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Christopher Dromey
Brigham Young University, dromey@byu.edu

Christine M. Sapienza
University of Florida

Elaine T. Stathopoulos
State University of New York at Buffalo

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Approximations of Open Quotient and Speed Quotient from Glottal Airflow and EGG Waveforms: Effects of Measurement Criteria and Sound Pressure Level

*Christine M. Sapienza, †Elaine T. Stathopoulos, and ‡Christopher Dromey

**Department of Communication Sciences and Disorders, The University of Florida, Gainesville, Florida; †Department of Communicative Disorders, State University of New York at Buffalo, Buffalo, New York, U.S.A.; and the ‡Toronto Hospital, Toronto, Ontario*

Summary: Noninvasive measures of vocal fold activity are useful for describing normal and disordered voice production. Measures of open and speed quotient from glottal airflow and electroglottographic (EGG) waveforms have been used to describe timing events associated with vocal fold vibration. To date, there has been little consistency in the measurement criteria used to calculate quotient values. In this study, criteria of 20% and 50% were applied to the AC amplitude of glottal airflow and inverted EGG waveforms for measurement of open quotient. Criteria of 20%, 50%, and 80%, and a midslope criterion that segmented the waveform between 20% and 80% of the waveform amplitude, were used for the calculation of speed quotient. Subjects produced waveforms at sound pressure levels (SPL) of 70, 75, 80 and 85 dB. Results indicated that approximations of open quotient obtained from the glottal airflow waveform significantly decreased using both the 20% and 50% criteria as SPL increased from 80 to 85 dB. No significant changes were found in open quotient from the EGG waveform as a function of SPL. Results of speed quotient measures from the glottal airflow and EGG waveforms showed a generally increasing trend as SPL increased, although the differences were not statistically significant. The data suggest that the signal type, measurement criterion and SPL must be considered in interpreting quotient measures. **Key Words:** Glottal airflow—Electroglottography—Criterion—Sound Pressure Level.

Empirical measurement of open quotient (OQ) and speed quotient (SQ) requires a definition of the precise instants of opening and closing of the vocal folds. In 1958, Timcke et al. (1) identified these instants by filming vocal fold vibration with a high-speed motion camera. They defined open quotient as a ratio of the duration of the open phase to the duration of a glottal period. Speed quotient was defined as the duration of the opening phase divided by the duration of the closing phase. Although the method of high-speed motion filming was useful in quantifying the timing characteristics of vocal fold vibration, the process never became clinically useful because it was invasive, time-consuming, and expensive.

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Address correspondence and reprint requests to Christine M. Sapienza, Department of Communication Sciences and Disorders, 63 Dauer Hall, University of Florida, Gainesville, FL 32611 U.S.A.

While more indirect than high-speed filming, inverse filtering of the oral airflow waveform and electroglottography (EGG) both provide information about vocal fold physiology. In fact, combining electroglottography with high-speed motion filming (2,3), videostroboscopy (4–7) and photoglottography (8–10), led to the development of models describing the relationship between EGG waveform characteristics and vocal fold vibratory events. The models depict temporal landmarks on the EGG waveform relative to the physiological events of vocal fold vibration (e.g., 11). A depiction of the models can be found in Childers (2), Childers et al. (12), and Rothenberg (13). Although the EGG model is generally accepted (12), error in solely interpreting results from EGG waveforms can arise from extreme variations in waveform shape within and across subjects. Vertical phase differences between the lower and upper margins of the vibrating folds and mucus strands across the glottis can make the EGG signal difficult to interpret (2,12). In addition to the physiological variations in vocal fold vibration, methodological error can occur due to poor placement of the electrodes and residual effects from high pass filtering (14).

Less information has been gained about the relationship between vocal fold vibratory events and the glottal airflow waveform, which is derived from inverse filtering an oral airflow signal. Hertegard et al. (15) described a method which incorporated electroglottography, inverse filtering of the oral airflow waveform and videostroboscopy. This method was used to determine the instants of vocal fold closure more exactly by visually examining the vocal folds via videostroboscopy, while simultaneously recording glottal airflow and EGG waveforms. Their methodology proved useful in indicating the correspondence between the observed movements of the vocal folds and the properties of both the glottal airflow and EGG waveforms. The instant of glottal closure was indicated near the baseline of a glottal airflow waveform and near the peak of an inverted EGG waveform. The findings of Hertegard et al. (15) were experimentally useful in establishing where glottal closure occurs on airflow and EGG waveforms. From an experimental perspective, details regarding the phases of vocal fold vibration and the corresponding points on the waveforms are invaluable. Yet the signals analyzed in that study were produced from trained singers who phonated at a comfortable SPL while matching fundamental frequency. This would be a challenging task for individuals with untrained voices. Consequently, it is difficult to apply Hertegard et al.'s synchronous validation technique when assessing a patient's vocal performance during a routine clinical examination.

The present study applied selected measurement criteria to glottal airflow and inverted EGG waveforms to determine their relationship to open and speed quotient and sound pressure levels (SPLs). Criterion levels have been established to decrease measurement error associated with subjective definitions of temporal landmarks on glottal airflow and EGG waveforms (16–18). This method results in high intrameasurer reliability because the same temporal landmarks can be selected by algorithms programmed into waveform analysis software programs (17,18).

