

Photoglottography: A Clinical Synopsis

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Summary: Although photoglottography (PGG) has been used as a measure proportional to glottal area, it has not been widely applied in the clinic to study dysphonic patient populations. Historically, PGG has required the insertion of either a light source or photosensor at least to the level of the oropharynx or nasopharynx. This invasive nature of PGG has probably limited its appeal to those who are unwilling to risk injury or discomfort to subjects. Additionally, the effort and time necessary to carefully hand-mark glottal events for analysis has limited its clinical use. This report presents a brief overview of PGG and describes two techniques to help enhance its clinical application: a minimally invasive transoral technique of illumination and an automated technique to identify glottal events. In addition, two possible factors that may confound the interpretation of transoral PGG results were evaluated: the effects of transoral versus transnasal light sources, and effects of change in articulatory configuration on PGG results. **Key Words:** Glottography—Photoglottography—Larynx.

Over the years, studies of vocal fold movement have used progressively less invasive techniques, with the advantage that information can be obtained from living human subjects. For example, ultra-high-speed photography has been used since 1935 and has proven to be a useful method for studying the details of vocal fold vibration. However, this technique is difficult to perform, requiring a subject to sustain phonation while a mirror is suspended in the oropharynx. Videostroboscopy can also provide much information about vocal fold movement. Because the method is a composite over portions of different glottal cycles, however, interpretation is problematic, especially when vocal fold movement is highly irregular. Glottographic techniques such as

photoglottography (PGG) and electroglottography (EGG) have been used more commonly in recent years as an alternative or addition to these other methods of studying vocal fold movement. An important advantage of these techniques is that they provide voltages that can be digitized and measured relatively easily and inexpensively.

In PGG, or transillumination, the amount of light transmitted through the glottis is monitored during the vibratory cycles of phonation (1,2). The light source may be placed either above or below the vocal folds. A light sensor is then placed on the other side of the folds to convert light intensity to a voltage. As the vocal folds vibrate, the amount of light varies in proportion to the degree of glottal opening. Although the PGG intensity cannot be calibrated for actual glottal area, the technique provides timing information regarding glottal activity during phonation, such as points of maximal glottal opening and the initial moments of opening and closing within a cycle. These data are necessary for calculation of the commonly used measures of *speed quotient*, the ratio of duration of the opening

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phase to duration of the closing phase (3), and *open quotient*, the ratio of the open period to the entire duration of the glottal cycle (4). This timing information has demonstrated clinical potential in helping to distinguish among several types of laryngeal paralyses and normal speakers (5). In comparison to imaging techniques, PGG is easier to record simultaneously with other measures of vocal fold activity. This is important, because it is thus possible to provide numerous concurrent, instrumental measures for the study of vocal fold movement (see, for example, refs. 6 and 7).

Although PGG has been used for many years, its validity as a method for representing glottal area had been questioned by a number of authors. Coleman and Wendahl (8) compared glottal area measurements from PGG and high speed films and described a number of possible limitations in relating the PGG signal to glottal area. They pointed out that the light density distribution within the vocal folds may not be constant. The light reflections from the mucosal surfaces may vary also, thereby affecting the PGG signal. Additionally, vertical laryngeal height changes may alter the signal. Finally, the position of the light sensor may produce differing waveforms. Vallancien et al. (9) added to this list of cautions in the interpretation of the PGG signal. They pointed out that the amount of light projected through the larynx varies not only with the placement of the photosensor, but also with the placement of the light source. Furthermore, movement of the articulators can affect the position of the illuminator or transducer, changing the signal.

In a more recent study, Harden (10) compared PGG and area waveforms derived from ultra-high-speed films and stated, "Although the correspondence between the curves is not exact in modal and vocal fry register phonations, the photoelectric cell does appear to be capable of generating reasonably approximate information" (p. 734). In addition, Baer et al. (11), in another study comparing high-speed filming and PGG, found that both types of measurement gave essentially the same information for peak glottal opening and glottal closure. However, they pointed out that the moment of glottal opening is less certain than closure because the process of glottal opening is more gradual than closure. Hartmann and Wullstein (12) demonstrated that there is a noticeable contribution to the PGG signal from the translucence of the vocal folds. Presumably, this effect is greatest during the relatively

gradual thinning of the folds just before glottal opening.

