OBJECTIVE COMPARISON OF THE ELECTROGLOTTOGRAM TO SYNCHRONOUS HIGH-SPEED IMAGES OF VOCAL-FOLD CONTACT DURING VIBRATION

Maria E. Golla[1], Dimitar D. Deliyski[1,2], Robert F. Orlikoff[3], Habib J. Moukalled[1,2]
[1] Department of Communication Sciences and Disorders, University of South Carolina, Columbia, SC, USA
[2] Department of Computer Sciences and Engineering, University of South Carolina, Columbia, SC, USA
[3] Department of Speech Pathology and Audiology, West Virginia University, Morgantown, WV, USA

Abstract: **This study investigated vocal-fold contact characteristics through electroglottography (EGG) and related them to vibratory behavior as seen through high-speed videoendoscopy (HSV). When the EGG cycle was broken down into phases, the contacting phase represented an increasing percentage of the whole cycle as the EGG signal moved through three registers (pulse, modal, and falsetto). Conversely, the decontacting phase corresponded to a decreasing percentage of the EGG cycle as it moved through the same registers. Furthermore, comparisons of the HSV images and the EGG signal indicated close relationships between specific EGG features and the onset of contact of the vocal folds, maximal contact between the vocal folds, and maximal loss of contact between mucus bridges.**

***Keywords*: Voice; Electroglottography; High-Speed Videoendoscopy; Vocal-Fold Vibration**

I. Introduction

Electroglottography (EGG), a valuable tool for both voice researchers and clinicians, is sensitive to changes in vocal-fold contact area during phonation. Clinical observation and the application of various physical and mathematical models have been used to identify important EGG signal landmarks and relate changes in signal morphology to specific aspects of laryngeal physiology. The continued refinement and applicability of high-speed videoendoscopy (HSV) allows for the synchronization of the EGG signal with endoscopic images of the vocal folds.

The purpose of this study is to investigate variations of specific EGG features and relate them to HSV-observed changes in vibratory behavior. To this end, the following **research questions** are addressed: **(1)** Are the objective measures of fundamental frequency (*Fo*) consistent with the elicited samples across three registers (pulse, modal, falsetto)? **(2)** To what degree do five established EGG landmark features (Fig. 1) [1] vary as related to objective measures? **(3)** What are the relationships between the EGG markers and the physiology of the vocal fold movement as visible through HSV and digital kymography (DKG)?

II. Methods

Human Data: Fourteen vocally-normal speakers (7 men and 7 women, between 22 and 29 years of age) were recorded using precisely-synchronized ($\leq$ 11 µs) HSV (16,000 fps) with EGG (96,000 Hz) as they produced one or more trials of the vowel /i/ sustained in three different registers: pulse, modal, and falsetto [2]. After the data was collected, each HSV trial recording was reviewed by 2 experts who selected three 1,000-frame segments extracted from the whole recording, producing 3 smaller samples. One pulse register trial was excluded due to significant supraglottic compression which precluded visualization of the true vocal folds. The dataset included 72 modal register samples, 42 pulse register samples, and 45 falsetto samples. All 159 samples were used in answering the first two research questions; however, for the third research question, the data set was narrowed to allow for adequate analysis of the large amount of data. Only the middle of each three samples was analyzed for each trial, producing 24 modal register samples, 14 pulse register samples, and 15 falsetto register samples, a total of 53 samples.

Analysis: Using custom-designed software with a specialized graphic user interface, the EGG signals were visually aligned with DKGs taken at 5 equally-spaced locations along the anterior-posterior axis of the vocal folds (Fig. 2). Based on contemporary EGG models [1,4], 5 EGG landmark features were identified

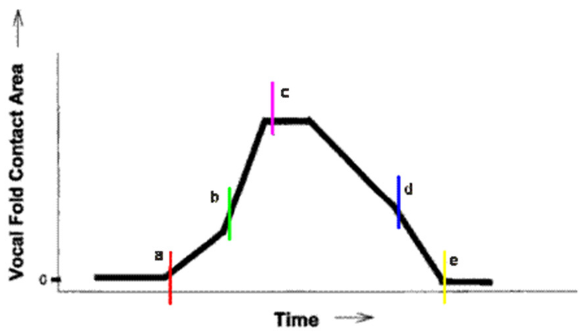

Fig. 1: Model Waveform of the EGG. a) Red marker; b) Green marker (estimated); c) Purple marker; d) Blue marker; e) Yellow marker.