A criterion level is typically applied to the AC component of a waveform, which is the portion of the waveform that fluctuates between a minimum and maximum value above any baseline offset. Criteria applied to inverted EGG waveforms have ranged from 30–75% (11,14,19,20). Criteria applied to glottal airflow waveforms have ranged from 15–50%, (14,16,19–21). Although each of the cited researchers operationally defined the open and closed portions of the vibratory cycle in a rational way, the use of a wide range of criteria has made it difficult to compare results across investigations or to establish normative databases. Furthermore, an assumption seems to exist that one criterion level provides more accurate information than another. For example, do some criterion levels analyze too little of the AC amplitude of a waveform or examine an inappropriate part of the waveform when calculating quotient values? It is an interesting question although no study has actually experimentally compared open and speed quotient data while applying several criterion levels to the same waveform.

The criteria which were selected for study represent the range of criteria used in previous investigations (11,14,16,19,20). For the purpose of this paper, open quotient and speed quotient will be referred to as OQ' and SQ' to acknowledge that they are approximations of the original quotient definitions of Timcke et al. (1).

PURPOSE OF THE PRESENT STUDY

The goals of this investigation were: (a) to segment glottal airflow and inverted EGG waveforms using different baseline criteria; (b) to statistically assess differences in OQ' and SQ' as a function of SPL; and (c) to aid in the development of standardized measurement procedures for segmenting these waveforms.

METHODS

Subjects

Ten adult females, ranging in age from 20–29 years (mean age = 22.6 years) participated in the investigation. All subjects passed a screening for normal speech, language, and hearing ability. The subjects were native speakers of North American English, nonsmokers, free from history of respiratory and/or voice difficulties, and had no professional voice training.

Speech tasks

The subjects produced a syllable train consisting of seven repetitions of /pɑ/. Three trials of the syllable train at each of four different sound pressure levels (70, 75, 80, and 85 dB) were produced. SPLs for each target were monitored within ±1 dB by the subject and investigator using a modified voltmeter calibrated to display SPL. The SPLs used in this study represented a soft to loud range. To reduce the vocal demands placed on the subjects and to allow for a more natural production of the speech stimuli, no control of pitch was required. Pitch variations within each of the SPL conditions ranged from 5 to 19 Hz across the 5 dB SPL conditions and 14 to 28 Hz across the 10 dB SPL conditions.

Equipment and procedures

A circumferentially vented pneumotachograph mask coupled to a differential pressure transducer (PTW-1) and preamplifier system (Glottal Enterprises, Syracuse, New York, model MS 100 A-2) were used to sense the wideband oral airflow signal. The pressure transducer and mask were calibrated with a known flow through a Fischer and Porter rotameter (model 114 A RS-583) prior to collection of the data. The wideband airflow signal was low-pass filtered at 3 kHz using a Frequency Devices 901 8-pole Butterworth Filter prior to digitization. Digital inverse filtering was completed using CSpeech 3.0 (Madison, Wisconsin) to yield a glottal airflow waveform (22). A 100 ms window was selected by the investigator from the midportion of the second vowel in the /pɑ/ syllable train, and the inverse filtering procedure was applied to the signal. Linear predictive coding (LPC) by the covariance method for calculation of the formant frequencies was completed on the selected segment. The first and second formants fall below the 3 kHz filter and are removed with a LPC filter (22). The inverse filtering procedure computes the glottal derivative and the resulting signal is integrated to produce an estimate of a glottal airflow waveform. The frequency and bandwidth parameters are automatically adjusted for each subject by CSpeech, which minimizes the residual formant energy regardless of the frequency and intensity of the signal (23).

The EGG signal was obtained from a Kay Elemetrics, (Pine Brook, New Jersey) Laryngograph (Pine (Fourcin) and low-pass filtered at 3 kHz (Frequency Devices 901 8-Pole Butterworth Filter). Additionally, the signal was digitally filtered in CSpeech prior to extracting the quotient data. A zero-phase high-pass filter with a cutoff at approximately 20 Hz was applied (23). This was done to remove low-frequency artifact, which is often found in an EGG signal. The EGG signal was inverted so that the opening and closing phases corresponded to the glottal airflow waveform.

SPLs were obtained from the pressure transducer inside the pneumotachograph calibrated in dB (re:0.0002 dynes per cm^2) for a 15-cm mouth to microphone distance (16). Data were collected and stored on VHS tape using a PCM data recorder (Vetter 3000). Measurements were completed using CSpeech and a DTK 486 microcomputer modified with a Data Translation 12-bit analog-to-digital signal processing board (Model 2821). Signals were digitized at a sampling rate of 10 kHz.

Measurements

The different measurement criteria were independently applied to the AC component of the glottal airflow and inverted EGG waveforms using an algorithm within CSpeech. This algorithm measured the peak and minimum values of the AC component and identified the percentage criterion levels in each of the waveforms. Criteria of 20% and 50% of the AC component were selected for the OQ' measures. Criteria of 20%, 50%, 80%, and a midslope criterion were selected for SQ' measures. The midslope measure was calculated by measuring the duration of the opening and closing phases that occurred between the 20% and 80% levels.

The measures of OQ' and SQ' allowed for analysis of open vs. closed time as a function of SPL and measurement criteria. Time alignment between the glottal airflow and inverted EGG waveforms was not necessary during the analysis because the algorithm was independently applied to each waveform.

The criteria used to segment the waveforms are described below and diagrammed in Fig. 1 and Fig. 2 for the glottal airflow and inverted EGG waveforms, respectively.

I. Measures from the glottal airflow waveform:
   A. Airflow open quotient($OQ'^{20\%,50\%}$): the time that airflow is greater than 20% or 50% of the AC component divided by the period of one vibratory cycle.
   B. Airflow speed quotient ($SQ'^{20\%,50\%,80\%}$): the time taken for airflow to increase from 20%, 50%, or 80% of its AC value to its maximum divided by the time for it to decrease from the maximum value to 20%, 50%, or 80% of its AC value.
   C. Airflow speed quotient (SQ'mid): the time taken for airflow to rise from 20% to 80% of the AC component divided by the time taken to fall from 80% to 20% of the AC component.

