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GLOTTOGRAPHIC MEASUREMENT OF VOCAL DYSFUNCTION
A PRELIMINARY REPORT

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Objective measurement of vocal function is important in evaluating phonatory disorders, planning treatment, and documenting the effects of therapy. Glottographic measurement, ie, measures that describe glottal movement, can be performed and analyzed relatively easily, and can be related to the pathophysiology of vocal dysfunction. In our clinic, simultaneous recording of acoustic, photoglottographic and electroglottographic signals is being used in the evaluation of patients with voice disorders associated with neurologic impairments. Our experience with these measures indicates that they may provide detailed information about the vibratory patterns of the vocal folds, which appears to differentiate some phonatory characteristics among patients with differing types of disorders.

INTRODUCTION

Historically, physicians have relied on two basic techniques in the assessment of laryngeal pathology: listening to the voice and viewing the larynx with a mirror or other device. While much can be learned by the perceptual evaluation of voice quality, these judgments often are unreliable in a clinical setting. Although careful visual examination is of fundamental importance, particularly in the case of anatomical abnormalities, indirect laryngoscopy is limited by lack of objective documentation. Normal-speed cine or video documentation of the laryngoscopic examination allows the examiner to review the movements of the laryngeal structures at a slightly reduced speed,[1] but fine details of vocal fold vibration which are intimately related to voice production are not captured by these techniques.

Other means of measuring vocal function can provide more objective information. Acoustic measurements, such as perturbation analysis of frequency,[2,3] and amplitude[4] of the acoustic voice signal and various spectral measures of signal to noise,[5-7] provide reliable information which has been related to listener evaluation of roughness, breathiness, and other deviant vocal qualities. Although acoustic measurements are important clinically applicable techniques, they do not necessarily have a direct physiological correspondence to abnormal glottal activity.[8] Aerodynamic measures such as glottal air flow and subglottal air pressure offer another perspective on voice production from which some inferences on abnormal glottal configurations can be made. These measures also have been reported to be related to listener ratings of deviant voice dimensions.[9] Electromyographic recording of laryngeal muscle activity has provided important and useful information about the physiology of specific muscles during phonation. However, while there are special clinical applications for electromyography, this technique has not been generally accepted as a clinical tool.

Measurements that can be directly related to the pathophysiology of laryngeal behavior are highly desirable. Since phonatory dysfunction usually manifests itself in abnormal oscillatory movements, the measurement and analysis of the vibratory pattern of the vocal folds has the potential to provide detailed information on the pathophysiology of the vocal folds during phonation. Movement of the vocal folds can be observed by ultra-high-speed filming (4,000-10,000 frames/s). Frame-by-frame analysis can yield measures such as glottal area and excursion of selected points on the visible surface of the vocal folds. Such measures provide valuable information to help understand the pathophysiology of individual patients. Although high-speed filming does provide useful data, it is technically difficult to use with untrained subjects or patients, and is especially limited by the great time and expense of frame-by-frame data analysis. In fact, the difficulties of this method are so great that over 40 years after first being used, it is estimated that not more than five minutes of ultra-high-speed film of vocal fold vibration have been analyzed in detail.[10]

As a rapid and relatively inexpensive alternative to high-speed filming, glottographic techniques have received considerable attention in the study of normal laryngeal activity. The analysis of glottal waveforms, ie, waveforms that describe glottal movement during phonation, has potential for measuring vocal fold activity with little discomfort to the subject. In addition, data analysis can be performed much faster than by the frame-by-frame method of analysis used in high-speed filming.

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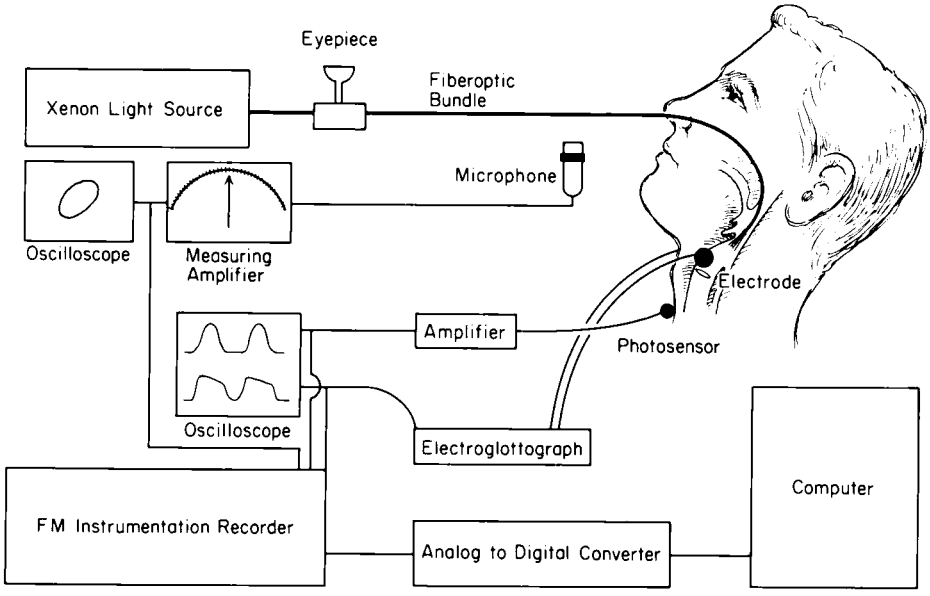

Fig 1. Block diagram illustrating recording and digitization apparatus.

