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PHOTOELECTRIC MEASUREMENT OF LARYNGEAL PARALYSES CORRELATED WITH VIDEOSTROBOSCOPY*†§

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ABSTRACT

Photoglottography and electroglottography are relatively noninvasive techniques that provide detailed information about vocal fold vibration. However, few significant clinical applications have been made by correlating photoelectric waveforms to specific pathologic changes in laryngeal vibration. Videostroboscopy has recently been used to document vibratory patterns of laryngeal paralyses in a canine model of phonation. A study of PGG and EGG waveforms correlated with videostroboscopy in an in-vivo canine model of phonation with simulated unilateral recurrent or superior laryngeal nerve paralysis is presented. The shift quotient—a new glottographic parameter which identifies flaccid laryngeal paralyses—is presented.

Photoglottography and electroglottography have existed as techniques for measuring laryngeal movement since the early 1960s. These photoelectric techniques are relatively noninvasive and provide detailed, although inferential, information about vocal fold vibration. However, few significant applications have been made to clinical patient care.

Gerratt, *et al.*[1] applied glottographic analysis to patients with laryngeal nerve paralyses. Although the waveforms were distinctly different in each instance, the abnormalities could not be directly related to specific pathologic changes in laryngeal vibration. This was due, in part, to the difficulty in interpreting the pathophysiology reflected in glottographic waveforms.

Childers, *et al.* using high-speed photography, have recently demonstrated a plateau phase in the rising limb of electroglottographic (EGG) signals in patients with polyps of the true vocal cords.[2] The plateau phase occurs because, as the vocal cords move laterally during opening, the presence of a mass in the glottic aperture causes a constant area of vocal fold contact. Constant vocal fold contact during opening appears on the EGG signal as a plateau in the opening limb of the EGG.

As the body of photoelectric data accumulates and is shared between researchers, recognition of characteristic patterns depicting a variety of laryngeal pathologies may someday be possible. Two measures of the glottal cycle, with potential clinical application that can be calculated using photoglottographic (PGG) and EGG waveforms, are the open quotient (OQ) and speed quotient (SQ). Open quotient is defined as the fraction of time the cords are open during the glottic cycle. Speed quotient is the duration of time the cords are opening, divided by the duration of time the cords are closing. A number of authors have observed abnormal values of speed quotient and open quotient related to phonatory disorders associated with increased or decreased laryngeal tension.[3-5] However, actual morphologic changes in laryngeal vibration as a result of increased or decreased laryngeal tension have rarely been correlated with photoelectric waveforms.[6] Moore, *et al.*[7] recently used videostroboscopy in a canine model from supraglottic and subglottic views to document vibratory characteristics in simulated phonation with unilateral recurrent, superior, and vagal laryngeal nerve paralyses. The authors observed that unilateral recurrent nerve paralysis was characterized by a homogeneous movement to the paralyzed cord, lack of the travelling mucosal wave bilaterally with little movement of the normal cord except for a small travelling wave occurring at the upper margin. In addition, frequently closure was afforded by the nonparalyzed cord crossing over the midline to meet the flaccid homogeneous paralyzed cord. However, both cords vibrated at the same frequency. The addition of paralysis to the ipsilateral superior laryngeal nerve to an already existing recurrent laryngeal nerve paralysis did not appear to significantly alter the vibratory pattern when compared to an isolated recurrent nerve paralysis. However, isolated superior laryngeal nerve paralysis was characterized by an exaggerated vertical movement in the nonparalyzed cord with a shifting of the glottic aperture from the nonparalyzed to the paralyzed side during each glottic cycle.

Clinicians in the near future may be able to confirm photoelectrically the clinical diagnosis of paralysis of the larynx in a method analagous to the use of electrocardiograms to confirm suspected cardiac disorders. Toward this end, videostroboscopic images of recurrent and superior laryngeal nerve paralyses were correlated in a canine model of phonation with measured PGG and EGG waveforms. There are sev-