II. Measures from the inverted EGG waveform:
   A. EGG $OQ'^{20\%,50\%}$: the time which the impedance was greater than 20% and 50% of the

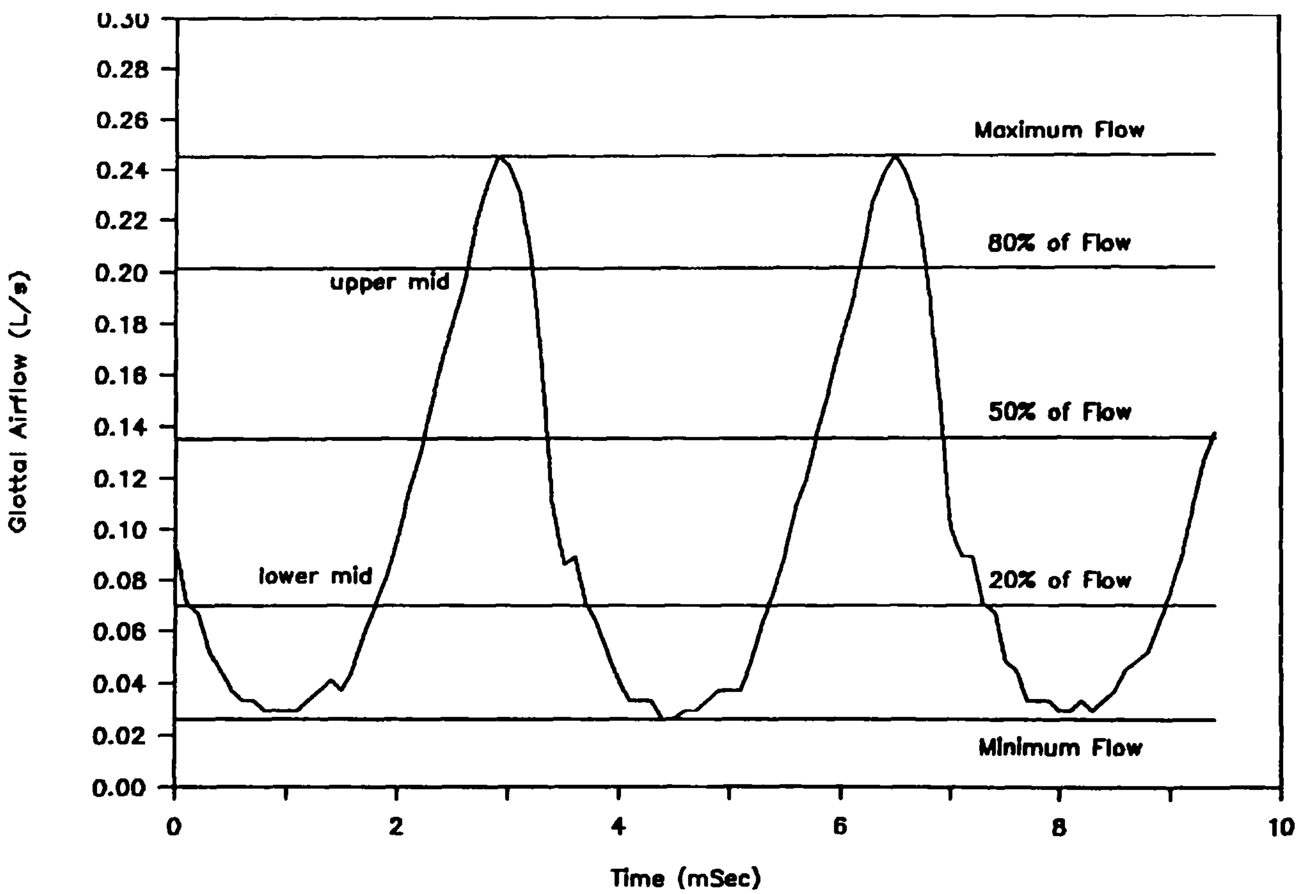

FIG. 1. Two cycles of a glottal airflow waveform depicting the 20%, 50%, 80% and mid-slope criteria.