One further confounding factor in the use of photoglottography is the contribution of noise from the light source. Methods using fiberoptics in the delivery of light to the larynx often employ endoscopic xenon light supplies. Although these light sources are often termed "continuous," the light flickers and is not truly DC.

Another and possibly more familiar method for examining vocal fold movement indirectly is EGG, which monitors the amount of contact between tissues in the neck, in the vicinity of the glottis (13). However, a number of problems associated with EGG have been identified and described, including those of the instrument itself, electrode placement, subject variables, and speech-induced artifacts that can interfere with the use and interpretation of EGG (14,15). Because of these shortcomings, some researchers combine EGG and PGG so that each method can complement the limitations of the other.

Historically, PGG has required the insertion of either the light source or photosensor at least to the level of the oropharynx or nasopharynx. Sonesson (2) used a curved light-conductive rod connected to a multiplier phototube positioned in the mouth to the base of the tongue in the oropharynx. The light source was directed onto the skin over the trachea. Kitzing and Sonesson (16) used a similar approach. Kitzing and Lofqvist (17) also illuminated the neck below the glottis but modified the technique by using a phototransistor placed in a flexible catheter that was directed through the nose into the pharynx to the level of the uvula. Lisker et al. (18) used a slightly different technique in which a miniature incandescent bulb was introduced through the nose into the pharynx to shine a beam of light onto the glottis, while a photosensor was placed against the neck just below the thyroid cartilage to monitor the light intensity. Lofqvist and Yoshioka (19) modified this approach by delivering the light to the pharynx above the glottis using a small, fiberoptic light source introduced through the nose. Most recent studies report the use of this transnasal approach using a nasopharyngoscope (5,6,20,21). An advantage to this technique is that commercially available fiberoptic nasopharyngoscopes not only carry light, but also have a lens through which the position of the larynx can be monitored. Because the PGG signal can be affected by changes in position of the

nasopharyngoscope in relation to the glottis, such monitoring of scope position is often performed.

Although PGG has been used more extensively in recent years, its clinical use in the study of patient populations remains somewhat limited. There are several possible reasons for this general lack of clinical application. The invasive quality of PGG may have reduced its appeal to some researchers and clinicians who might otherwise make use of the information it can provide about the glottal cycle. Nonphysicians such as speech pathologists and speech scientists may be unwilling to risk injury or discomfort to subjects by the placement of a fiberoptic endoscope through the nose or a rod in the pharynx over the base of the tongue, and some states allow only medical personnel to insert a nasopharyngoscope. Furthermore, some subjects or patients may refuse to participate if a fiberoptic tube must be inserted through the nose for PGG.

Another problem limiting the use of PGG is the difficulty in identifying and marking initial vocal fold opening, peak glottal aperture, and vocal fold closing. Unfortunately, the PGG signal has no absolute zero reference to indicate when the glottis is truly closed or opened. Therefore, a flat baseline could indicate either true glottal closure or a constant-size glottal opening during the most closed portion of the glottal cycle. Because identification of these glottal events is unavoidably equivocal, they require a definition demanding careful hand-marking, which is usually tedious and very time-consuming. For example, Gerratt et al. (6) described one such method.

This report describes two techniques to enhance the clinical application of PGG. First, a transoral technique of illumination is presented as an alternative to the more invasive transnasal approach. Second, an automated technique to identify glottal events is described. In addition, we evaluated two possible factors that may confound the interpretation of PGG results. Because it has been suggested that movement of the articulators affects the PGG signal using the transoral approach (22), we evaluated this method in subjects who intentionally changed their articulatory configuration during PGG recording. Second, because of the potential contribution of illumination noise to the PGG signal, the spectrum of the transoral light source-photosensor combination was compared with that of the transnasal light source-photosensor combination.