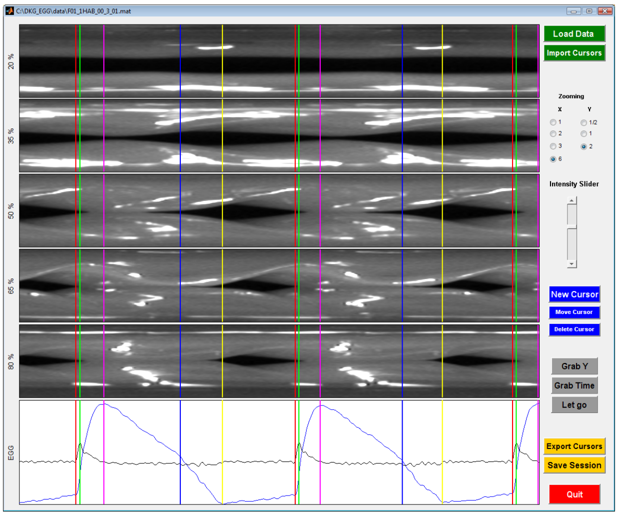

Fig. 2: EGG and DKG visually aligned for color-coded tagging.

and coded with a unique colored marker: (1) intra-cycle onset of contact during the increasing-contact (contacting) phase (red marker); (2) maximum of the derivative/velocity during the contacting phase (green marker); (3) intra-cycle EGG maximum or maximum contact (purple marker), (4) EGG "knee" formed during the decreasing-contact (decontacting) phase (blue marker); and (5) intra-cycle offset of contact during the decontacting phase (yellow marker). Using the custom software, each EGG sample was manually tagged for the 5 landmark features using this color coding system (Fig. 1) and a consensus of the markings was established.

Once the EGG signals were tagged, the time stamps of all markers for each of the 5 color sets were imported into a custom Matlab script. First, the time stamps were converted into vectors of period measurements corresponding to each different feature (color) in every EGG sample. Based on period information, mean frequencies and first-order perturbation functions were computed for each feature and sample to determine the most stable EGG feature.

The 5 EGG feature markers were then exported to another custom-designed software with a specialized graphic user interface, which allowed concurrent visualization and playback of HSV and DKG, with the colored EGG feature markers overlaid in both the HSV and DKG (Fig. 3). User-controlled interface allowed playback of either: HSV frames dynamically-linked to a time stamp on the DKG display or DKG frames dynamically-linked to the corresponding anterior-posterior line. Using each frame as the base measuring unit, each of the 5 EGG feature markers were measured relative to the following 4 HSV landmark features: (1) first contact of the vocal folds, (2) maximum contact of the vocal folds, (3) complete loss of contact between the vocal folds, and (4) complete loss of contact of any mucus bridges.

III. Results

Consistency of Fo with registers.

Analysis of the acoustic signal determined that the *Fo* for the modal and falsetto registers fell within normal limits [2] for the elicited register. Moreover, the modal registers and falsetto registers did not overlap within or across sexes (Table 1). The *Fo* could not be calculated for the pulse register phonations based on the acoustic signal due to the aperiodicity of the samples; therefore, the mean frequency for each sample was computed based on the EGG signal. Several of the pulse register samples had higher frequencies than expected [2]. Closer visual inspection of the DKG for these samples revealed multiple pulses for an individual glottal cycle. Since the EGG signal tracks the change in contact between the vocal folds, it would naturally be sensitive to these multiple pulses. After excluding the markers corresponding to the repeated pulses within a glottal cycle as determined from DKG, the frequency of the glottal cycle fell within normal limits for the pulse register [3,5].