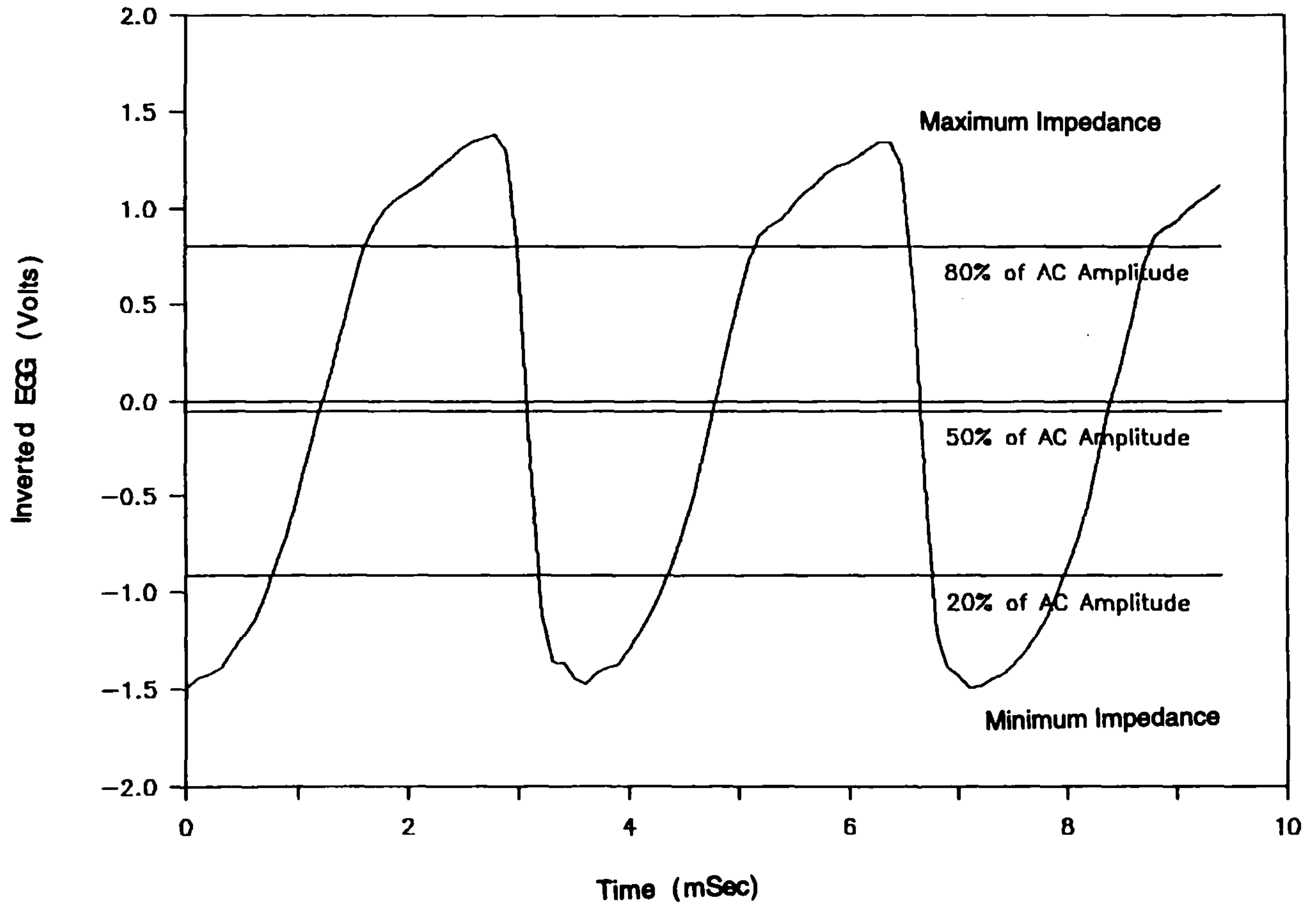

FIG. 2. Two cycles of an inverted EGG waveform depicting the 20%, 50%, and 80% criteria for calculation of OQ'.

AC component divided by the period of one vibratory cycle.

B. EGG SQ'$^{20\%,50\%,80\%}$: the time taken for impedance to increase from 20%, 50%, or 80% of its AC value to its maximum divided by the time for it to decrease from the maximum value to 20%, 50%, or 80% of its AC value.

C. EGG SQ'mid: the time taken for impedance to rise from 20% to 80% of the AC component divided by the time taken to fall from 80% to 20% of the AC component.

Open Quotient was derived from: C-A/D-A and speed quotient from B-A/B-C where: These landmarks are depicted on a glottal airflow waveform in Fig. 3.

A represents the positive criterion level crossing;

B represents the moment the signal reached its maximum;

C represents the negative criterion level crossing;

D represents the positive criterion level crossing for the following cycle.

Data Analysis

Interjudge reliability was calculated on 10% of the data. The results of a Pearson r correlation test revealed high correlation between the original measures and the remeasured data for OQ' ($r(29) = 0.896$, $p \leq 0.05$ and SQ' ($r(29) = 0.878$, $p \leq 0.05$). The reliability analysis represents both experimenter reliability and machine reliability. In order to yield high interjudge correlations two experimenters each consistently marked the waveforms and invoked the algorithm. This procedure coupled with consistent performance of the algorithm, resulted in the aforementioned reliability results.

