [12]. Subsequent analysis of the GAW can determine the amplitude and frequency of vibration and can determine the open/closed quotient. Programs used to rapidly detect the position of the VF edges from successive high-speed images and then calculate the GAW have been developed. Zhang et al. developed software that uses Lagrange interpolation, differentiation, and Canny edge detection to process 100 high-speed images in 1.2 minutes. They have demonstrated the software to be effective in clinical situations [17]. Other methods of data analysis have applied a Hilbert transform to the GAW to calculate instantaneous amplitude and frequency measures. This software program presents the data as a Nyquist plot [10, 20].

Phonovibrograms are another mechanism for the evaluation of large amounts of high-speed data. This method transforms the motion of the entire VF from all the images in a high-speed video sequence into one single image, representing the VF motion with color. The software allows the calculation of the Glottal Closure Index (a measure of the relative size of any glottic opening at maximal closure), the Relative Amplitude Ratio (a measure of vibration asymmetries between the right and left VF), as well as Normalized Amplitude Shift (used to measure any temporal mismatch between the right and left VF) [19-20]. All of these software programs depend on a lack of movement artifact when making measures of VF vibration as movement alters the lighting and inhibits automatic edge detection. Furthermore, it must be kept in mind that measures made with these programs are “relative” measures usually made with AP distance of the glottic opening used as the referent.

Absolute measures of the VF displacement during vibration can be calculated based on the optical properties of the endoscope if the distance from the tip of the scope to the superior surface of the VF is known. This variable changes in every patient but can be determined with the use of a two-point laser triangulation system. Refinements have led to the development of laser systems that are small enough to be clinically practical. Patel et al. have recently demonstrated the feasibility of such a system that was small enough to be used successfully in a child for the measurement of membranous VF length, the entire VF length, and the mid-membranous vibratory amplitude. They concluded that size calculations could be done with one laser point allowing laser triangulation systems to be made even smaller and more easily embedded into an endoscope [21]. A significant advantage of making “absolute” measures over “relative” measures is that the actual size of various lesions can be determined, which might impact treatment decisions and can be used to follow the response to treatment.

### **Normal vibratory characteristics**

Many studies using HSDI have focused on normal VF vibratory behaviors. Collecting normative data and understanding what distinguishes normal from abnormal vibration is necessary to accurately interpret HSDI studies. Differences in the frequency of VF vibration between the two VF and even within the margin of one VF can be seen with HSDI [22]. Because normal voices demonstrate a range of vibratory patterns, it is important to determine if certain vibratory characteristics are required for normal voicing and if the restoration of these characteristics can improve a disordered voice. HSDI has allowed the evaluation of normal laryngeal functioning in situations of rapid pitch change, such as during the onset and offset of voicing and during a glissando. Tissue characteristics as well as the influence of other forces such as aerodynamics, muscle tension and VF length have been studied [23-25].

Recent HSDI studies of normal populations have demonstrated little variation of VF vibratory characteristics within the same and different HSDI recordings. Kunduk et al. made several recordings of 14 normal females and used phonovibrograms to analyze various characteristics of VF vibration. No statistically significant difference in glottal gap,

frequency and amplitude ratios, asymmetrical vibration, open quotient, or speed quotient was found. This study has helped to establish the validity of a single HSDI recording in normal individuals as representative of vibratory characteristics over time [19].

Ahmad et al. used HSDI to study VF vibration in 26 normal females. These authors used Nyquist plots rather than phonovibrograms to view the data. Four vibratory patterns were identified and described as follows. Fifty percent of the women were found to have gradual apposition of the VF at phonation onset, periodic vibration, and an open quotient (OQ) of 0.74. The next most common pattern was identified in 27% of the subjects and was characterized by regular vibration with the VF being together for longer: OQ 0.4-0.7. Fifteen percent of the subjects in the study had a persistent opening at the posterior of the glottis, regular vibration, and wider variations in amplitude and frequency: OQ 0.8. Two subjects from the group (8%) presented with atypical vibratory patterns. All the subjects were rated as having a normal voice. The authors of this study concluded that voices perceived as normal can be produced with several glottal vibratory patterns but regularity of vibration is a consistent characteristic in clear voice production. The authors went on to propose that because females are more likely to develop VF nodules, one of these “normal” vibratory patterns might predispose to voice problems or the development of pathology such as nodules [18].