METHOD

Subjects

Fourteen normal adults (8 men and 6 women), 26 male adults with Parkinson's disease, and 20 male adults with unilateral recurrent laryngeal nerve paralysis participated in the evaluation of the automated procedure to identify glottal events. All subjects with disorders had a voice impairment as judged by two speech pathologists and one otolaryngologist. Subjects with these types of neurological disorders were selected particularly because previous research has demonstrated their great effects on measures of speed quotient (6,15). In addition, transnasal and transoral illumination were compared in one male adult with normal laryngeal function. Finally, nine adults with normal phonatory function (five men and four women) took part in evaluating the effect of change in articulatory configuration on the PGG signal.

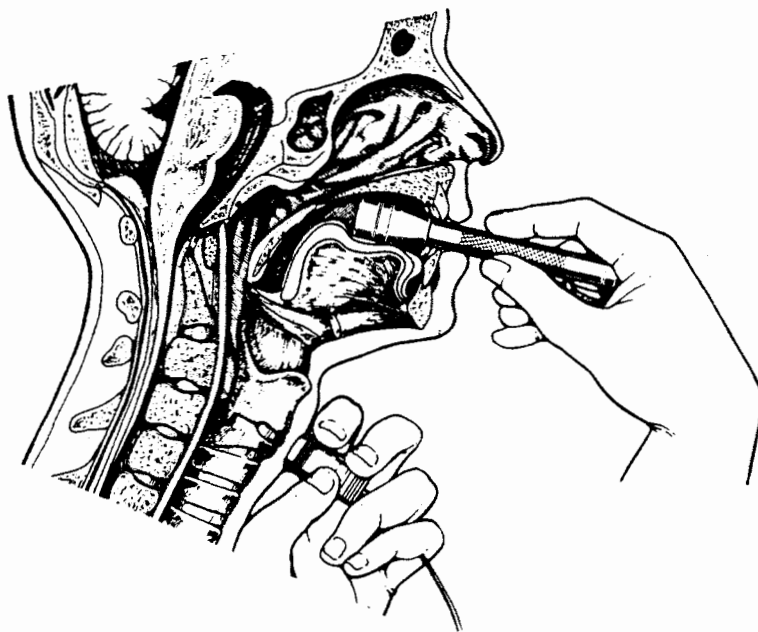
Materials

The light source for PGG was a small, hand-held, high-intensity flashlight (Mini-Maglite, AA battery size, Mag Industries). The photosensor was a single-element, red-optimized photodetector with an active area of 50 mm² (Centronic, OSD 50-2). The sensor was packaged in our laboratory with its associated electronics in a shielded, plastic cylinder.

Transoral illumination

Figure 1 demonstrates the transoral procedure. The flashlight was first covered with clear plastic wrap as a sanitary precaution and was then inserted 3-4 cm beyond the central incisors. The light was directed at the soft palate and reflected by the palate and surrounding pharyngeal structures, providing illumination in the supraglottal area. The subject was then asked to prolong the vowel /i/ at a comfortable loudness level and conversational pitch level. This vowel was selected because it is produced with the epiglottis positioned anteriorly and therefore minimizes obstruction of the supraglottal illumination. The experimenter held the photosensor unit on the surface of the subject's neck at the level of the cricothyroid membrane. The positions of the flashlight and the photosensor were then adjusted until the intensity of the resulting PGG signal was greatest on an oscilloscope display. Once adjusted, the flashlight and sensor were held in position by the experimenter for the duration of the glottographic recording. Because the flashlight was

FIG. 1. Supraglottal illumination for photoglottography.



only inserted in the mouth a short distance, subjects did not gag or complain about discomfort. However, some subjects humped the tongue against the palate, thereby reducing the light level reaching the glottis, and causing an unacceptably low PGG signal. When this occurred, the subject was instructed to place the tongue in a slightly lower position. Occasionally it was necessary to move the flashlight head further back in the oral cavity between the tongue constriction and the palate to keep the tongue from making contact with the palate. Subjects tolerated the procedure well. When asked, they reported no discomfort.