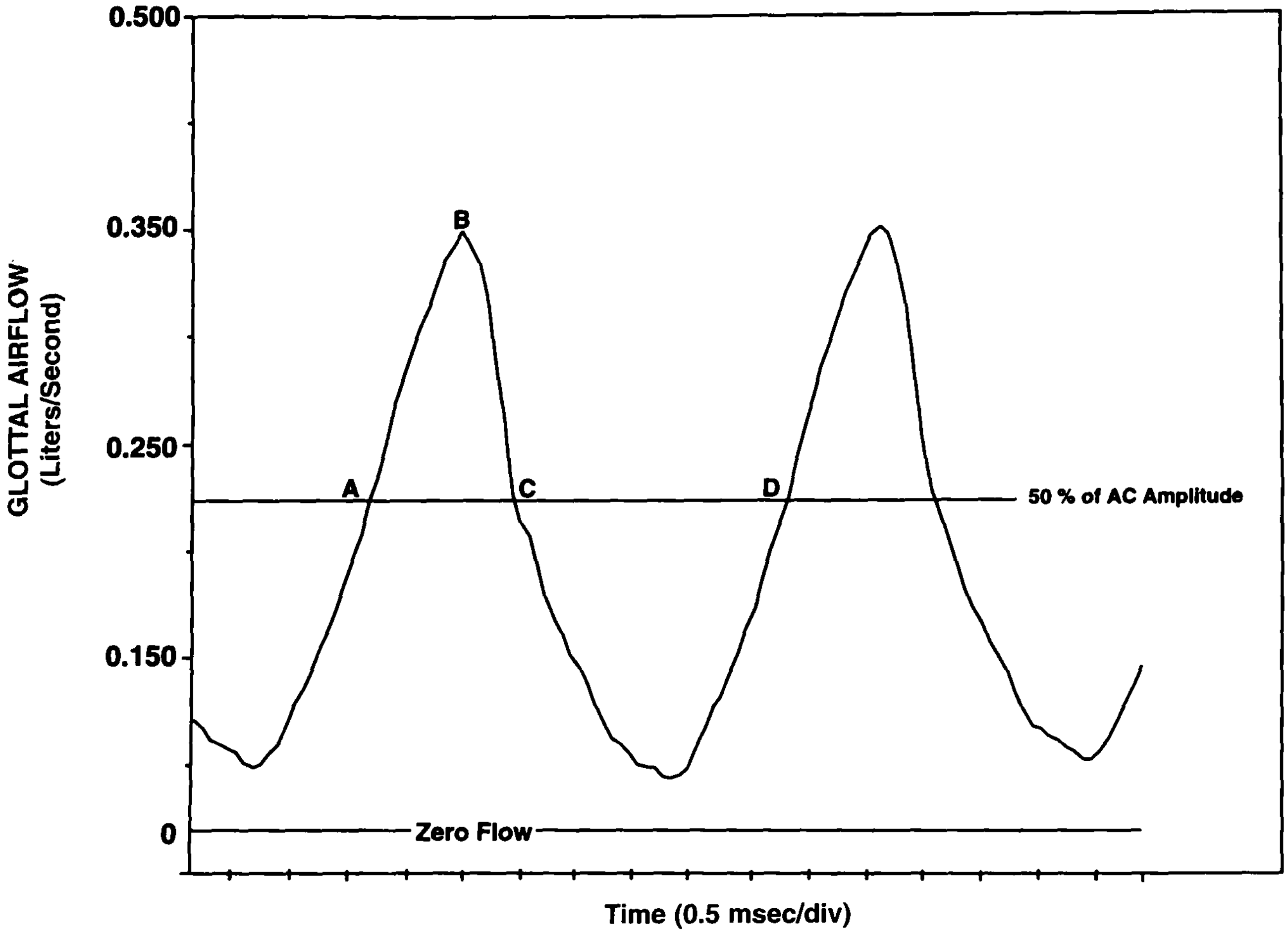

FIG. 3. Two cycles of a glottal airflow waveform showing the temporal landmarks used with a 50% criteria for the measurement of OQ' and SQ'.

The means and standard deviations for the OQ' and SQ' measures for each criterion level at sound pressure levels of 70, 75, 80 and 85 dB can be found in Table 1. Measures of OQ' and SQ' from both the airflow and EGG waveforms were compared for increases of 5 dB and 10 dB. For the analysis of the 5 dB step increase, three statistical contrasts were tested; 70 vs. 75 dB SPL, 75 vs. 80 dB SPL and 80 vs. 85 dB SPL. For the analysis of the 10 dB step increase, two contrasts were tested; 70 vs. 80 dB SPL and 75 vs. 85 dB SPL. Pairwise t-tests were used to evaluate the OQ' and SQ' values from all criteria for the 5 and 10 dB increases. Tables 2 and 3 provide a summary of the pairwise comparisons for OQ' and SQ' measures for both waveform types. The alpha level was adjusted to 0.020 using the Bonferonni test of inequality for the 5 dB contrasts and 0.025 for the 10 dB contrast.

Results for the 5 dB increase in SPL

Glottal airflow waveform. For all measurement criteria, OQ' and SQ' mean values from the glottal airflow waveform indicated no statistically significant change with increases of 5 dB, except for OQ' 20% and OQ'50% values for the 80 vs. 85 dB SPL contrast (Fig. 4A).

Electroglottographic waveform. No statistically significant differences in OQ' across the 5 dB SPL increases were found for the two criteria of 20% and 50% (Fig. 4, B). The SQ' midslope criterion showed a statistically significant difference for the 5 dB increases from 70 to 75 dB SPL and 80 to 85 dB SPL (Fig. 5B).

TABLE 1. *Means and standard deviations for open quotient (OQ') and speed quotient (SQ') measures from the glottal airflow and inverted electroglottographic waveforms for each measurement criterion at 70 to 85 dB SPL*[1]

I. OQ' GLOTTAL AIR FLOW

	70dB		75 dB		80 dB		85 dB	
Criteria	M	SD	M	SD	M	SD	M	SD
20%	0.706	0.047	0.692	0.052	0.639	0.070	0.573	0.060
50%	0.445	0.038	0.438	0.031	0.398	0.057	0.363	0.034

II. OQ' EGG

	70dB		75 dB		80 dB		85 dB	
Criteria	M	SD	M	SD	M	SD	M	SD
20%	0.732	0.021	0.733	0.042	0.740	0.038	0.699	0.060
50%	0.526	0.036	0.551	0.071	0.559	0.050	0.535	0.074

III. SQ' GLOTTAL AIR FLOW

	70dB		75 dB		80 dB		85 dB	
Criteria	M	SD	M	SD	M	SD	M	SD
20%	1.547	0.278	1.776	0.467	1.997	0.539	2.109	0.512
50%	1.530	0.205	1.677	0.254	1.826	0.384	1.926	0.383
80%	1.627	0.288	1.526	0.256	1.425	0.268	1.477	0.234
MID	1.760	0.477	2.200	0.912	2.645	0.888	2.766	0.840

IV. SQ' EGG

	70dB		75 dB		80 dB		85 dB	
Criteria	M	SD	M	SD	M	SD	M	SD
20%	1.742	0.559	1.971	0.984	2.426	1.305	2.710	1.301
50%	1.729	0.696	1.762	1.017	2.194	1.271	2.761	1.557
80%	1.545	0.579	1.456	0.906	1.874	1.246	2.572	1.673
MID	2.284	0.818	3.687	1.182	4.233	1.386	3.331	0.805

[1]SD=standard deviation.