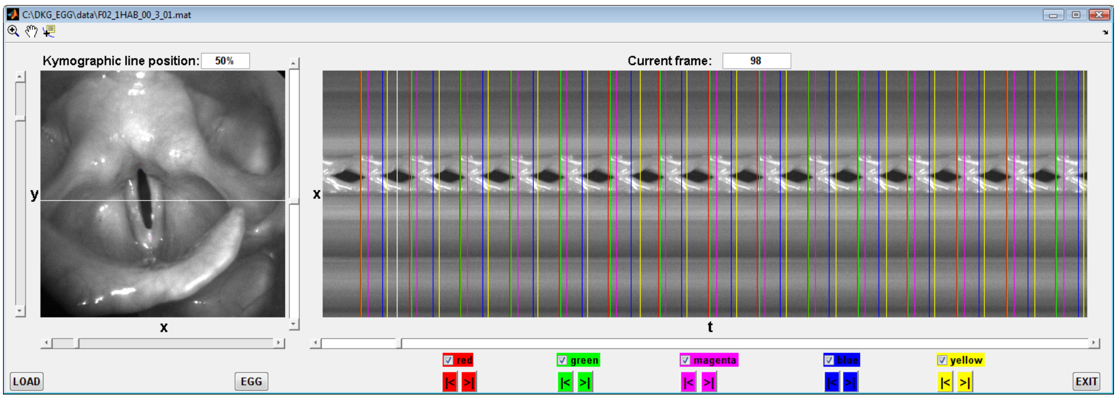

Fig. 3: HSV and DKG visually aligned with EGG markers for concurrent playback.

Table 1: *Fo* (Hz) of habitual and falsetto registers.

Register	Range	Male Range	Female Range
Modal	90.02 Hz – 269.05 Hz	90.02 Hz – 164.45 Hz	152.29 Hz – 269.05 Hz
Falsetto	300.5 Hz – 1041.71	300.05 – 496.04 Hz	411.59 Hz – 1041.71 Hz

One trial (and its subsequent three samples) had a higher frequency of EGG cycles than expected for the pulse register which could not be explained by double or multiple pulses. Listener judgment found this trial consistent with pulse register phonation, and visually the open phase of the cycle represents less than 25% of the entire cycle. It is reasonable to assume that despite the high frequency, this trial met the characteristics of pulse register, and thus, the sample should be considered in the remaining portions of the study. It is likely that this sample contained elements of both pulse and modal register as described by Hollien, Girard, and Coleman [3].

Measuring variation of five EGG landmark features.

Across registers perturbation values reveal significant trends, specifically the large degree of perturbation within the pulse register compared to the modal and falsetto registers. Table 2 records the range of perturbation for each register. It is likely that the higher perturbation levels within the pulse register were related to the overall aperiodicity expected for the register and the presence of the double and multiple pulse phenomena within the register, given that the secondary or tertiary pulses are significantly shorter than the initial pulse of the vibratory cycle. It was not surprising that the modal register demonstrated the least amount of perturbation due to its periodicity (relative to the pulse register) and consistent contact (relative to the falsetto register).

Significant variability was noted within samples and across registers. Table 3 reports the extent of the variability of perturbation for each of the 5 EGG landmark features. For all markers variability was noted within the 1,000-frame samples, as demonstrated by not only the high mean of perturbation values, but also the differences between the mean and median values (indicating the presence of outliers within the data). The most variant marker was the yellow marker, whereas

Table 2: Breakdown of relative perturbation range (%) for each register.

Phonatory Behavior	Mean (%)	Median (%)
Pulse	17.91 – 19.95	8.65 – 11.17
Modal	0.78 – 3.38	0.50 – 3.04
Falsetto	5.98 – 7.19	2.75 – 7.13

Table 3: Mean (median) values of relative perturbation (%) for each EGG landmark feature.

Phonatory Behavior	Red Marker	Green Marker	Purple Marker	Blue Marker	Yellow Marker
Pulse	19.54 (8.65)	19.31 (8.97)	19.95 (11.17)	17.91 (9.71)	19.64 (10.61)
Modal	.82 (.65)	.78 (.50)	1.74 (1.49)	2.77 (2.57)	3.38 (3.04)
Falsetto	5.98 (4.38)	6.81 (2.75)	6.30 (3.73)	7.19 (7.13)	6.49 (5.67)
Combined	5.94 (1.12)	6.12 (.83)	6.61 (2.34)	7.02 (3.41)	7.47 (3/91)

the marker with the least overall perturbation was the green marker. Based on these results, the green marker was considered to be the most stable feature. Thus, a glottal cycle was defined as the distance between consecutive green markers.

Since the green marker was established as the most consistent feature, the intra-cycle ratios of the glottal cycle were calculated in percent relative to the green marker. By doing this, the EGG landmark features naturally break the EGG signal into 5 phases:

Phase 1: Red-Green—time between the red and green markers (onset of contact and the point of maximum velocity during the closing phase).
Phase 2: Green-Purple—time between the green and purple markers (point of maximum velocity during the closing phase and the point of maximum contact between the vocal folds).
Phase 3: Purple-Blue—time between the purple and blue markers (point of maximum contact between the vocal folds to the EGG "Knee").
Phase 4: Blue-Yellow—time between the blue and yellow markers (EGG "Knee" and the offset of contact between the vocal folds).
Phase 5: Yellow-Red—time between the yellow and red markers (offset of contact between the vocal folds and the onset of contact between the vocal folds.)