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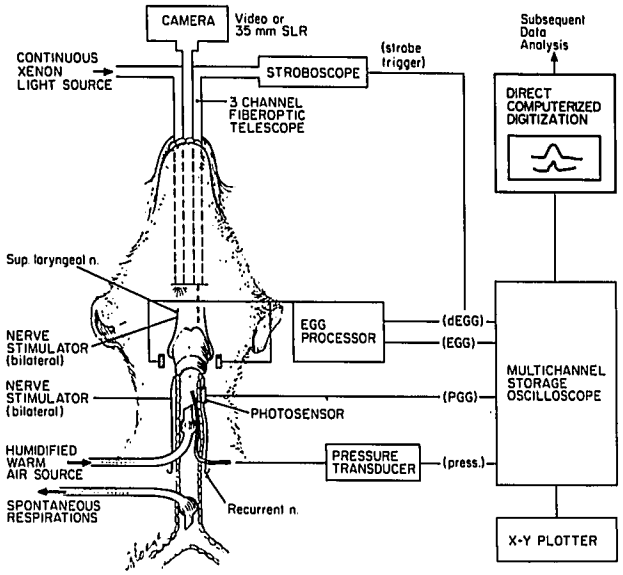

Fig. 1. Schematic representation of the experimental set-up.

eral characteristic features that distinguish the paralyzed larynx from the nonparalyzed larynx using photoelectric techniques, and we discuss their significance in this report.

MATERIALS AND METHODS

Surgical/Photoelectric

Subjects. — Twelve healthy adult male mongrel dogs were examined by direct laryngoscopy to confirm normal canine laryngeal anatomy. The animals were premedicated with Innovar® (1cc/7 kg body weight) intramuscularly. Intravenous pentothal was administered to a level of corneal sensation loss and additional pentothal was used throughout the experiment to maintain this level of anesthesia with spontaneous respirations.

The animals were placed supine on the operating table and secured. The neck was shaved and a midline incision made to expose the trachea from the hyoid to the sternal notch. The strap muscles and sternocleidomastoid muscles were retracted laterally and the recurrent laryngeal nerves identified several centimeters below their entrance into the larynx. The external branch of the superior laryngeal nerves were identified just superior and lateral to their entrance into the cricothyroid muscles. A low tracheotomy was performed at the level of the suprasternal notch through which an endotracheal tube was passed to allow spontaneous respirations. A second tracheotomy was performed in a more superior location through which a cuffed endotracheal tube was passed in a rostral direction for several centimeters and positioned 10 cm below the vocal cords. The cuff was inflated to just seal the trachea. Humidified, heated air was passed subglottically through this second endotracheal tube from a compressed air cannister, and flow was controlled with a valve and flowmeter. The warmth and humidification of the air was provided by bubbling the air through 5 cm of heated water to provide a constant temperature of 37 °C as measured at the laryngeal lumen. A 1-cm button was used to suspend the epiglottis from a fixed point to provide direct visualization of the larynx through the oral cavity (Fig. 1).

A 1-cm segment of the recurrent and superior laryngeal nerves was isolated and a 1/4-in by 2-in strip of gauze packing was applied around the nerve. The gauze was then soaked with 0.9N saline solution and sutured to a silver electrode. The gauze/silver electrode was then isolated from the surrounding tissue with a rubber insulator. A 0.5-cm silver electrode was applied directly to the anterior tracheal wall as a ground. Two nerve stimulators

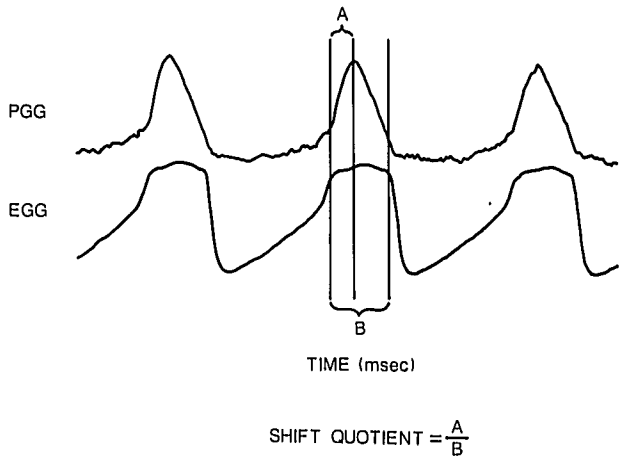

Fig. 2. Electroglottographic and photoglottographic waveforms from a canine with phonation produced in the normal state depicting calculation of the shift quotient (ShQ).

(Grass instruments) with direct current isolation units were used to stimulate the recurrent and superior laryngeal nerves. These nerves were stimulated at 70 to 90 Hz stimulus frequency, with 2 to 7 mA intensity for 1.5 msec pulse duration. Phonation was produced with airflow of 375 cc per second supplied through the laryngeal aperture by the rostrally directed endotracheal tube while the laryngeal nerves were being stimulated.