Results for the 10 dB increase in SPL

Glottal airflow waveform. The 20% and 50% criteria showed a statistically significant decrease in OQ' as SPL increased from 75 to 85 dB (Fig. 4A). A significant increase in SQ' values was demonstrated using the 20% and midslope criterion levels as SPL was increased from 70 to 80 dB (Fig. 5A).

Electroglottographic Waveform. No statistically significant differences for OQ' as a function of the 10 dB increases were found for any of the criteria (Fig. 4B). Significant increases in SQ'20%, SQ'50%, and SQ'80% values were found for the 75 to 85 dB SPL increase. A significant increase in SQ' mid values was found with the SPL increase from 70 to 80 dB (Fig. 5B).

DISCUSSION

Glottal airflow

OQ'

The results for the OQ' measures from the glottal airflow waveform are consistent with previous findings showing that the vocal folds stay closed for a longer portion of the vibratory cycle as SPL increases (19–21,24). In particular, the OQ' trends corroborate with the quotient results obtained from direct views of vocal fold motion, which also indicate longer vocal fold closure as SPL is increased (1). The OQ' means, obtained when the criterion levels of 20% and 50% were applied to the glottal airflow waveform, consistently decreased as SPL increased from 70 dB to 85

TABLE 2. *Results of t-test pairwise comparisons for OQ' and SQ' from the glottal airflow and inverted EGG waveforms for 5 dB SPL contrasts (df = 9)*

	70–75 dB SPL		75–80 dB SPL		80–85 dB SPL	
	t	p	t	p	t	p
Glottal Airflow						
OQ' 20	0.668	0.521	0.178	0.110	3.832	0.004
OQ' 50	0.541	0.602	2.252	0.051	3.210	0.010
SQ' 20	−2.639	0.027	1.846	0.098	−0.909	0.387
SQ' 50	−1.845	0.098	1.727	0.118	−0.118	0.268
SQ' 80	1.762	0.112	1.115	0.281	−0.726	0.486
SQ' MID	−2.607	0.028	−2.641	0.027	−0.474	0.647
EGG						
OQ' 20	0.001	0.994	0.466	0.466	1.673	0.129
OQ' 50	0.835	0.425	−0.885	0.399	1.178	0.269
SQ' 20	−1.334	0.215	−1.943	0.084	−0.816	0.436
SQ' 50	−0.197	0.848	−1.462	0.178	−0.133	0.216
SQ' 80	0.422	0.683	−1.323	0.218	−1.427	0.187
SQ' MID	−7.472	0.000	−2.261	0.500	2.974	0.015

$p < .02$.

TABLE 3. *Results of t-test pairwise comparisons for OQ' and SQ' from the glottal airflow and inverted EGG waveforms for 10 dB SPL contrasts (df = 9)*

	70–80 dB SPL		75–85 dB SPL	
	t	p	t	p
Glottal airflow				
OQ' 20	2.294	0.048	3.720	0.005
OQ' 50	2.238	0.052	5.373	0.000
SQ' 20	3.050	0.014	−2.093	0.066
SQ' 50	2.568	0.030	−2.475	0.035
SQ' 80	1.773	0.110	0.533	0.607
SQ' MID	4.177	0.002	−1.995	0.077
EGG				
OQ' 20	−0.697	0.503	1.344	0.212
OQ' 50	−1.452	0.180	0.634	0.542
SQ' 20	−2.252	0.051	−2.730	0.023
SQ' 50	−1.400	0.195	−2.980	0.015
SQ' 80	−0.906	0.389	−3.026	0.014
SQ' MID	−5.673	0.000	1.325	0.218

$p < .025$.

dB. However, the decrease in OQ' was only statistically significant for 5 dB changes at high SPLs (80 vs. 85 dB SPL) or when comparing OQ' over a large SPL increase (10 dB). It is well known that increased glottal closure is one of the mechanisms for increasing SPL (1). Yet, there are other factors that contribute to increased SPL, such as increasing respiratory drive or altering other aspects of glottal configuration.

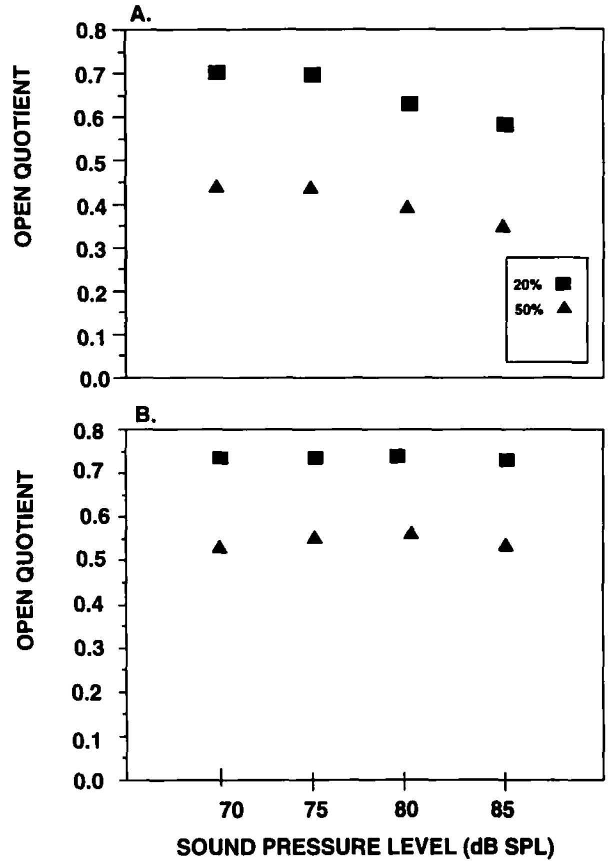

FIG. 4. OQ' results from the glottal airflow waveform (A) and the inverted EGG waveform (B) for the sound pressure levels of 70, 75, 80, and 85 dB using the 20% and 50% criterion levels.