Three glottographic techniques are commonly used. Inverse filter glottography is an acoustic procedure in which the inverse of the lip radiation and the vocal tract spectral contributions are used to remove the acoustic effects of the supraglottal vocal tract, leaving the glottal volume flow.[11,12] However, the more abnormal the voice, the more difficult it becomes to choose the proper inverse filter parameters. Consequently, application of this method for the study of dysphonia requires further refinement of the technique. Another method is photoglottography (PGG), which monitors light transmitted through the glottis. The light source may be above or below the vocal folds, while the light output is transduced by a photosensor on the other side of the glottis. The amount of light passing through the glottis is considered proportional to the glottal area during the vibratory cycle.[13] The third method, electroglottography (EGG), measures the electrical impedance across the neck in the vicinity of the glottis.[14,15] There is evidence that changes in impedance are related to variation in vocal fold contact.[16] The first two methods provide more information during the open portion of the glottal cycle, while EGG yields more information during the period of glottal closure.

A sensible approach to capture as much detail as possible about vocal fold movement is to employ a combination of measurements of glottal opening area and vocal fold contact.[17] Consequently, the purpose of this paper is to demonstrate the use of PGG as a measure of glottal area, while simultaneously measuring vocal fold contact by EGG for the study of laryngeal pathophysiology in a clinical setting.

METHODS

The following methods are used in our clinic for the evaluation of patients with phonatory disorders.

Filming the Larynx. The larynx of each subject is first examined with a 90° Ward-Berci telescopic laryngoscope.[18] Next, the laryngoscope is coupled to a 16-mm endoscopic cine camera (Beaulieu), which is used to photograph the larynx during phonation at a film speed of 12 frames/s. The subject is asked to sustain the vowel /i/ (ee), inspire as deeply as possible, rapidly interrupt and resume the production of /i/, and produce the vowel at the lowest and highest pitches of his or her range. The vowel /i/ was chosen to allow an unobstructed view of the glottis for viewing and illumination for PGG, since it is articulated with the epiglottis pulled anteriorly.

Glottographic Measurement. The recording apparatus is presented in Fig 1. Each subject is seated in a dental chair located in a sound-treated booth of double-walled construction. The vibratory pattern of vocal fold activity is monitored by means of an electroglottograph (FJ Electronics) and a custom-built photoglottograph. After a brief spray of topical anesthesia to the nasal passage, a flexible fiberscope (Olympus BF type 3C3) is introduced through the nose, passed into the pharynx, and positioned above the glottis. The fiberscope is fixed in position at the nose by a device designed to stabilize a nasogastric tube. The body of the fiberscope is held in position by a balanced mechanical arm. A phototransistor and its housing are then placed on the surface of the neck just below the cricoid cartilage and held in position by a neckband. The light from the fiberscope passing through the glottis during phonation is transduced by the photosensor and is amplified prior to recording. An adjustable neck band supports the two electrodes of the electroglottograph which are placed on either side of the thyroid alae. Prior to recording, the electrodes of the electroglottograph and the phototransistor of the photoglottograph are adjusted on the subject's neck to produce maximum output as observed on an oscilloscope.

A microphone (B&K, model 4144) positioned 5 cm in front of the lips is used to transduce the subject's voice. The subject's head is held in a constant position on the headrest while sustaining phonation of /i/ at constant pitch and loudness levels and at different fundamental frequencies. A brief presentation of a pure tone is provided initially to give the subject a target frequency to match. The subject is assisted in maintaining a given loudness level by observing the meter display on a microphone-measuring amplifier (B&K, model 2609). Maintenance of targeted fundamental frequency (Fo) level is aided by the visual display of a Lissajous pattern on an oscilloscope. A sinusoid of a given frequency is fed to one channel, while the microphone signal is connected to another channel. When the Fo of the vowel production matches the frequency of the sinusoid, the display on the oscilloscope appears as a fixed elliptical figure. Unfortunately, many patients with laryngeal problems and some normal subjects cannot

sustain phonation at specific pitch and loudness levels. In this situation, patients are asked to sustain phonation at normal conversational levels and lowest and highest pitches at low, normal and high levels of loudness.