Changes in glottal area were monitored by photoglottography. The larynx was illuminated from above with a fiberoptic xenon light source secured in the oral cavity and directed toward the glottis. Light transmission through the vocal cords was transduced with a photosensor (Centronics OSD 502) placed on the

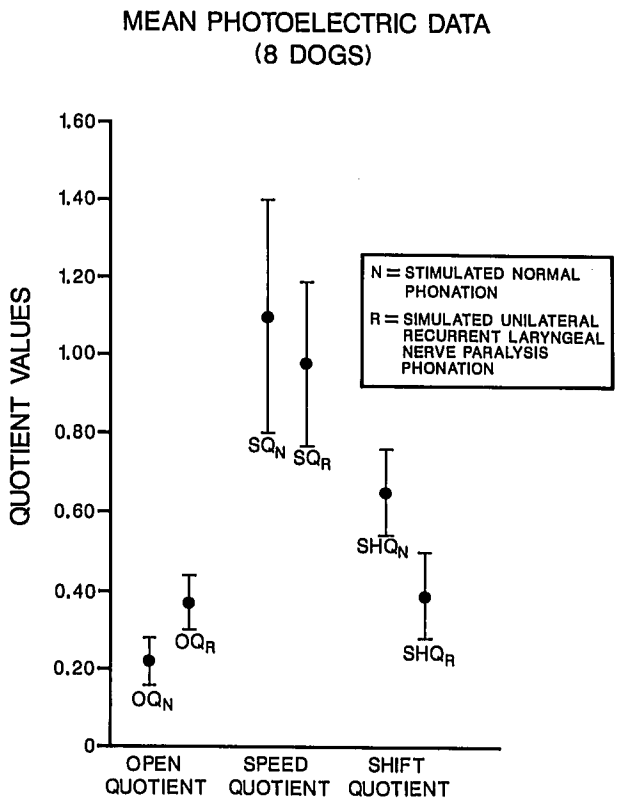

Fig. 3. Graph depicting the mean OQ, SQ, and ShQ for eight dogs with phonation produced in the normal and unilateral recurrent laryngeal nerve paralyzed states.

TABLE I.
Mean Glottographic Measures for Phonation During Simulated Unilateral Recurrent Laryngeal Nerve Paralysis.

	Open Quotient		Speed Quotient		Shift Quotient	
Dog	Normal	RLNP	Normal	RLNP	Normal	RLNP
1	0.22	0.30	1.14	1.01	0.76	0.38
2	0.31	0.39	1.13	0.85	0.62	0.47
3	0.24	0.28	1.17	0.96	0.65	0.57
4	0.24	0.34	1.48	1.04	0.81	0.52
5	0.14	0.34	0.84	1.00	0.44	0.25
6	0.14	0.42	1.02	0.57	0.58	0.41
7	0.22	0.42	1.10	1.21	0.56	0.33
8	0.23	0.42	1.02	1.03	0.68	0.38
Mean	0.22	0.37	1.10	0.98	0.65	0.39

Mean open quotient, speed quotient, and shift quotient for simulated canine phonation in the normal and unilateral recurrent laryngeal nerve paralysis states.

trachea just below the cricoid cartilage. Electroglottographic signals were obtained with a laryngograph (Synchrovoice) with the two recording electrodes placed in pockets just above the cricothyroid muscles adjacent to the thyroid cartilage. The ground electrode was secured to adjacent strap muscles. Photoglottographic and electroglottographic tracings were observed on a storage oscilloscope (Tektronix 5116) and directly digitized and stored onto the hard disk of a personal computer (80286 microprocessor).

Computerized Data Digitization, Storage, and Analysis

Analog data from electroglottographic and photoglottographic signals were low-pass filtered at 3,000 Hz and digitized real-time at 20,000 Hz using the personal computer equipped with a math coprocessor (80287) and a commercial software program ("C-speech," Paul Milenkovic, PhD, University of Wisconsin). EGG and PGG waveforms obtained were examined briefly after each trial of phonation to evaluate the adequacy of the waveforms. Three seconds of waveform data were stored on the computer's hard disk and later recovered for analysis and calculation of open quotient (OQ) and speed quotient (SQ). In addition, a new value termed shift quotient (ShQ), was also derived from the EGG and PGG waveforms (Fig. 2). This was done by calculating the distance from the beginning of the plateau phase of the EGG to the apex of the PGG as it was directly superposed on the EGG and dividing this by the duration of the plateau phase of the EGG (Fig. 3). Points of glottal opening and closing were determined in the manner previously described by Childers[8] and Berke.[9] Opening occurred at the peak of the differentiated EGG waveform and closing at the nadir of the differentiated EGG waveform.