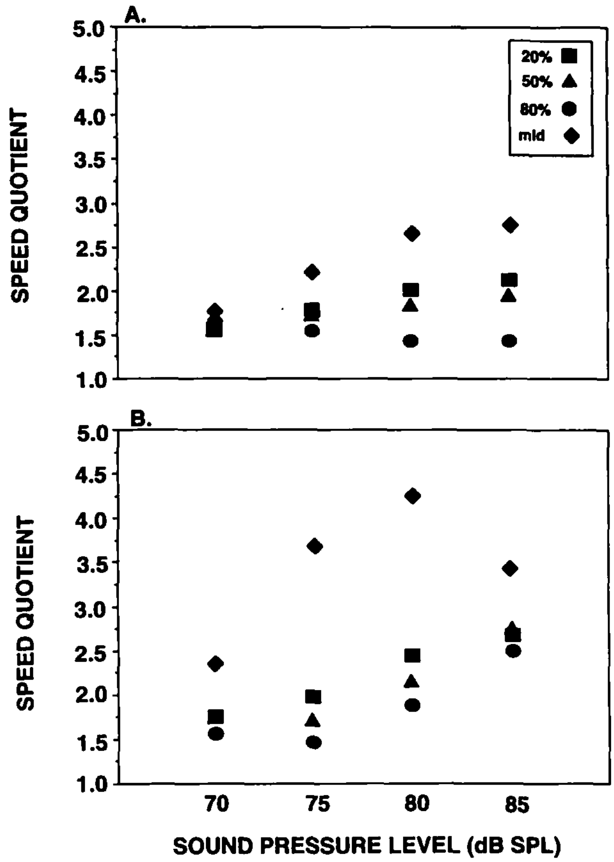

FIG. 5. SQ' results from the glottal airflow waveform (A) and the inverted EGG waveform (B) for the sound pressure levels of 70, 75, 80 and 85 dB using 20%, 50%, 80%, and mid-slope criteria.

For the 10 dB change, decreased glottal closure duration became an especially active mechanism and consequently led to a statistically significant effect. It follows that in order to adequately interpret quotient data for evaluating the physiology of vocal fold vibration control or measurement of SPL is necessary (19). Last, an important finding is that the trends in OQ' values from the glottal airflow waveform were consistent for both the 20% and 50% criteria. Therefore, speculating whether a 20% or 50% criterion level makes a difference in documenting temporal changes of the glottal cycle does not appear to be worthwhile.

EGG

OQ'

When applied to the EGG waveform, the criterion levels of 20% and 50% yielded OQ' means that consistently increased as SPL increased from 70 to 80 dB but then decreased as SPL was increased from 80 to 85 dB. No statistically significant differences in EGG OQ' as a function of SPL were found for either the 20% or 50% criteria. This was true for both the 5 dB and 10 dB increases. Although identifying the instant of glottal opening from an EGG waveform has been described as the basic difficulty in measuring OQ (8,25), it is unlikely that this affected the present EGG OQ' data since objective criteria were used to identify the moment of opening. Some other factors which may have contributed to the lack of statistically significant change in the EGG OQ' measure were discussed in the introductory comments of this paper. These include vertical phase differences between the lower and upper margins of the vibrating folds and mucus strands across the glottis. Further details about these influences are discussed by Childers et al. (12) and Colton and Conture (26).

Higgins and Saxman (20) and Kempster et al. (24) measured the duration of glottal opening from EGG waveforms and found a decrease with increases in SPL. Some difficulty does exist in comparing the current results to these studies. There are differences in the procedures in that the degree of SPL change was not the same, differences exist in the criteria employed for defining the instant of opening, and the data analysis included only descriptive statistics (24). Also, when statistical comparisons were completed for these studies there was no indication of the statistical contrasts between the different SPLs (20,24). Consequently, it is difficult to determine whether the decrease in their approximations of OQ as a function of SPL was statistically significant.

Baer et al. (8) found that the duration of glottal opening extracted from EGG waveforms did not show a consistent decrease with increases in SPL unless very low and very high SPLs were compared. To examine whether the present EGG OQ' data were similar to those of Baer et al., the present EGG OQ' values from the lowest SPL condition (70 dB) were compared to the EGG OQ' values from the highest SPL condition (85 dB). A mean decrease in EGG OQ' was in fact found between these conditions, but only for the 20% criteria. For the SPL range investigated here, the EGG OQ' results agree with an observation of Childers et al. (12, p. 253), regarding the use of the EGG for tracking vibratory characteristics of the vocal folds. They state "the EGG cannot recognize some significant features of vocal fold physiology" and that "monitoring non-contact types of vibratory events" is difficult, so that a measure such as EGG OQ' may not be capable of yielding reliable results (27). The current data strongly support statements such as these and reinforce that using the EGG for making measures of OQ may not be beneficial, particularly if the extremes of the voice are not being evaluated.

Glottal airflow

Speed quotient'

From the glottal airflow waveform, SQ', mean values consistently increased as SPL increased for the 20%, 50% and midslope criteria, but generally decreased using the 80% criterion. The basis for the decreasing values obtained using the 80% criterion may be explained by the fact that the temporal points are taken very high in the waveform (the top 20%). The measure likely failed to identify the greatest rate of change in the closing slope. None of the criteria resulted in a statistically significant change in SQ' values from the glottal airflow waveform with a 5 dB increase in SPL. This result is interesting because it implies that there is little change in the closing slope or possibly that there are concomitant changes in the opening and closing slope of the waveform.