Automated marking

An automated method of marking glottal events was compared with an interactive hand-marking method. Our primary goal was to locate the glottal events necessary for calculating speed quotient. Because of the limitations described above in determining the precise moment of vocal fold separation and closure from the PGG signal, we chose PGG waveform points designated as beginning, ending, and maximum light transmission of the glottal cycle. Figure 2 demonstrates how the computer algorithm operated in marking glottal events. First, the program found the positive peak amplitude of the PGG signal (point A). Next, a baseline was plotted by drawing a line between the negative peak amplitudes preceding (point C) and following this positive peak (point D). A perpendicular line intersecting the

baseline was then drawn from the positive peak (point B). Defining the length of this line as maximum peak amplitude, the program then found the point on this line that was 90% down from the positive peak (point E). A line intersecting both the rising slope of the PGG trace (point F) and the falling slope (point G) was then drawn parallel to the baseline from this point. The beginning of the glottal cycle was defined as point F, and the ending of the glottal cycle as point G. We have additionally evaluated two other definitions set at 80 and 70% of positive peak amplitude of the PGG trace.

Hand-marking of glottal events was performed using the interactive method described by Gerratt et al. (6). Essentially, this technique involved using peaks in the first derivative of the EGG signal, with

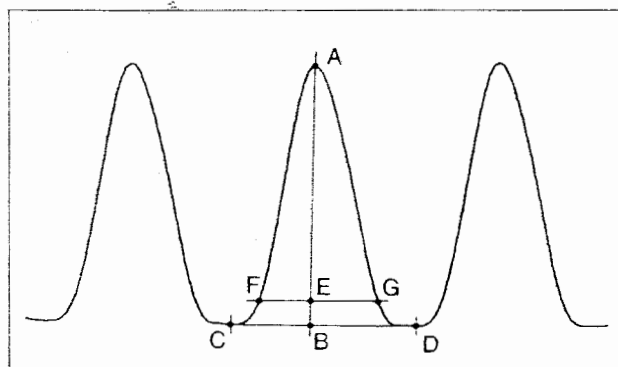


FIG. 2. Points on a photoglottographic cycle used by the computer algorithm in the automatic marking of glottal events.

peaks in the third derivative of the PGG signal as an aid in determining beginning and ending of the glottal cycle.

The PGG signals were recorded on an FM tape-recorder (Tandberg, 115). These signals were then low-pass-filtered at 3,000 Hz, and a 0.5-s sample from the middle portion of phonation was digitized at 20,000 samples/s on a 16-bit A/D converter. Mean measurements were derived from at least 45 glottal cycles per vowel production.

Change in articulatory configuration

Subjects were instructed to sustain the vowel /i/ for ~2 s, produce a brief glottal stop, and then sustain the vowel /u/ for another 2 s, while maintaining a steady pitch, loudness, and vocal quality for both vowels. The subjects practiced and then performed this task while using the transoral method of illumination. The PGG signals were digitized as described above, and 0.5-s samples from the middle portions of the /i/ and /u/ vowels were selected for analysis. The automated method of identifying beginning and end of vocal cycles was then used for calculation of the 90% speed quotient (calculated at 90% down from the positive peak) for both vowels from each subject.

Comparison of light sources

The spectra of the flashlight and an endoscopic light source (Olympus CLV Cold Light Supply) for a fiberoptic nasopharyngoscope (Olympus BC3) in combination with the photosensor were compared. First the "noise" output by the sensor in response to no light input was determined; then each light source was placed close enough to the sensor to produce an output level at least 38 dB higher than the noise level. A 1.64-s sample of each signal was low-pass-filtered at 3,000 Hz and digitized at 20,000 samples/s on a 12-bit A/D converter. The samples were analyzed using a fast Fourier transform, resulting in spectra with a resolution of ~0.6 Hz per output point.