Recordings were taken for a minimum of three trials each from normal (simultaneous bilateral recurrent and superior laryngeal nerve stimulation), unilateral recurrent laryngeal nerve paralyzed, and unilateral superior laryngeal paralyzed states.

Data were analyzed in the following format. Within each trial of simulated phonation, a stable 0.25-second portion was chosen in four equally separated parts of the 3-second recording. Within these segments, five consecutive waveforms were interactively analyzed and averaged to calculate a single value for OQ, SQ, and ShQ (normal or paralysis). The values were then compared with those obtained in the three other 0.25-second segments, and a mean value was calculated and recorded as the QQ, SQ, and ShQ for each stimulated phonation. The values of each of three trials were compared and averaged so that each treatment cell had one value for OQ, SQ, and ShQ.

Video Imaging

A Storz model 8000 Laryngostrob unit was used for video imaging performed with each trial of phonation after the photoelectric data had been recorded. This was connected to a Storz 0-degree telescope via a fluid-filled light cable. The image from the 0-degree scope was recorded using a Storz CCD (charge-coupled device) video camera (Model 9000), and Sony U-matic videocassette-recorder (VO-5800). The video images were analyzed frame-by-frame using the same unit.

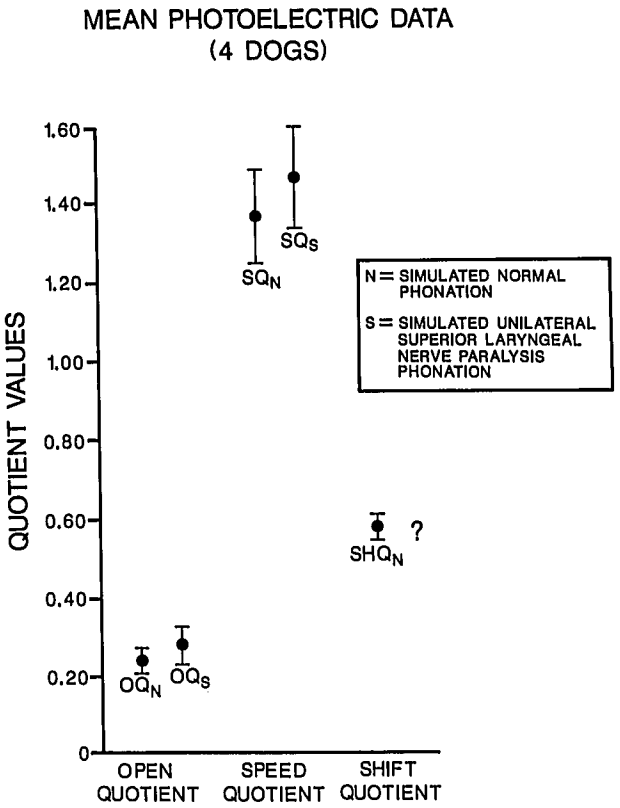

Fig. 4. Graph depicting the mean OQ, SQ, and ShQ for four dogs with phonation produced in the normal and unilateral superior laryngeal nerve paralyzed states.

Experimental Design

A constant low level of cricothyroid tension (0.2-mA stimulation) was maintained in all 12 dogs using stimulation of the superior laryngeal nerves, and the recurrent laryngeal nerves were then bilaterally stimulated until phonation ensued to provide data for normal phonation. These 12 dogs were then divided into two groups. The first group consisted of eight dogs with one recurrent laryngeal nerve transected, and stimulation to both superior laryngeal nerves and the remaining recurrent laryngeal nerve. A second group of four dogs had one superior laryngeal nerve transected, and stimulation of the remaining superior laryngeal nerve and both recurrent laryngeal nerves to produce phonation. During each of these trials EGG and PGG waveforms were recorded.

Analysis of Waveforms

Signals were examined to determine how their overall shape related to the vibratory patterns seen on videostroboscopy.

Statistical Analysis

Bidirectional *t*-testing was performed on the open quotient and speed quotient values and compared to the normal and paralyzed states. The test was performed for a comparison of two means and a test for paired observations.

Unidirectional *t*-testing was performed on the shift quotient values between the normal and paralyzed states again using the test to compare two means and to test for paired observations. (The unidirectional test was used because we had noted the shift to the left.)