Differences on HSDI between old and young normal subjects were studied by Yamachi et al. This study did not use computer-based analysis of the data, but rather subjective ratings performed by clinicians familiar with image evaluation. The study found no difference identified between old and young individuals with respect to symmetry, periodicity, closed phase, supraglottic activity, amplitude of vibration, and mucosal wave. Similar to studies using videostroboscopy to evaluate vibratory characteristics, this study found that older females were more likely to have an anterior glottic gap (50%), and that young females were more likely to have a posterior glottic gap compared to males who generally had complete glottic closure. Interestingly, because this study was done using HSDI, the authors were able to identify phase differences in the anterior-posterior direction in 44% of young males, 100% of young females, 50% of elderly males, 42% of elderly females [7].

While HSDI has been demonstrated to be superior to videostroboscopy in the evaluation of vibratory aperiodicity and asymmetry, it has not yet been definitively shown to be more accurate in the measurement of the open/closed quotient and the mucosal wave. The closed quotient is defined as the ratio of the closed phase of vibration and the period and is considered to be reflective of the resistance to airflow during vibration. The closed phase is high with a “pressed” voice and is low in situations of VF atrophy or weakness such as presbyphonia or VF paresis. When using videostroboscopy, the closed phase measurement is based on the “montage” function of the strobe system which selects ten images from a single “virtual” composite “cycle” of vibration and displays them on the screen. The rater then counts the number of images with open vs. closed VF. This method results in an estimate of the percent open/closed phase that is a multiple of ten. The normal closed quotient as measured with videostroboscopy ranges from 40 to 60%.

With HSDI, the assessment of the closed quotient depends on the number of images captured per vibratory cycle and has the potential to be more accurate than videostroboscopy because the measure is made from an “actual” cycle of vibration. However, both VF opening and the mucosal wave start at the lower border of the VF and both videostroboscopy and HSDI are limited to a view of the superior surface of the VF and may not take into account the activity of the lower boarder of the VF on these measures.

Mecke et al. used HSDI, Electroglottography (EEG), and airflow measures to calculate the closed quotient in a study of two boys. HSDI demonstrated the shortest closed quotient, possibly reflecting the problem of not identifying the impact of the lower lip of

the VF on airflow [26]. This may also explain the findings of Ahmad et al., who found that 50% of the women they studied with HSDI had closed quotients of 30%, lower than would be considered to be normal when using videostroboscopy to make the measure [18]. Krausert et al. suggest that the use of EEG simultaneously with HSDI can help to determine when the lower part of the mucosa of the VF margin begins to open in the vibratory cycle, impacting both the closed quotient and mucosal wave [16]. EEG measures the electrical conductance across the VF and therefore, reflects both their vertical and horizontal contact. And indeed, Echterneck et al. used simultaneous HSDI and EEG to study register transitions in 18 normal male subjects and found differences in the open quotient measurement between two modalities. Interestingly, HSDI and EEG measures of the open quotient were only weakly correlated with one another [27]. Further study is needed to understand how HSDI and EEG data should be integrated to reflect true VF movement.