RESULTS AND DISCUSSION

Transoral illumination

Figure 3 demonstrates two PGG signals from the same subject, a 40-year-old man with normal laryngeal function. The top tracing is the signal recorded when a light source in the mouth provided illumination. The signal on the bottom was recorded when illumination was provided by a fiberoptic nasopharyngoscope. Even though these two signals

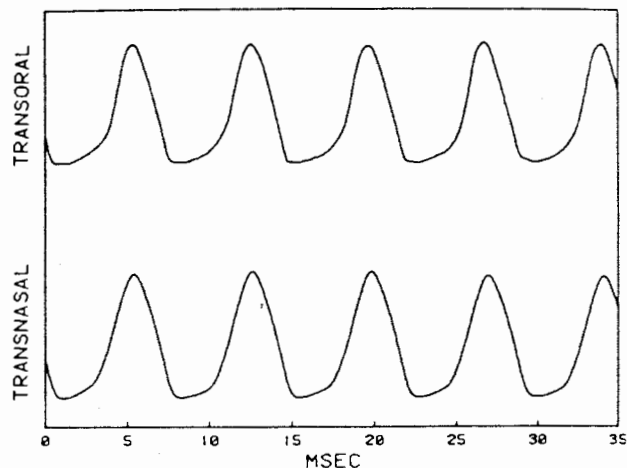


FIG. 3. Two photoglottographic signals from a 40-year-old man. The upper signal was generated during transoral illumination and the lower during transnasal illumination.

were produced during different phonations, the waveforms are very similar. Time-related measures are essentially identical for the two recordings. For example, the speed quotient was 0.911 for the signal produced by transnasal illumination and 0.916 for the transorally illuminated signal.

Baken (22) argued for the use of illumination by a fiberoptic nasopharyngoscope to reduce the chance of movement by the articulators, which may invalidate the data. We paid close attention to the presence of articulatory movement that could easily be observed through the oral cavity alongside the shaft of the flashlight during production of the sustained vowel. Subjects were not observed to move their articulators during this task. Although visual monitoring of possible pharyngeal or laryngeal movement was not performed, the fact that no noticeable change in vowel quality was observed during the vowel production probably indicates that no significant movement of these structures occurred either. The effects of intentional articulatory movement on the PGG signal are discussed below. Some patients with movement disorders causing vocal tract unsteadiness may indeed manifest articulatory movement, making the interpretation of the signal difficult. However, it is likely that this involuntary articulatory movement would affect the PGG signal using either transoral or transnasal illumination methods. Thus, PGG may not be a recommended vocal measurement for these patients.

One of the greatest limitations of this method is that laryngeal activity cannot be monitored during connected speech because the flashlight in the oral cavity would interfere with articulation. If informa-

tion about connected speech is required, transnasal illumination would be preferable, although still not ideal, because movements of the velopharynx affecting the location of the fiberoptic tube in the pharynx and epiglottal activity will alter the level of illumination.

Automated marking

Table 1 lists the correlations (Pearson's r) among the hand-marking and automated marking procedures for speed quotient. As expected, results from the three automated methods are highly correlated. The relatively high correlations between the hand-marked and automated methods validate our automatic procedures. Apparently, automated estimates of the beginning, ending, and maximal opening of the glottal cycle provide information very similar to that derived using hand-marking. It does not appear to matter very much at which percent of glottal opening the definition is set. Presumably, speed quotient is robust enough that the placements of beginning and ending of the glottal cycle do not have much of an effect on the measure, as long as the points are marked symmetrically on the rising and falling slopes.

Change in articulatory configuration

The means and SDs of the 90% speed quotient from the /i/ and /u/ productions are presented on the left side in Table 2. Differences between the two vowels were analyzed using a repeated-measures, one-way analysis of variance (ANOVA) for each subject, in which at least 50 glottal cycles per vowel were compared. Although six of the nine between-vowel comparisons were significantly different at $p < 0.01$, the actual differences between the means of five of the pairs were very small, ranging from 1.2 to 14.2%. Subject 6 was an exception, with a 40% difference. The mean speed quotient for /i/ was larger than that for /u/ in four of these six pairs of vowels, but smaller in the other two cases. These results were difficult to interpret. Although there were sig-

nificant differences between vowels, these differences were rather small, and mean speed quotient was not consistently larger for either of the vowels.

