Objective Evaluation of the Voice

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The Need for Objective Tests

Recent advances in arts medicine have produced major improvements in otolaryngologic care for professional voice users. Cooperation among laryngologists, voice scientists, speech-language pathologists, voice teachers, professional voice users, and other professionals has led to increasing sophistication in the clinical ability to examine professional vocalists and accurately diagnose their maladies. State-of-the-art approaches include not only specialized techniques for clinical physical examination of the voice,[1–3] but also airflow analysis, electroglottography, strobovideolaryngoscopy, and other measures of vocal function. Selected instrumentation has proven invaluable in increasing diagnostic accuracy.

The use of objective tests allows reliable and valid assessment of subtle changes in voice function as a "meter of the voice." These tests are necessary not only to treat professional singers, but also to assess the results of laryngeal surgery and treatments for spasmodic dysphonia or other conditions, and to help to diagnose the many systemic diseases associated with voice change. Reporting that a patient's voice is "better" without objective measures is as unsatisfactory as reporting that a patient's hearing is "better" without an audiogram. This article reviews certain tests that may be clinically useful in selected circumstances. All of them may well be forerunners to a new era of routine objective voice assessment.

Strobovideolaryngoscopy

Strobovideolaryngoscopy is the single most important technologic advance in diagnostic laryngology with the possible exception of the fiberoptic laryngoscope. Stroboscopic light allows routine, slow-motion evaluation of the mucosal cover layer of the leading edge of the vocal fold. This improved physical examination permits detection of vibratory asymmetries, structural abnormalities, small masses, submucosal scars and other conditions that are invisible under ordinary light.[4] For example, in a patient with a poor voice following laryngeal surgery and a "normal-looking larynx," stroboscopic light reveals adynamic segments that explain the problem even to an untrained observer. The stroboscope is also extremely sensitive in detecting changes caused by fixation from small laryngeal neoplasms in patients who are being followed for leukoplakia or following laryngeal irradiation. Coupling stroboscopic light with the video camera allows later re-evaluation by the laryngologist or by other physicians. A relatively standardized method of subjective assessment of video stroboscopic pictures is in wide clinical use, allowing comparison of results among various physicians and investigators.[5,6] Characteristics assessed include fundamental frequency, symmetry of bilateral movements, periodicity, glottal closure, amplitude, mucosal wave, the presence of nonvibrating portions, and other unusual findings (such as a tiny polyp). In addition, objective, frame-by-frame computer analysis is also possible, although not practical (or necessary) on a routine clinical basis, yet.

Other Techniques to Examine Vocal Fold Vibration

Ultra high-speed photography provides similar images but requires expensive, cumbersome equipment and delayed data processing. *Electroglottography* uses two electrodes on the skin of the neck above the thyroid laminae. A weak, high frequency voltage is passed through the larynx from one electrode to the other. Opening and closing of the vocal cords varies the transverse electrical impedance, producing variation of the electrical current in phase with vocal fold vibration. The resultant tracing is called an electroglottogram. It traces the opening and closing of the glottis, and can be correlated with stroboscopic images.[7] Electroglottography allows objective determination of the presence or absence of glottal vibrations, easy determination of the fundamental period of vibration, and it is reproducible. It reflects the glottal condition more accurately during its closed phase, and quantitative interpretation of the glottal condition is probably not valid.[8] *Photo-electroglottography* and *ultrasound glottography* are less useful clinically, but may be reviewed in Hirano's invaluable book *Clinical Examination of the Voice.*[8]

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Measures of Phonatory Ability

Objective measures of phonatory ability are among the easiest and most readily available for the laryngologist, helpful in treatment of professional vocalists with specific voice disorders, and extremely useful in assessing the results of surgical therapies. *Maximum phonation time* is measured using a stopwatch. The patient is instructed to sustain the vowel "ah" for as long as possible following deep inspiration, vocalizing at a comfortable frequency and intensity. In select cases, the frequency and intensity may be controlled using an inexpensive frequency analyzer and sound level meter. The test is repeated three times, and the greatest value is recorded. Normal values have been determined.[8] *Frequency range of phonation* is recorded in semitones and records the vocal range from the lowest note in the modal register (excluding vocal fry) to the highest falsetto note. This is the *physiological frequency range of phonation* and disregards quality. The *musical frequency range of phonation* measures lowest to highest musically acceptable qualities. Tests for maximum phonation time, frequency range, and many of the other parameters discussed below (including spectrographic analysis) may be preserved on a tape recorder for analysis at a convenient future time and used for pre-treatment and post-treatment comparisons. Frequency limits of *vocal register* may also be measured. The registers are (from low to high): vocal fry, chest, mid, head and falsetto. Overlap of frequency among registers occurs routinely. Testing the *speaking fundamental frequency* frequently reveals excessively low pitch, an abnormality associated with chronic voice abuse and development of vocal nodules. This parameter may be followed objectively throughout a course of speech therapy. *Intensity range of phonation* (IRP) has proven a less useful measure than frequency range. It varies with fundamental frequency (which should be recorded), and is greatest in the middle frequency range. It is recorded in SPL (sound pressure level) re: 0.0002 microbar. For normal adults who are not professional vocalists, measuring at a single, fundamental frequency, IRP averages 54.8 dB for males and 51 dB for females.[9] Alterations of intensity are common in voice disorders, although IRP is not the most sensitive test to detect them. Information from the above tests may be combined in the *fundamental frequency-intensity profile*.[8] *Glottal efficiency* (the ratio of the acoustic power at the level of the glottis to subglottal power) provides useful information but is not clinically practical because it is difficult to measure acoustic power at the level of the glottis. *Subglottic power* is the product of *subglottal pressure* and *air-flow rate*. These can be determined clinically. Various alternative measures of glottic efficiency have been