The signals from the electroglottograph, photoglottograph, and microphone are recorded on FM channels of an instrumentation recorder (Tandberg, model 115D). After each subject's recording, a 100-Hz triangular wave is amplified and fed to a loudspeaker placed 5 cm in front of the microphone. This tone is recorded as a sound pressure level calibration signal for each subject.

Data Analysis. Representative, stable, 1-second portions from the middle of vowel productions are selected for analysis. A pulse is then placed at the beginning of these segments on another channel of the instrumentation recorder as a trigger for analog-to-digital conversion. Each of the three signals on the FM channels are then low-pass filtered (Krone-Hite, model 3343) at 3 kHz, digitized at 10,000 times/s, and stored in disk memory of a LSI 11/23 computer (DEC). Since the digital sampling of each signal begins at the same place on the tape, synchronization of all three signals is assured.

A general purpose, custom designed software package (MAP) is used to display, edit, and perform the necessary calculations on the acoustic EGG and PGG waveforms. First, the EGG and PGG signals are differentiated in order to derive their velocities, and all four waveforms are displayed simultaneously on a video terminal.

For appropriate interpretation of the glottographic waveforms, it is helpful to know where along each waveform the glottis first opens and where it first closes. The precise moment of opening of the glottis may be difficult to define by PGG alone,[19,20] particularly in patients with abnormal vocal cord posture. For example, it appears that in many patients with Parkinson's disease, complete vocal cord closure does not occur, as in case 1. In order to make comparisons between temporally related events among patients, the point of opening on the PGG waveform was defined, for the purpose of the measurements demonstrated here, as the time corresponding to the peak of opening velocity of the differentiated EGG (DEGG) signal. Krishnamurthy et al[21] found that the peak DEGG velocity during opening corresponded very closely to the exact moment of visible upper vocal cord opening on simultaneously filmed ultra-high-speed film, and that the peak of closing EGG velocity occurred at the point of visible upper vocal cord closure. Since each of the displayed waveforms has the same time base, the peak velocities of opening and closing were related to points on the EGG and PGG signals by projection of straight lines perpendicular to the x axis, from the DEGG waveform. Patients with Parkinson's disease who do not have complete cord closure may also have a poorly defined peak opening velocity in the EGG, but usually a peak is present. Thus the timing measurements represent "most open phase" and "most closed phase" as defined by the maximum peaks in opening and closing velocities of the DEGG. In the case where opening is very poorly defined, this definition may be somewhat inaccurate. We are evaluating a method using computer-triggered stroboscopy to provide more accurate details of glottal opening. This method will be reported separately.

TIME, AMPLITUDE, AND VELOCITY MEASURES

Measure	*Normal Subject*	*Case 1*	*Case 2*	*Case 3*
Fundamental frequency (Hz)	106.00	119.00	158.00	197.00
Mean period (ms)	9.43	8.40	6.31	5.70
Mean frequency perturbation	0.13	0.35	0.13	0.15
Frequency perturbation ratio	3.27	41.67	19.81	29.48
Open quotient	0.44	0.84	0.42	0.55
Speed quotient	1.13	5.20	2.66	1.90
Lateral excursion/ entire cycle (%)	23.00	71.00	27.00	31.00
Medial excursion/ entire cycle (%)	21.00	14.00	12.00	23.00
PGG amplitude fluctuation ratio	30.74	114.82	55.18	362.59
Peak velocity quotient	0.95	1.29	0.98	1.12
Peak velocity fluctuation ratio	73.48	72.77	150.93	436.09

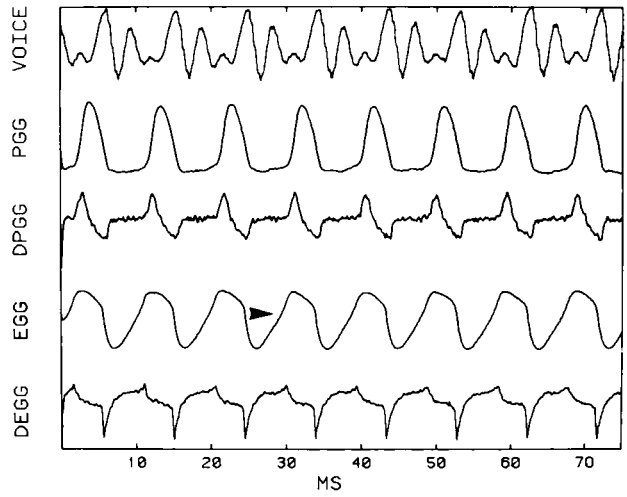

Fig 2. Simultaneous display of acoustic (voice), photoglottographic (PGG), differentiated photoglottographic (DPGG), electroglottographic (EGG), and differentiated electroglottographic (DEGG) signals of vowel production from 35-year-old man with normal voice.