RESULTS

Simulated Recurrent Laryngeal Nerve Paralysis

The averaged open quotient values ranged from

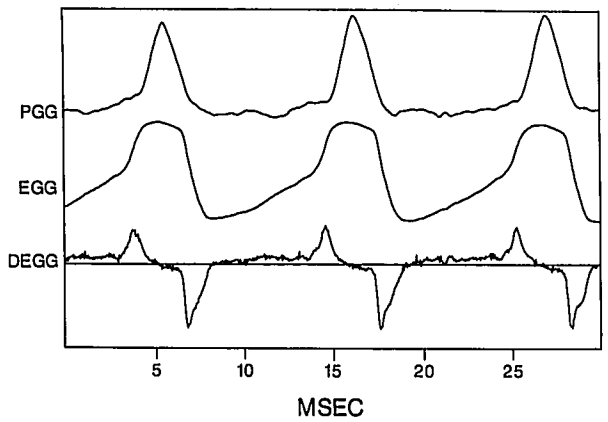

Fig. 5. EGG, PGG, and differentiated EGG (dEGG) waveforms for a canine with phonation produced by stimulation of the recurrent and superior laryngeal nerves bilaterally-"normal."

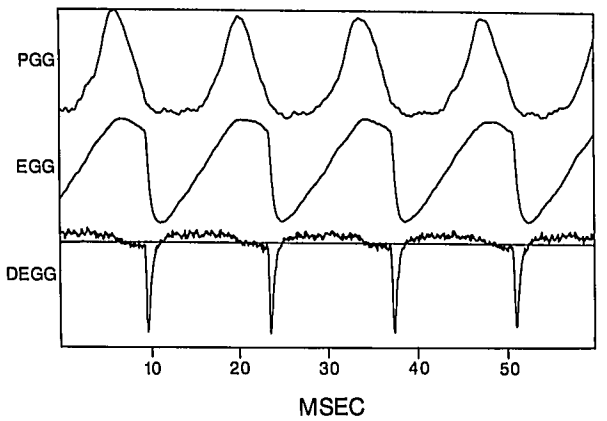

Fig. 6. EGG, PGG, and differentiated EGG (dEGG) waveforms with phonation produced in a canine with unilateral recurrent laryngeal nerve paralysis.

0.11 to 0.34 for all dogs in the normal state. The mean value for all normal dogs was 0.22. Averaged open quotient values ranged from 0.26 to 0.49 for all dogs with a unilateral recurrent laryngeal nerve paralysis, and their mean open quotient was 0.37 (Table I).

The averaged speed quotient values ranged from 0.57 to 1.80 for all dogs in the state of simulated normal phonation, and from 0.54 to 1.46 for all dogs with phonation during a simulated unilateral recurrent laryngeal nerve paralysis. The mean SQ was 1.10 for all normal dogs and 0.98 for all dogs with unilateral recurrent paralysis (Table I).

The shift quotient values ranged from 0.43 to 0.86 in the normals. The mean value was 0.65 for these dogs. The shift quotient ranged from 0.15 to 0.60 in the dogs with unilateral recurrent laryngeal nerve paralysis with a mean of 0.39. All data and the mean for each dog are depicted in Table I.

Figure 3 presents a graph comparing the mean OQ, SQ, and ShQ for eight dogs during phonation in the normal and unilateral recurrent laryngeal nerve paralyzed state.

The values for open quotient and shift quotient in the normal and recurrent laryngeal nerve paralyzed states were compared statistically using the *t*-test for the comparison of two means and found to be significantly different with *p*-values of less than 0.01 and 0.005, respectively. These open quotient and shift quotient values were also compared using the *t*-test for paired observations and found to be significantly different with *p*-values of less than 0.01 and 0.005, respectively. A comparison of the speed quotients in the normal and paralyzed state using the *t*-tests for comparison of two group means and paired observations was performed but was not significantly different.

Review of the videostroboscopic images that had been recorded were analyzed and correlation with the EGG and PGG waveforms was performed. We observed the following morphologic information.

The morphology of the EGG and PGG waveforms were distinguishable from normal (Fig. 4) because of the following reproducible characteristics. A shift of the peak of the PGG to the left in relation to the EGG occurred because the paralyzed flaccid vocal fold vibrates in a one-mass mode (Fig. 5). This implies little phase lag between the opening of the lower to upper margin. The homogeneous lateral excursion of the

TABLE II.
Mean Glottographic Measures for Phonation During Simulated Unilateral Superior Laryngeal Nerve Paralysis.