Table 4 summarizes the percentage to which each of these phases comprise the entire glottal cycle. The results indicate that, although Phase 1 comprises the smallest percentage of the entire glottal cycle for every register, there are visible trends between registers. Specifically, the pulse register has the shortest Phase 1 (relative to the overall glottal cycle), followed by the modal register, whereas Phase 1 comprises slightly more of the overall glottal cycle in the falsetto register. This trend continues for Phase 2, so that the time between the onset of contact and the point at which maximum contact is achieved becomes a greater part of the overall glottal cycle as the subject's phonation moves through the registers.

Phases 3 and 4 could be grouped together to represent the time in which the vocal folds are losing contact. When viewed this way, clear trends relative to the register are again visible. The combination of Phases 3 and 4 represent approximately 61% of the entire glottal

Table 4: Means of the intra-cycle ratios (%) for the 5 EGG phases relative to the green marker.

Cycle Phase	All Registers	Pulse Register	Modal Register	Falsetto Register
Phase 1: Red-Green	**3.85%**	**1.69%**	**2.97%**	**6.68%**
Phase 2: Green-Purple	**9.49%**	**4.98%**	**7.41%**	**15.74%**
Phase 3: Purple-Blue	**33.37%**	**46.51%**	**34.14%**	**23.76%**
Phase 4: Blue-Yellow	**13.97%**	**14.87%**	**12.75%**	**15.39%**
Phase 5: Yellow-Red	**39.32%**	**31.94%**	**42.73%**	**38.43%**

cycle within the pulse register, whereas the two phases make up approximately 46% of the cycle for the modal register, and approximately 37% for falsetto. These findings are consistent with our understanding of the physiology of the vocal folds and the degree of contact expected for each of the registers [2-4].

Interestingly, Phase 5 does not follow the expected trend for the registers. It would be reasonable to assume that if the yellow marker represents the offset of contact, and the red marker represents the onset of contact of the next cycle, then there should be maximum loss of contact between the vocal folds during Phase 5. It would also be reasonable to assume that since falsetto is thought to have the least amount of contact for the entire cycle then Phase 5 should represent the largest percentage of the entire glottal cycle. However, Phase 5 represents a greater portion of the cycle in modal register than in falsetto.

Relationship between EGG markers and HSV

Results indicate there is a strong relationship between the red and green markers (which generally fell within 100 µs of each other) and the onset of contact between the vocal folds. There also appears to be a strong relationship between the purple marker and maximum contact of the vocal folds. The blue marker was calculated relative to both the maximum contact and the offset of contact between the vocal folds, and results indicate it is more closely related to the offset of contact of the vocal folds than the maximum contact between the vocal folds. Generally the blue marker was placed before the loss of contact of the vocal folds; however, occasionally the blue marker was placed at the loss of contact when a mucus bridge was present. The yellow marker is strongly related to the offset of contact between the vocal folds or the offset of contact between mucus bridges if present.

IV. Discussion

Results of this study indicate that EGG signal does directly relate to the changing contact between the vocal folds. When broken down into phases, the contact phases (Phases 1-2: Red-Purple Marker) constitute the smallest percentage of the cycle in pulse register, a slightly larger percentage of the cycle in modal register, and an even greater percentage of the cycle in falsetto. Conversely, the loss of contact phases (Phases 3-4: Purple-Yellow Marker) constitutes the smallest percentage of the falsetto register cycle, a larger percentage of the modal register cycle, and the largest percentage of the pulse register cycle. These findings are consistent with current literature on the physiology of the vocal-fold vibration in various registers [2-5].

Comparison of the EGG signal and HSV recordings reveal that the EGG markers do closely align with the onset of contact, the point of maximum contact, and the offset of contact between mucus bridges. Also, the blue marker was found to be more closely related to loss of contact between the vocal folds–sometimes appearing at the point of loss of contact. Additionally, mucus bridges play a significant role in the morphology of the EGG signal at the offset of contact.

V. Conclusion

This study is unique in terms of the method's accuracy and the direct linkage of an indirect measure of vocal-fold contact through EGG, to visual physiologic measures of vocal-fold contact through HSV. The results cross-validate several EGG features and pose new questions about others, especially the EGG knee appearing during the opening phase.

Acknowledgments

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