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proposed including the *ratio of radiated acoustic power to subglottal power*,[10] *air flow-intensity profile*,[11] and *ratio of the root mean square value of the AC component to the mean volume velocity (DC component)*.[12] Although glottal efficiency is of great interest, none of these tests is particularly helpful under routine clinical circumstances.

Aerodynamic Measures

The abdomen and thorax form the "power source" of the voice, propelling a controlled stream of air between the vocal folds. Singers refer to this anatomic complex as the "diaphragm" or "support." Effective, well-trained abdominal-thoracic muscle control and efficient respiratory function are essential to healthy vocalization. Traditional *pulmonary function testing* provides the most readily accessible measures of respiratory function. The most common parameters measured include:

1. *Tidal volume*—the volume of air that enters the lungs during inspiration and leaves during expiration and normal breathing.
2. *Functional residual capacity*—the volume of air remaining in the lungs at the end of expiration during normal breathing. It may be divided into *expiratory reserve volume* (maximal additional volume that can be exhaled) and *residual volume* (the volume of air remaining in the lungs at the end of maximal exhalation).
3. *Inspiratory capacity*—the maximal volume of air that can be inhaled starting at the functional residual capacity.
4. *Total lung capacity*—the volume of air in the lungs following maximal inspiration.
5. *Vital capacity*—the maximal volume of air that can be exhaled from the lungs following maximal inspiration.
6. *Forced vital capacity*—the rate of air flow with rapid, forceful expiration from total lung capacity to residual volume.
7. FEV_1—the forced expiratory volume in one second.
8. FEV_3—the forced expiratory volume in three seconds.
9. *Maximal mid-expiratory flow rate* or *forced mid-expiratory flow*—the mean rate of air flow over the middle half of the forced vital capacity (between 25% and 75% of the forced vital capacity).

It is commonly assumed that singers have "big chests." In fact, it has been shown that the primary respiratory difference between trained and untrained singers is not a large increase in total lung capacity. Rather, the trained singer learns to use a higher proportion of the air in his lungs, decreasing his residual volume and increasing his respiratory efficiency.[13] In most established singers, routine pulmonary function testing is not helpful. However, in singers and professional speakers with pathology caused by voice abuse, abnormal pulmonary function tests may confirm deficiencies in aerobic conditioning, or may reveal previously unrecognized asthma. Testing before and after bronchodilator therapy helps to establish this diagnosis. In selected instances, when asthma is suspected clinically, methacholine challenge is justified. Even a mild or moderate obstructive pulmonary disease may have substantial deleterious effect on the voice; asthma may be present and clinically significant even in the absence of obvious wheezing.

The *spirometer*, readily available for pulmonary function testing, can be used for measuring airflow during phonation. However, it does not allow simultaneous display of acoustic signals, and its frequency response is poor. A *pneumotachograph* consists of a laminar air resistor, a differential pressure transducer, and an amplifying and recording system. It allows measurement of air flow and simultaneous recording of other signals when coupled with a polygraph. A *hot-wire anemometer* allows determination of air flow velocity by measuring the electrical drop across the hot wire. Modern hot-wire anemometers containing electrical feedback circuitry that maintains the temperature of the hot wire provide a flat frequency response up to 1 KHz and are useful clinically.[12]

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The four parameters traditionally measured in analyzing the aerodynamic performance of a voice include: *subglottal pressure* (P_{sub}), *supraglottal pressure* (P_{sup}), *glottal impedance*, and *volume velocity of the airflow at the glottis*. These parameters and their rapid variations can be measured under laboratory circumstances. However, clinically their mean value is usually determined. They are related as follows:

$$P_{sub} - P_{sup} = MFR \times GR$$

where MFR is the mean (root mean square) flow rate and GR is the mean (root mean square) glottal resistance.