	Open Quotient		Speed Quotient		Shift Quotient	
Dog	Normal	SLNP	Normal	SLNP	Normal	SLNP
1	0.24	0.23	1.21	1.29	0.57	N/C
2	0.20	0.26	1.35	1.55	0.60	N/C
3	0.24	0.31	1.40	1.58	0.61	N/C
4	0.27	0.33	1.50	1.48	0.55	N/C
Mean	0.24	0.28	1.37	1.47	0.58	N/C

Mean open quotient, speed quotient, and shift quotient for simulated canine phonation in the normal and unilateral superior laryngeal nerve paralysis.

N/C=Non-Calculable.

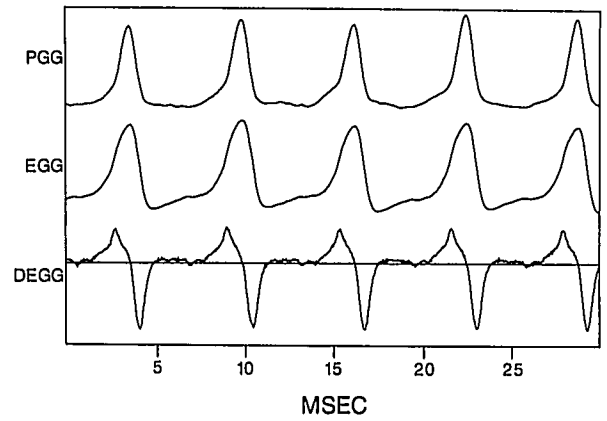

Fig. 7. EGG, PGG, and differentiated EGG (dEGG) waveforms with phonation produced in a canine with unilateral superior laryngeal nerve paralysis.

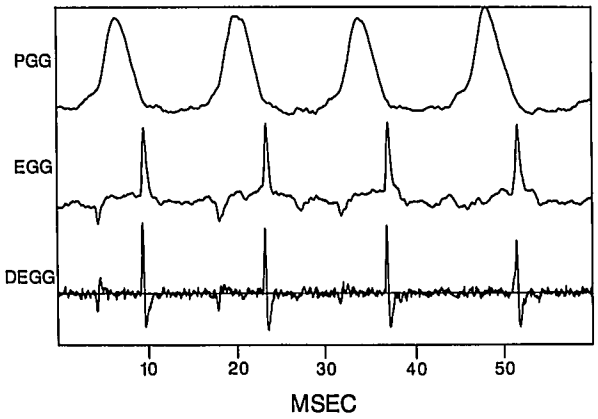

Fig. 8. EGG, PGG, and differentiated EGG (dEGG) waveforms with phonation produced in a canine with unilateral vagal paralysis.

paralyzed fold caused the glottic aperture to be at its maximum (*i.e.*, peak of PGG) when the cord finally unzips completely in the horizontal plane (*i.e.*, plateau phase of EGG). There was failure of the PGG to return to the baseline during the phase of vocal fold closure representing lack of complete glottic competence with unilateral RLN paralysis. The slope of the opening phase of the EGG waveform also failed to demonstrate the discontinuity which represents the normal transition from vertical to horizontal cord separation. The loss of change in EGG slope is probably due to simultaneous opening of the upper and lower vocal fold margins that results when the two-mass movement is lost. A distinct portion of the opening phase slope in the paralyzed state was not attributable to lower margin opening as well.

Simulated Superior Laryngeal Nerve Paralysis

Values of open quotient, speed quotient, and shift quotient were calculated for the simulated phonation in the normal and unilateral superior laryngeal nerve paralyzed states (Table II). The shift quotient was not calculable in the paralyzed state because of

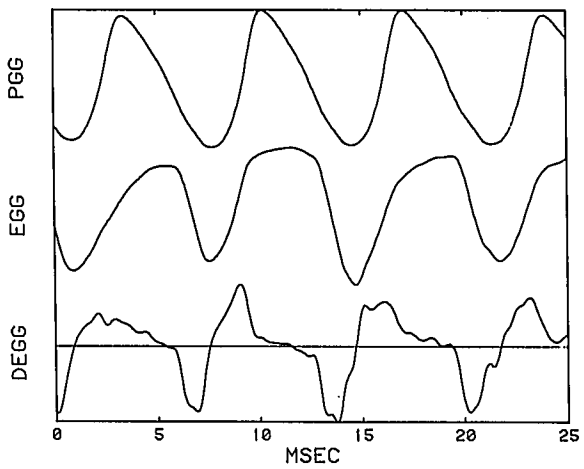

Fig. 9. EGG and PGG waveforms in a human with unilateral recurrent laryngeal nerve paralysis. Note the location of the peak of the PGG relative to the EGG plateau phase.