Measurements of various amplitudes, times, and velocities of the waveforms are then made. Some formulas for these measurements are presented in the Appendix. A number of duration measures are computed from the PGG. These include the time from moment of opening, as defined by the peak in opening velocity in the DEGG, to the peak of opening and the time from the peak in opening to the moment of closure, again defined by the peak in the closing velocity from the DEGG. The fundamental frequency, the open quotient (duty cycle), speed quotient,[22] and fundamental frequency perturation[3] are calculated from these duration values.

Another perturbation measure, the PGG amplitude fluctuation, was chosen to portray the cycle-to-cycle variability in light transmitted through the glottis. In addition, measures were developed to assess the magnitude, symmetry, and variability in glottal opening and closing slopes. First, the means of the maximum opening and closing velocities are measured from the differentiated PGG (DPGG) waveform. Next, a peak velocity quotient is calculated to assess the symmetry of the opening and closing slopes. The closer this value approaches unity, the more symmetrical the slopes. Finally, the cycle-to-cycle variability in this quotient, peak velocity fluctuation, is computed to measure the stability in the opening and closing velocities.

CASE REPORTS

The Table presents some representative results of the time, amplitude, and velocity measures in a normal subject and three patients with normal larynges who have distinct phonatory abnormalities. These representative patients were selected because they appear, on the basis of clinical evaluation and laryngoscopy, to have distinctly different phonatory problems.

For purposes of comparison with the case report waveforms, data from a 35-year-old man with a normal voice, phonating at an Fo of 106 Hz and an intensity level of 90 dB SPL, is presented in Fig 2. The relatively high intensity values found in these recordings can be attributed in part to the 5-cm microphone distance which was used during the recording session. The acoustic signal (voice) shown in Fig 2 is quite stable from cycle to cycle. It lags slightly because of the time it takes for the acoustic

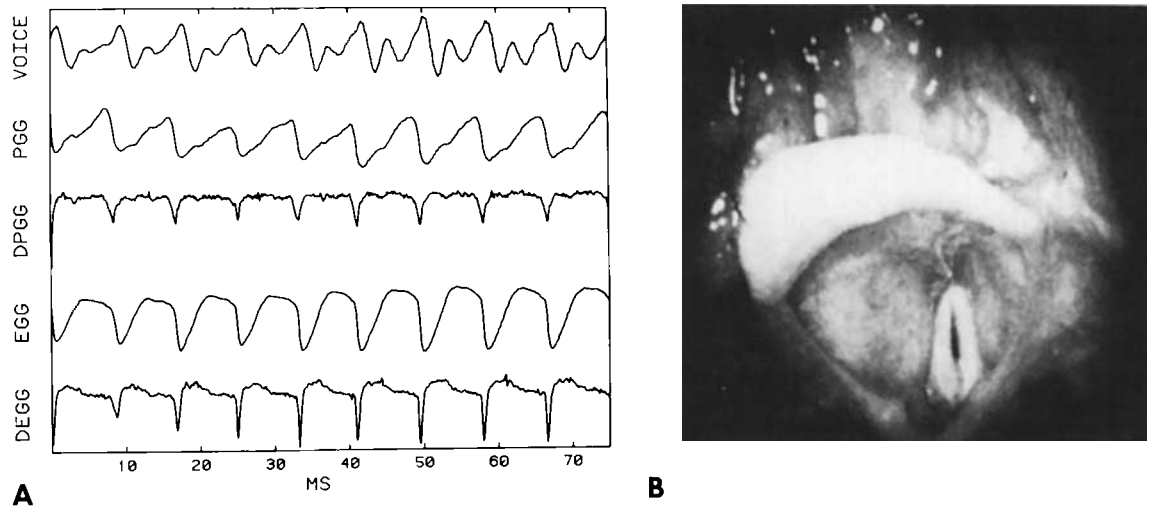

Fig 3. (Case 1) Production of vowel /i/ by 72-year-old man with Parkinson's disease. A) Simultaneous display of acoustic (voice), photoglottographic (PGG), differentiated photoglottographic (DPGG), electroglottographic (EGG), and differentiated electroglottographic (DEGG) signals. B) Reproduction of single 16 mm-frame taken from cine photography of larynx at 12 frames/s.

energy to travel from the glottis, through the vocal tract, to the microphone.

The PGG waveform is similarly stable in normal subjects. Increased light transmission during glottal opening is represented in the PGG waveform by increased voltage. As the vocal folds begin to separate, there is a sharp upward deflection of the waveform. Maximum opening corresponds to the peak, while the beginning of glottal closure is signalled by the sharp downward deflection. Return to the baseline is associated with maximum glottal closure which can take up a considerable proportion of time during a complete glottal cycle in an individual with normal phonation. The shape of the area function peaks derived from PGG is somewhat between a half sinewave and a triangular wave, as would be predicted by the Flanagan-Ishizaka two-mass model.[23] Opening and closing velocities are relatively symmetrical and repeat regularly, indicated by the similarity in amplitude of the peaks in the DPGG waveform of this representative normal subject.