### **Study of abnormal vibration**

Although HSDI is without question the preferred tool for research of normal VF vibratory characteristics, before it is likely to be adopted for widespread clinical use, it must be demonstrated to improve the assessment of abnormal vibration in a way that is clinically significant. Inwald et al. studied 80 normal controls, 232 patients with functional dysphonia, 171 patients with unilateral VF paralysis, and 13 patients with bilateral VF paralysis using HSDI. In this study, 1000 frames from each HSDI recording were used to create a phonovibrogram, as a method for identifying individuals with asymmetries of vibration. The extracted perturbation measures were able to distinguish between normal and abnormal voices as no asymmetry was found in the healthy group. By combining both a blinded subjective assessment of the HSDI recordings and the objective parameters calculated from the studies, an accurate classification was made for 63% of the female subjects and 87.5% of the male subjects in the study [20]. This study demonstrates the potential of using HSDI to differentiate between patient populations but is limited by the fact that the populations studied are not difficult to distinguish clinically without advanced imaging techniques.

On the other hand, Patel et al. used HSDI to study patients with Muscle Tension Dysphonia (MTD) and Adductor Spasmodic Dysphonia (SD). These two pathologic entities can be difficult to distinguish clinically. Both are characterized by aperiodicity and are not able to be adequately evaluated with videostroboscopy. Currently, auditory perceptual features are used to differentiate between the two. In this study, analysis of the HSDI recordings demonstrated definite oscillatory breaks and micro-motions in the SD patients that were not seen in those with MTD. Hyperfunction was seen in MTD but not in SD. Although further study is needed to determine if these characteristics can be used prospectively to distinguish MTD from SD, these results demonstrate one instance where HSDI may prove beneficial over videostroboscopy in the clinical setting [28].

In addition to improving diagnostic accuracy, HSDI has the potential to significantly improve the ability to assess the results of various interventions on VF pathology. Many advances in the surgical treatment of voice disorders depended on the initial evaluation of the technique in an animal model. However, an identical animal match to the human larynx has not been found. HSDI has been used recently to evaluate VF vibratory characteristics in several species and to determine that canine and porcine larynges demonstrate vibratory characteristics closest to those of human larynges [29]. The development of such an animal model has allowed the subsequent assessment of biomaterials designed to treat VF scarring in a canine model using HSDI [30].

In humans, HSDI analysis of glottal area and the amplitude of vibration for each VF has been applied to the evaluation of patients with unilateral VF paralysis both pre- and

post-medialization [8, 31]. Kimura et al. found two distinct frequencies of vibration when comparing the paralyzed with the normal VF with HSDI. Post-operatively, symmetric vibration was restored [32]. Mehta et al. used HSDI to study post-operative results in 14 patients treated with surgery for early glottic carcinoma. The study revealed that patients demonstrated normal closed quotient and vibratory periodicity but cycle vibratory asymmetries of phase, amplitude, and closure axis were identified that likely would have been missed on videostroboscopy. The authors concluded that the asymmetries identified with HSDI may account for the elevated acoustic perturbations found in these patients [33]. This group of researchers went on to assess the relationship between HSDI-based measures and acoustic measures in 20 patients after phonosurgery. They found a relationship between a combination of the HSDI measures of fundamental frequency deviation and average speed quotient and the acoustic measure cepstral peak magnitude, a measure shown to correlate well with perception of vocal quality [34]. HSDI-based measures may ultimately prove to better correlate with perception of vocal quality, making them useful in the evaluation of treatment outcomes.

### Conclusion

In summary, refinements in HSDI, such as software to aid in the quantitative analysis of large amounts of data, and the potential to make actual size and distance measures have increased the clinical usefulness of this technology. Additionally, HSDI-based studies of normal VF vibration have increased our knowledge with regards to those parameters needed for clear voicing (regularity of vibration) while demonstrating that clear voice can be produced by several glottal vibratory patterns. HSDI has the potential to improve diagnostic accuracy, especially in cases of VF paresis, muscle tension dysphonia, and spasmodic dysphonia. Furthermore, HSDI can be used to demonstrate the successful restoration of vibratory characteristics after surgery and will likely remain an important tool in the evaluation of both surgical and therapy-based treatments for voice disorders.

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