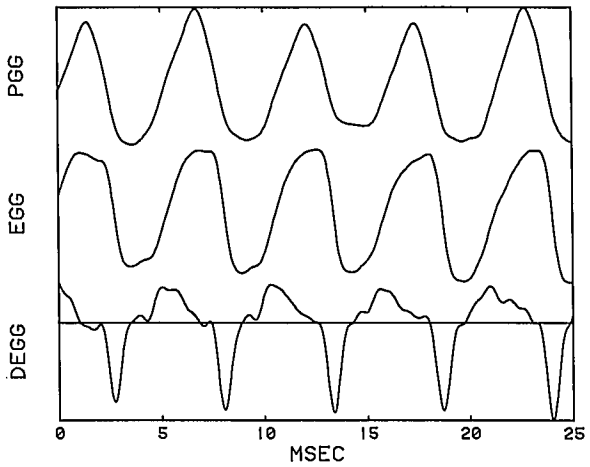

Fig. 10. EGG and PGG waveforms in a human with unilateral superior laryngeal nerve paralysis. Note the lack of the plateau phase.

lack of a consistently indentifiable EGG plateau. A *t*-test to compare normal versus paralysis revealed no significant difference in the open and speed quotients.

Figure 6 presents a graph depicting the mean OQ, SQ, and ShQ for four dogs with phonation produced in the normal and unilateral superior laryngeal nerve paralyzed states.

A correlation of the photoelectric waveforms was made to the videostroboscopy recorded. In unilateral superior laryngeal nerve paralysis there was a loss of the plateau phase on the EGG due to the presence of constant glottic shifting from the abnormal horizontal movements during each cycle (Fig. 7). The differentiated EGG waveform did not go to 0 slope, indicating that the glottis itself was mostly opening or closing with a very small portion of the glottic cycle spent open.

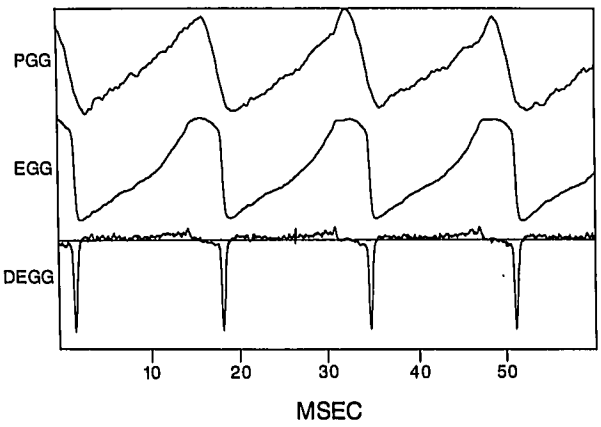

Fig. 11. EGG and PGG waveforms in a canine with a unilateral recurrent laryngeal nerve paralysis and high cricothyroid muscle tension. The resultant high speed quotient (duration of opening/duration of closing) contrasts the speed quotient in Figure 5 where the dog also has phonation produced with a simulated unilateral recurrent laryngeal nerve paralysis.

DISCUSSION

Our data for simulated recurrent laryngeal nerve paralysis is a comparison of the mean values of open quotient, speed quotient, and shift quotient calculated from EGG and PGG recordings for eight dogs in the normal and unilateral recurrent laryngeal nerve paralyzed states. We also experimented with four dogs in the unilateral superior laryngeal nerve paralyzed state. Each of the 12 dogs served as its own normal control. When the normal versus recurrent laryngeal nerve paralysis states are compared statistically, the open and shift quotients are significantly different.

The plateau phase of the EGG waveform represents minimal vocal fold contact (maximum impedance) which occurs when the cords are no longer in contact in the horizontal plane. The apex of the PGG waveform represents maximal vocal fold opening (maximum transmittance of light). We noticed that the apex of the PGG usually fell on the latter portion of the plateau phase of the synchronous EGG waveform in the normal unparalyzed state. During normal phonation the vocal folds move in a fluid, wavelike manner that is lost with unilateral recurrent laryngeal nerve paralysis. The glottal air puff is released earlier because of lack of tension in the paralyzed vocal fold and the resultant loss of pressure build-up across the cross-sectional area of the subglottis. The early release of the glottal air puff causes earlier opening of the vocal folds and, thus, the peak amount of transmitted light across the glottis occurs earlier during the period of relatively little (but nearly constant) vocal fold contact.