Complementary information is contained in the EGG waveform. Increased impedance occurring as medial vocal fold contact decreases also is represented by increased voltage in the EGG waveform. Portions of the EGG waveform have been related to the sequence of physiological events occurring along the glottal cycle.[24] The lowest point on the waveform corresponds to the most closed period when the vocal folds are compressed at their medial edges. The waveform begins to rise as the lower margins of the vocal folds begin to separate. At the discontinuity in the slope of the waveform, ie, a slight indentation at the large arrowhead in Fig 2, the upper margins of the vocal folds probably first open. It is interesting that the point immediately above this indentation, as the slope begins to rise more steeply, corresponds in time to the point on the PGG waveform signalling the start of a glottal opening phase in the cycle. Following this ascent, there is a short, relatively flat region corresponding to the period when the vocal folds are maximally apart. The slope than descends rather slowly, a period associated with medial adduction of the vocal fold margins, until the waveform falls steeply to the baseline. The instant of glottal closure is probably close to the point corresponding to the minimum of the DEGG waveform.[21] In abnormal phonation, these physiological distinctions may be more difficult to make.

The waveform seen in this example corresponds closely to other normal subjects that we have recorded. The exact waveform shapes vary, of course, with frequency and intensity; however, the basic features described above are present in normal modal phonation. The normal range of waveform characteristics and their derived measures remain to be described for a large population of subjects to account for normal variations and changes with age and sex.

CASE 1

Data from a 72-year-old man with Parkinson's disease, phonating at an Fo of 119 Hz and an intensity level of 76 dB SPL, is shown in Fig 3A. The patient's voice is breathy, weak, and lacks normal pitch and loudness changes. The position of the patient's vocal cords is seen in Fig 3B, taken from a single frame of cine film during phonation of the vowel i .

The PGG waveform is markedly different from normal. It remains at the baseline for only a short proportion of the cycle, demonstrated in the abnormally high open quotient value (Table). In fact, of the entire glottal cycle, only 15% of the time was spent in the "most closed period." The opening portion takes up 71% of the entire cycle, while the closing phase takes up only 14%. In addition, the maximum and minimum intensity of light transmission varies from cycle to cycle, as measured in the PGG amplitude fluctuation ratio, suggesting variation in degree of maximum glottal closure and opening across cycles. The opening and closing slopes are rather asymmetrical, a condition reflected in the peak velocity quotient. In addition, waveform shape varies widely from cycle to cycle, suggesting marked variability in the control of vocal fold posture.

The EGG and DEGG waveforms indicate less easily identifiable segments for physiological interpretation. The rising slope is constant, without the indentation described in the characteristic EGG waveform of the illustrated and other normal speakers. The flat section is wider, indicating a longer period of maximal glottal separation. The waveform then descends to baseline with a constant slope, instead of a gentle descent followed by a steep roll-off, observed in the normal case. One interpretation of this pattern is that the vocal folds move toward the midline, but do not make complete contact at their medial edges. Consequently, the rising and falling slopes lack the discontinuities associated with the medial contact of the upper and lower vocal fold margins occurring during normal phonation. The overall picture is one of little or no glottal closure, allowing the breathy escape of air through the glottis.

Comment. The waveforms generated from the phonation of this patient with Parkinson's disease are quite different from normal. Furthermore, they deviate from normal patterns in a manner that is predictable from observation of the phonatory posture of the patient's larynx during phonation. His vocal folds remain bowed during phonation. There is a visibly greater than normal glottic gap during phonation. This correlates with breathy voice production, short phrasing of speech, and decreased ability to sustain phonation. This basic appearance of phonatory posture is observed in a majority of patients with Parkinson's disease that we have studied with cine laryngoscopy.[25] The recorded glotto-