If differences in speed quotient between vowels resulted only from changes in articulatory configuration rather than from changes in the voicing source, then we would not expect to find significant differences in speed quotient within the same vowel. To test this hypothesis, we split each of the /i/ and /u/ vowels produced by each subject into halves, and then compared the means of both halves within each vowel, again using repeated-measures, one-way ANOVAs. These results are shown on the right in Table 2. Six of the 18 comparisons of means were significant at $p < 0.01$, although the size of the differences is again very small. Four of the nine subjects had at least one within-vowel comparison that demonstrated significant differences. Both within-vowel comparisons for two of these four subjects were significantly different.

These findings reveal that even when articulatory configuration is held steady within a vowel, variability in vocal fold vibration apparently resulted in significant change in the speed quotient over time for almost half of the subjects. Thus, although some of the difference between mean speed quotients for the vowels /i/ and /u/ may have occurred from change in articulatory configuration, a portion of that difference can be accounted for by the natural variability in the vocal mechanism itself.

Comparison of light sources

Comparison of the two light sources yielded spectra that are the products only of the light sources themselves and of the characteristics of the sensor and its associated electronics. In Fig. 4, the top trace shows the spectrum of the sensor output in response to no light input, the middle trace is the spectrum resulting from the flashlight input, and the bottom trace is from the fiberoptic nasopharyngoscope input. The bottom two signals are normalized for equal DC amplitude, so what is shown here is the additional noise given equal amounts of useful (DC) light. The no-light spectrum is on a different amplitude scale from that of the other two spectra, because the no-light signal was ~38 dB smaller; it is provided merely to suggest the origin of the noise spikes in the flashlight spectrum. These spikes must also be present in the fiberoptic nasopharyngoscope spectrum, but they are apparently out of phase with

TABLE 1. Pearson's correlations for speed quotient values ($n = 60$) derived by identification of glottal events by interactive hand-marking and by automatic marking at 90, 80, and 70% of glottal opening

	90%	80%	70%
80%	0.97		
70%	0.92	0.98	
Hand	0.84	0.87	0.90

TABLE 2. Means and SDs of the 90% speed quotient (calculated at 90% down from the positive peak) of 0.5-s samples of /i/ and /u/ for between-vowel comparison and split halves from each of these vowel samples for within-vowel comparisons

Subject	Between vowel comparisons				Within-vowel comparisons							
	/i/		/u/		/i/ ₁		/i/ ₂		/u/ ₁		/u/ ₂	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	1.61	0.055	1.55*	0.052	1.60	0.052	1.61	0.059	1.55	0.050	1.55	0.054
2	0.85	0.018	0.78*	0.027	0.85	0.017	0.85	0.017	0.79	0.029	0.78	0.024
3	1.22	0.053	1.21	0.049	1.25	0.048	1.18*	0.036	1.20	0.046	1.22	0.051
4	0.97	0.032	0.96	0.035	0.97	0.036	0.97	0.027	0.96	0.036	0.96	0.033
5	1.60	0.055	1.40*	0.065	1.58	0.049	1.63*	0.049	1.43	0.059	1.37*	0.059
6	0.90	0.046	1.26*	0.063	0.89	0.047	0.90	0.046	1.27	0.068	1.26	0.057
7	0.77	0.036	0.82*	0.048	0.78	0.039	0.77	0.031	0.83	0.047	0.81	0.047
8	0.67	0.029	0.66	0.026	0.65	0.023	0.69*	0.022	0.65	0.028	0.67*	0.018
9	0.72	0.037	0.69*	0.036	0.74	0.032	0.70*	0.028	0.69	0.038	0.70	0.034

* Comparison of means significant at $p < 0.01$.

the considerable noise of that light source, and may have been cancelled out. Summing the energy in the spectral range of 0–1,000 Hz reveals that for the flashlight, approximately 94% of the energy is at DC (i.e., will not contaminate the shape of a PGG waveform), whereas for the fiberoptic nasopharyngoscope, only 86% of the energy is at DC. The 8% difference represents noise components in the endoscopic light supply. In addition to the energy at DC for the nasopharyngoscope, prominent harmonic energy occurred at 40, 120, and 240 Hz, which are unfortunately in the frequency region of modal fundamental frequencies.