A statistically significant increase in SQ' values was obtained using the 20% and mid-slope criteria with a 10 dB increase from 70–80 dB SPL. The significant increase in SQ' values with both of the criteria suggests that a faster rate of change in the closing slope is occurring between 20% and 80% of the AC amplitude. The 50% and 80% criteria missed this change as indicated by the lack of a significant increase in SQ' values. The collective observations of SQ' values across criteria reflect an increasing closing slope above 20% of the AC amplitude with less information about the slope change being provided by criteria that are 50% and above. This is in agreement with results of an investigation of maximum flow declination rate which showed the fastest rate of change in the closing slope of glottal airflow waveforms to be within a range of 40% to 50% of the waveform amplitude (28).

EGG

Speed Quotient'

Data from the EGG waveform showed similarities to the airflow data. For the measure of SQ', mean values derived from the EGG waveform for the 20% and 50% criteria consistently increased as SPL increased. The 80% and mid slope criteria each showed a reversal, whereby SQ' decreased from 70 to 75 dB SPL for the 80% criterion and decreased from 80 to 85 dB SPL for the midslope criterion.

The results of the present pairwise comparisons for EGG SQ' values indicated the SQ' midslope criterion level to be generally more responsive to the 5 dB steps in SPL. The EGG SQ' midslope results indicate that the closing phase is relatively faster than the opening phase with 5 dB increases in SPL. Yet the glottal airflow results presented above suggest no statistically significant change in the closing phase relative to the opening phase with 5 dB increases. What could account for this disparity between signal types? One factor that can influence SQ' measures is the presence of concurrent changes in the opening phase and closing phase with increases in SPL, as mentioned above. The EGG has been shown to demonstrate small changes in the opening phase relative to large changes in the closing phase with increases in SPL (16). It may be that the glottal airflow waveform manifests greater change in the opening phase than the EGG waveforms, resulting in a smaller difference in SQ measures as SPL is increased.

Another measure that has been used to reflect the speed of closing with changes in SPL is maximum flow declination rate, defined from the most negative peak of a differentiated glottal airflow waveforms. Maximum flow declination rate has a strong positive correlation with SPL (29–31) and appears to be much more consistent than SQ at distinguishing how the closing phase responds to variations in SPL (32). It is not influenced, as is SQ, by concurrent changes occurring in the opening phase of the waveform. Certainly, the airflow SQ' values obtained from any of the present criteria may be more difficult to interpret than are results from maximum flow declination rate measures.

Depending on the statistical contrast analyzed, any one of the four criteria used on the EGG waveform registered an increase in SQ' with a 10 dB SPL step increase. Statistically significant changes in EGG SQ' values were detected by SQ'20%, SQ'50% and SQ'80% criterion levels as SPL increased from 75 to 85 dB. The midslope criterion measured a significant increase in SQ' values from 70 to 80 dB SPL. Although there was a lack of consistency in the statistical results across the four criteria, the one criterion that appeared to provide the most consistent tracking of changes in SQ' values was SQ' mid. There were significant increases in SQ' mid values for some of the 5 dB SPL as well as the 10 dB SPL increases. The reason for this may be that SQ' mid evaluates a smaller portion of the closing slope and is analyzing an area which avoids peak and baseline changes which are not representative of the fastest rate of change. The EGG models (inverted) characterize the fastest rate of change in the closing phase to be near the peak of the waveform; these findings are based from a normal chest register phonation presumably produced at a comfortable effort level (6-8,13,33). It may be that the location of this change in the closing slope "shifts" with SPL, an event that was found to occur in glottal airflow waveforms (28). The rate changes in the closing slope may be different depending on whether SPL increases from 70 to 75 dB, 75 to 80 dB or 80 to 85 dB. This could explain the difficulty in finding one particular criterion capable of following all changes in EGG SQ' with increases in SPL.

CONCLUSIONS

A number of factors can influence interpretation of quotient measures: the measurement criterion, the signal type, and the SPL of the task. The fact that absolute differences exist between quotient values obtained from different measurement criteria is not surprising, particularly when comparing levels applied to the upper vs. the lower half of the AC component of a waveform. What is important to realize is that the relationship between the quotient measures and the physiologic event will vary depending on the criterion used to segment the waveform, the type of waveform used to interpret the mechanisms of sound production and the SPL produced by the subject.

The glottal airflow signal appears to track changes in OQ' with increases in SPL. A criterion of either 20% or 50% yields the same trends when SPL increases from 70 to 85 dB. The SQ' values from the airflow waveform were inconsistent across the SPLs studied. For the 10 dB contrast, the results of SQ' from all the criteria suggest the temporal changes in the opening and closing phases are occurring somewhere above 20% but below 50% of the AC amplitude, again this was not consistent for all the 10 dB SPL contrasts.

None of the criteria applied to the inverted EGG waveform yielded significant OQ' results which suggests that the EGG signal is limited in its ability to assess temporal changes in the opening phase of vocal fold vibration. This finding corroborates previous discussions on the limitations of using the EGG for particular types of measures and, in particular, indicates that OQ' measures from an glottal airflow signal may be more useful. Measures of EGG SQ' for all criteria showed consistent trends with increases in SPL, yet there was a lack of statistically significant change across the smaller 5 dB increment in SPL. There was no one single criterion capable of following all changes in EGG SQ' with increased SPL; a finding similar to the SQ' results from the glottal airflow waveform. The SQ' midslope criterion appeared to be the most sensitive, showing an ability to track SQ' increases with both 5 dB and 10 dB increases in SPL.

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