It is possible to measure this shift in the apex of the PGG with respect to the beginning of the plateau phase of the EGG (length A, Fig. 2). Its relative value is quantitated by using the duration of the EGG plateau phase as the denominator (length B, Fig. 2). Comparing Figures 5 and 6 shows the contrast in shift quotient for a typical dog in our study in the normal and unilateral recurrent laryngeal nerve paralyzed states, respectively.

The morphology of the EGG and PGG waveforms was studied and found to be distinctly different from normal in each state of paralysis. Figure 6 represents the typical morphology seen in a unilateral recurrent laryngeal nerve paralysis. Figure 7 represents the waveforms seen with unilateral superior laryngeal nerve paralysis. Figure 8 represents the EGG and PGG pattern for a simulated vagal paralysis. Note that the additional flaccidity induced by this combined superior and recurrent paralysis prevented the vocal folds from complete closure as indicated by the spiked appearance of the EGG waveform. Figures 9 and 10 depict recurrent and superior laryngeal nerve paralysis in humans, respectively. Preliminary observations in humans indicate that the shift of the PGG relative to the EGG plateau phase and the lack of a two-mass form of vibration are present in recurrent laryngeal nerve paralysis (Fig. 9). Also, superior laryngeal nerve paralysis demonstrated a lack of a plateau phase as seen in Figure 10.

A previous report by Karin, *et al.* suggested that the speed quotient was consistently different in the normal versus unilateral RLN paralyzed state.[10] Our data does not entirely support this conclusion. In contrast to Figure 6 (recurrent laryngeal nerve paralysis), Figure 11 shows a high-speed quotient obtained in the same animal by increasing superior laryngeal nerve stimulation to produce high cricothyroid muscle tension. This indicates that some laryngeal nerve paralyses may show a change in speed quotient related to cricothyroid tension. However, the shift quotient was not observed to change with changes in cricothyroid muscle tension.

CONCLUSIONS

In summary, it may eventually be possible to use photoelectric techniques as an aid to the diagnosis of laryngeal disorders and that understanding the morphology of these waveforms will provide the basis for this possibility. The shift quotient may be useful in differentiating the normal versus flaccid paralysis states. Further studies in humans afflicted with these types of laryngeal paralyses are needed to confirm these findings.

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July 22-27, 1988 — Basic Course in Otolaryngic Allergy. Course Description: A practical look at immunology, a brief comparison of various approaches to allergy past and present, an applied workshop for skin testing and food allergy evaluation and a practical format for integrating allergy into the ENT practice. Designed primarily for the otolaryngologist preparing to add allergy to his practice, of equal value to the pediatrician and family practitioner and essential for the allergy technician. Location: Royal Sonesta, Cambridge (Boston), MA. Credit hours: 30. Sponsoring organization and contact: American Academy of Otolaryngic Allergy Foundation, 1101 Vermont Avenue, N.W., Suite 303, Washington, DC 20005.

September 29-October 1, 1988 — American Academy of Otolaryngic Allergy Annual Meeting. Description: Comprehensive program including scientific papers and instruction courses covering various topics in otolaryngic allergy. Location: Washington, DC. Credit hours: Up to 16. Cost: not available. Sponsoring organization and contact: American Academy of Otolaryngic Allergy, 1101 Vermont Avenue, N.W., Suite 303, Washington, DC 20005.

November 30-December 4, 1988 — Intermediate Course in Otolaryngic Allergy and Immunology. Course Description: A review of the basics of skin endpoint titration, in-vitro testing techniques, and food evaluation-testing and treatment techniques. The basics of immunology will be reviewed as well as office evaluation for immune deficiency. The course will also include lectures on chemical sensitivity, asthma for the otolaryngologist, advances in cellular immunology, tumor immunology, emergency care, and marketing. Location: Sonesta Village Hotel Orlando, Florida. Credit hours: 30. Sponsoring organization and contact: American Academy of Otolaryngic Allergy Foundation, 1101 Vermont Avenue, N.W., Suite 303, Washington, DC 20005.

VI INTERNATIONAL SYMPOSIUM ON THE FACIAL NERVE

The VI International Symposium on the Facial Nerve will be held in Rio de Janeiro, Brazil, October 2-5, 1988.

Secretariat: Congrex, c/o Decio Castro, MD, Rua do Ouvidor 60, Suite 705, 20040 Rio de Janeiro, RJ, Brazil. 7/88