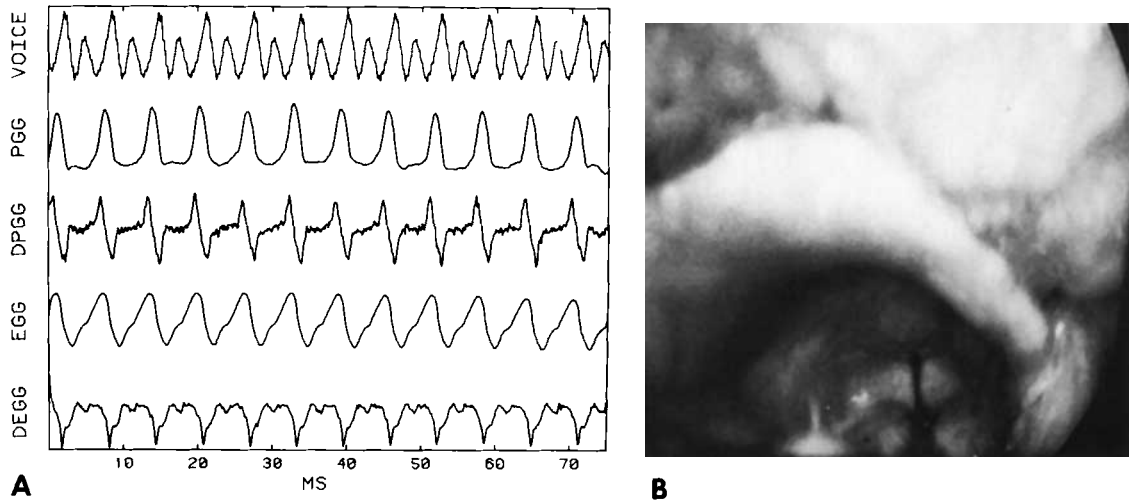

Fig 4. (Case 2) Production of vowel /i/ by 52-year-old man with spastic dysphonia. A) Simultaneous display of acoustic (voice), photoglottographic (PGG), differentiated photoglottographic (DPGG), electroglottographic (EGG), and differentiated electroglottographic (DEGG) signals. B) Reproduction of single 16 mm-frame taken from cine photography of larynx at 12 frames/s.

graphic signals correlate well with the laryngoscopic examination in this patient, and in others that we have examined with these methods. The lack of effective closure is documented in both the PGG and the EGG signals.

CASE 2

Waveform data from a 52-year-old man with spastic dysphonia of the adductor type, phonating at 158 Hz at an intensity level of 95 dB SPL, is presented in Fig 4A. The patient's phonatory and speech abnormalities are typical for mild to moderate spastic dysphonia. He has moderate strain-strangled quality during most of his phonation. He demonstrates particular difficulty with the initiation of phonation in voiced phonemes occurring in the initial position of words. Laryngoscopic examination demonstrates an appearance which is typical of adductor spasticity. Laryngeal posture during vowel production in this patient is pictured in Fig 4B. There is hyperadduction of the true cords and contraction of the supraglottal musculature.

The PGG waveform shows relatively long closure periods during the glottal cycle, a condition confirmed by the slightly smaller open quotient than that of the normal individual. Actually, 61% of the entire cycle is spent in glottal closure. The greatest difference from normal among the duration measures is the speed quotient, caused primarily by the abnormally short closing phase. In fact, of the entire cycle, only 12% of time is spent in medial excursion of the vocal folds. This pattern may reflect increased tension in the vibrating folds as compared to normal. The small indentation in the rising slope of the EGG signal described in the normal case is much more pronounced in all of the cycles portrayed in Fig 4B. This event can be identified as a notch in the upper segment of each cycle of the DEGG signal. There is no relatively flat area at the top of the peaks in the EGG waveform, indicating the short duration of maximum glottal opening. The impedance reaches a peak and then drops sharply during closure, in contrast to the normal pattern of slow followed by quick change in velocity. Again, the visible changes in the recorded waveforms correspond well with the pathological conditions in this case.

Comment. The data from this patient's phonation are quite different from those of the patient with parkinsonism. This is expected since the two cases represent somewhat opposite extremes in phonatory posture. This patient's voice sounds strained and at times strangled, while the patient with Parkinson's disease has a voice that is weak and breathy. These perceived vocal characteristics appear to relate to greater than normal tension in vocal fold vibration, on one hand, versus incomplete glottic closure on the other, as identified in the respective glottographic recordings of these two patients.

The waveforms presented in Fig 4A represent this patient's "best" voice. Although the voice sounds tensed during this sustained vowel production, the patient does not demonstrate the spasmodic and effortful "squeezing" of the glottis that occurs during spontaneous speech production. Nevertheless, these glottographic signals are quite visibly different from those of normal speakers, and seem to correlate well with laryngoscopically documented spastic function during phonation.

CASE 3

Data from a 39-year-old man who suffered severe acute arsenic poisoning 7 years prior to this examination is represented in Fig 5. He is phonating at 197 Hz at an intensity level of 87 dB SPL. The patient is confined to a wheelchair and has severe loss of tactile, vibratory, and proprioceptive sense throughout his body. His voice is distinctly abnormal and is best characterized as harsh and tremulous. Attempts at prolonged phonation produced marked variation in quality, pitch and intensity, and there were periods of diplophonia and vocal fry. This segment is taken from a period of phonation in which the voice sounds diplophonic, ie, two distinct tones are apparent to the ear.