Thus, a significant advantage of the transoral method is that the flashlight used for illumination is a DC light source and does not contribute noise to the signal. Furthermore, a small flashlight is far less costly (approximately 500 times less) than the light source and nasopharyngoscope combination.

CONCLUSIONS

Information about vocal fold movement has potential to help in clinical management of voice disorders. High-speed filming will provide the necessary time resolution for this purpose; however, the technical difficulties and expense involved in this method are such that its clinical application is impractical. PGG provides a signal associated with vocal fold movement, but previous literature has described limitations in relating the PGG signal to glottal area, so both the researcher and clinician must interpret these signals cautiously. Nevertheless, PGG signals have been shown to provide reasonable estimates of glottal opening and closing

(10,11) for measures such as speed quotient, which do have potential clinical application.

Automatic marking and transoral illumination provide an efficient means of adding information about vocal fold vibratory behavior to clinical voice evaluation. The correlation of automated and hand-marked selections of beginning, ending, and maximal opening of the glottal cycle necessary for calculation of speed quotient was very high. Thus, the automated method provides information very similar to that derived using hand-marking. Moreover, transoral illumination can allow more widespread clinical use because it is relatively noninvasive and is much less expensive than the equipment required for transnasal illumination. A further advantage of transoral illumination is that a flashlight is a true DC light source. Our comparison of light sources for the two illumination methods demonstrated the presence of noise in the endoscopic light supply used for transnasal illumination. Much of the energy of this noise occurred between DC and ~300 Hz, the frequency region of greatest interest. Although not studied, this noise could conceivably confound some vocal measurements.

Some have argued that articulatory movement poses a threat to the interpretation of a PGG signal produced using the transoral method. Unfortunately, the pattern of results comparing change in articulatory configuration on speed quotient is not clear. Although six of the nine subjects tested had significantly different mean speed quotients for /i/ than for /u/, the split-half, within-vowel comparisons demonstrated that a portion of the differences found between the production of /i/ and /u/ can be accounted for by the underlying variability in vocal

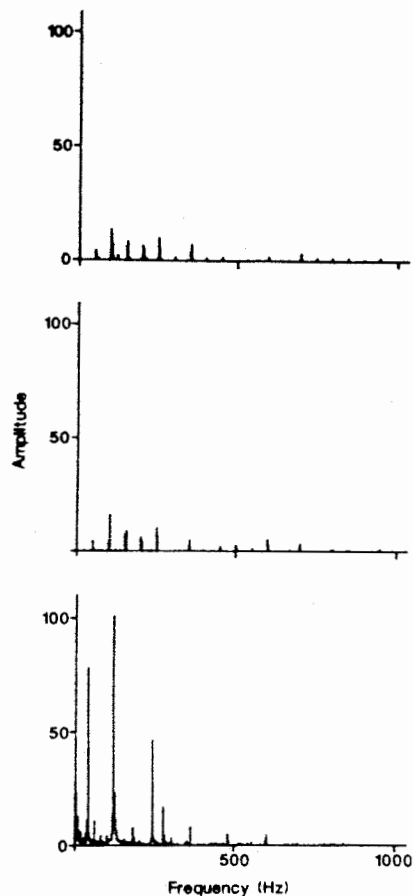


FIG. 4. Three fast-Fourier transform spectra of the photoglottography sensor output signal produced (top) in a no-light condition, (middle) in response to the flashlight, and (bottom) in response to the endoscopic light source/fiberoptic nasopharyngoscope combination. Amplitude is displayed in arbitrary units. The scales of the middle and bottom spectra are equal, whereas the top spectrum is greatly amplified (>38 dB).

function. How much of the observed differences between vowels is contributed by articulatory change and how much is contributed by variability in the voicing source is unknown. Nevertheless, in our experience, only an occasional subject with involuntary movements has demonstrated difficulty maintaining a steady vowel during recording. A steady vowel quality implies a constant vocal tract configuration, so possible effects of articulatory movement are not usually a problem.

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