The peaks in the PGG waveform vary widely in amplitude and shape; however, this variability seems to occur in a regular fashion across every five cycles. In other words, every fifth cycle appears to be similar in shape. This impression of variability is confirmed in the extremely large fluctuation values. The PGG amplitude fluctuation ratio is over 11 times as great as that for the normal individual. Since little vertical laryngeal movement was observed laryngoscopically during this phonation, we assume that these changes in light intensity correspond to variation in maximum glottal opening from cycle to cycle. Peak velocity fluctuation ratio is similarly much larger than this measure in the normal individual, confirming the visibly large changes in the symmetry of opening to closing slopes. In addition, the lack of a flat segment at the baseline indicates that the period of glottal closure is short.

The EGG signal also varies in a five-cycle pattern. There is little or no flat segment at the top of the peaks, indicating a very short or incomplete period of glottal opening. Additionally, the point of minimal impedance varies from cycle to cycle, suggesting a noticeable variability in degree of medial vocal fold contact during glottal closure.

Comment. Arsenic poisoning is known to affect the nervous system, with particular loss of peripheral sensory function.[26] This patient evidences marked loss of phonatory control. The waveform pattern that recurs over several cycles correlates with listener perception of diplophonia. Such a pattern conceivably could re-

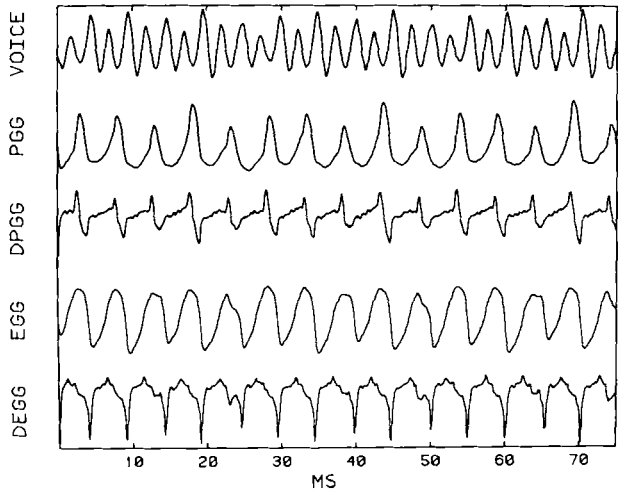

Fig 5. (Case 3) Simultaneous display of acoustic (voice), photoglottographic (PGG), differentiated photoglottographic (DPGG), electroglottographic (EGG), and differentiated electroglottographic (DEGG) signals from vowel /i/ produced by patient poisoned by arsenic.

sult from vibration of each vocal fold at different frequencies or by the generation of subharmonic frequencies when two or more natural tissue modes are excited in the same vocal fold.[27] This is an example where high-speed filming or waveform-triggered stroboscopy would clarify understanding of the vibratory mode which results in this perceived voice characteristic.

DISCUSSION

While the methods described here have been used primarily for the study of the normal voice, these methods are potentially of great value to the clinical laryngologist. Laryngologic surgery has evolved from basically lifesaving operations, which often left significantly disturbed phonatory function to sophisticated conservation and reconstructive techniques. For example, a number of innovative surgical approaches recently have been reported to improve neuromuscular function in certain laryngeal disorders. These procedures are being performed and evaluated by a number of individuals. Assessment of the results of such procedures have been noticeably impaired by lack of quantitative measures which can be applied in clinical settings. There is great clinical need for measures that can be related directly to vocal function to compare the results of different treatment techniques, to diagnose specific disorders of function, and to monitor changes with treatment.

Glottographic measures are not new or untested. The techniques have been used individually in research laboratories for many years. More recently, the use of simultaneously recorded glottographic measures has been advocated by speech scientists as a reasonable approach to the measurement of vocal function in normal individuals.[28] Our clinical experience with the application of these techniques to patients has been encouraging. The described techniques are relatively noninvasive and require no more time to perform than brainstem evoked audiometry. In fact our clinic recording system is located in the same double-walled audio booth that is used for evoked response recording. Visual analyses of the recorded signals correspond very well to laryngoscopic and other clinical evaluations of the patients' dysfunction yet appear to provide much greater detail of the vibratory characteristics of the cords than any existing clinical techniques. Furthermore, measurements from the waveforms hold some promise of providing quantification of important phonatory characteristics.

Data generated from these methods must be interpreted cautiously in light of laryngologic examination. For example, in patients who adduct the ventricular vocal folds during phonation (a compensatory strategy in some individuals), the PGG signal may not represent the glottal area accurately. In patients who have significant asymmetry in vocal cord closure (ie, one cord is crossed over the other), the PGG waveform also may not reflect the glottal opening, since it may not be oriented perpendicularly to the light.

Although the EGG waveform is obtained easily in nearly all patients, a few abnormal conditions can also make interpretation difficult. For example, the presence of a tissue or mucous bridge between the vocal folds, or contact of the ventricular folds, may affect the impedance between the two electrodes in an aberrant manner. Simultaneous recording of several measures with fiberoptic laryngoscopic monitoring allows informed interpretation of the glottographic measures.

Certainly, one of the most appealing features of these procedures is the graphic picturability of the waveforms. An overall impression of the pathophysiology can be gained rather quickly upon viewing the PGG and EGG waveform patterns. Moreover, documentation with quantitative data from the signals can be obtained. We have used a few traditional measurements such as the open quotient, speed quotient, and fundamental frequency perturbation. We have also developed some measures which appear to differentiate among subjects with differing pathologies. In addition, other measures may prove better able to define subtle changes in laryngeal control in patients with voice disorders. In theory, given the proper parameters, one may be able to reconstruct the glottal configuration and details of vocal fold tissue movement from glottographic waveforms.[17]

In our clinical practice we find that information obtained from glottographic studies is often diagnostically helpful, particularly in patients with voice abnormalities associated with neuromuscular disorders. Diagnosis of the dysphonia of a patient who has a vocal cord carcinoma, nodule, or polyp is fairly straightforward. However, determination of the cause of dysphonia in the patient who has an anatomically normal larynx may be very difficult un-

less there is obvious paralysis, paresis, or hyperfunction that is laryngoscopically visible. Glottographic techiques appear to offer some insight into the more subtle vibratory and tension abnormalities that are associated with pathological phonation in the otherwise normal-appearing larynx. For example, glottography, in our experience, reliably documents the presence of incomplete vocal cord closure. In some cases, this may be visible laryngoscopically, but often is not detected without the analysis of ultra-high-speed films. Similarly valuable diagnostic information, such as indications of abnormally increased vocal fold tension or cycle-to-cycle variability in vibration, may be identified and measured in the waveforms.

The apparent value of the simultaneous recordings of glottographic signals requires confirmation in sizable populations of clinical patients. Our experience to date indicates that the use of simultaneously recorded glottographic signals for better understanding of phonatory disorders has excellent potential, and such studies are probably well worthwhile. We are currently using these techniques for the analysis of phonatory disturbances in several populations of patients with movement disorders. The voice abnormalities of such patients are relatively poorly understood and often neglected. Glottographic studies of patients with anatomical vocal cord lesions are also of interest as they appear to help describe the effect of mass lesions on vocal fold vibration. Recordings over time may also be useful to document the results of treatment in a given patient.

In summary, glottographic measurements appear to have potential as a valuble component in a multilevel analysis of voice disorders. Simultaneous recordings of objective measures of glottal vibratory function are feasible in a clinical setting, and they appear to differentiate phonatory characteristics of patients with distinct phonatory abnormalities. Such measurements must be interpreted in light of accurate, documented examination of the larynx during phonation and ideally should be compared with simultaneously recorded photographic data. Our experience indicates that information from these measurements may be useful diagnostically in individual patients to understand the pathophysiology of abnormal phonatory characteristics, to plan therapy, and to follow the effects of treatment. Further data are likely to clarify the potential role of these techniques in general clinical care of the voice patient.

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APPENDIX

FORMULAS USED IN GLOTTOGRAPHIC MEASUREMENT

Open quotient:

$$\frac{\text{duration glottis is open}}{\text{total duration of glottal cycle}}$$

Speed quotient:

$$\frac{\text{duration of lateral excursion in ms}}{\text{duration of medial excursion in ms}}$$

Mean frequency perturbation:

$$\frac{\Sigma \text{ absolute difference between consecutive periods in ms}}{\text{number of periods}}$$

Frequency perturbation ratio:

$$\frac{\text{mean frequency perturbation}}{\text{mean period}} \times 1{,}000$$

Mean PGG amplitude:

$$\frac{\Sigma \text{ baseline to peak intensity in volts}}{\text{number of cycles}}$$

Mean PGG amplitude fluctuation:

$$\frac{\Sigma \text{ absolute difference in PGG amplitude between consecutive cycles}}{\text{number of cycles}}$$

PGG - Photoglottograph; DPGG - Differentiated photoglottograph.

PGG amplitude fluctuation ratio:

$$\frac{\text{mean PGG amplitude fluctation}}{\text{mean PGG amplitude}} \times 1{,}000$$

Mean maximum glottal opening velocity:

$$\frac{\Sigma \text{ baseline to positive peak in the DPGG}}{\text{number of cycles}}$$

Mean maximum glottal closing velocity:

$$\frac{\Sigma \text{ baseline to negative peak in the DPGG}}{\text{number of cycles}}$$

Peak velocity quotient:

$$\frac{\text{mean maximum glottal opening velocity}}{\text{mean maximum glottal closing velocity}}$$

Mean peak velocity fluctuation:

$$\frac{\Sigma \text{ absolute difference between velocity quotients from consecutive cycles}}{\text{number of cycles}}$$

Peak velocity fluctuation ratio:

$$\frac{\text{mean peak velocity fluctuation}}{\text{mean peak velocity quotient}} \times 1{,}000$$

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