When vocalizing an open vowel, the supraglottic pressure equals the atmospheric pressure reducing the equation to:

$$P_{sub} = MFR \times GR$$

The *mean flow rate* is a useful clinical measure. Using the vowel "ah", it is calculated by dividing the total volume of air used during phonation by the duration of phonation. The subject phonates at a natural pitch and loudness either over a determined period of time or for a maximum sustained period of phonation. *Air volume* is determined by the use of a mask fitted tightly over the face or by phonating into a mouthpiece while wearing a noseclamp. Measurements may be made using a spirometer, pneumotachograph or hot-wire anemometer. The normal values for mean flow rate under habitual phonation, with changes in intensity or register, and under various pathologic circumstances have been determined.[8] Normal values are available for both adults and children. Mean flow rate is a clinically useful parameter to follow during treatment for vocal nodules, recurrent laryngeal nerve paralysis, spasmodic dysphonia, and other conditions.

Glottal resistance cannot be measured directly, but it may be calculated from the mean flow rate and mean subglottal pressure. Normal glottal resistance is 20 to 100 dyne seconds/cml at low and medium pitches and 150 dyne seconds/cml at high pitches.[10] *Subglottal pressure* is less useful clinically because it requires an invasive procedure for accurate measurement. It may be determined by tracheal puncture, transglottal catheter or measurement through a tracheostoma. A transducer is used. Subglottal pressure may be approximated using an esophageal balloon. *Intratracheal pressure*, which is roughly equal to subglottal pressure, is transmitted to the balloon through the trachea. However, measured changes in the esophageal balloon are affected by intraesophageal pressure which is dependent upon lung volume. Therefore, estimates of subglottal pressure using this technique are valid only under specific, controlled circumstances. The normal values for subglottal pressure under various healthy and pathologic voice conditions have also been determined by numerous investigators.[8]

The *phonation quotient* is the vital capacity divided by the maximum phonation time. It has been shown to correlate closely with maximum flow rate[14] and is a more convenient measure. Normative data determined by various authors have been published.[8] The phonation quotient provides an objective measure of the effects of treatment and is particularly useful in cases of recurrent laryngeal nerve paralysis and mass lesions of the vocal folds, including nodules.

Acoustic Analysis

Acoustic analysis of voice signals is both promising and disappointing. The skilled laryngologist, speech pathologist, musician or other trained listener frequently infers a great deal of valid information from the sound of a voice. However, clinically useful technology for analyzing and quantifying subtle acoustic differences has not been developed. In many ways, the *tape recorder* is still the laryngologist's most valuable tool for acoustic analysis. Recording a patient's voice under controlled, repeatable circumstances prior to, during and at the conclusion of treatment allows both physician and patient to make qualitative, subjective acoustic analysis. Objective analysis may also be made from recorded voice samples. The parameters usually assessed include fundamental frequency (or period), intensity, amount and distribution of spectral harmonics, and amount of noise (turbulent air). Very high quality audio-recording for com-

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puter analysis can be done on video tape using a stereo video recorder with or without digital pulse code generator. *Sound spectrography* is readily available and displays the frequency and harmonic spectrum of a short sample of voice. It also visually records noise. Long-time-averaged-spectra (LTAS) analyzes spectral distribution of speech amplitude level over time,[15] providing some additional information. Although spectrographs demonstrate abnormalities and changes during therapy for vocal nodules or vocal fold paralysis, they are more effective in documenting gross changes that are obvious to the average listener than they are in validating more controversial and subtle alterations in vocal quality as might be seen in various stages of professional voice training, for example.

In analyzing acoustic signals, the microphone may be placed at the mouth, or it may be positioned in or over the trachea. Various techniques are being developed to improve the usefulness of acoustic analysis including inverse filtering and various multi-dimensional approaches to analysis. Because of the enormous amount of information carried in the acoustic signal, further refinements in objective acoustic analysis should prove particularly valuable for the clinician.

Laryngeal Electromyography

Electromyography requires an electrode system, an amplifier, an oscilloscope, a loudspeaker and a recording system. Either a needle electrode or a hooked-wire electrode may be used.[8] Because of the invasive nature of the procedure, electromyography is rarely utilized in caring for the customary problems of professional voice users. However, it may be extremely valuable in confirming cases of vocal fold paralysis, in differentiating paralysis from arytenoid dislocation, in differentiating recurrent laryngeal nerve paralysis from complete vocal fold paralysis, and in documenting functional voice disorders.

Psychoacoustic Evaluation

Because the human ear and brain are the most sensitive and complex analyzers of sound currently available, many researchers have tried to standardize and quantify psychoacoustic evaluation. Unfortunately, even definitions of basic terms such as hoarseness and breathiness are still controversial. Standardization of psychoacoustic evaluation protocols and interpretation does not exist. Consequently, although subjective psychoacoustic analysis of voice is of great value to the individual skilled clinician, it remains generally unsatisfactory for comparing research among laboratories or for reporting clinical results.

Conclusion

Current efforts to add objectivity to clinical assessment of voice function are encouraging. While they will never replace the skilled jusgment and "laying on of hands" of the experienced clinician, objective voice measures should be most helpful in improving the standard of care for all voice patients.

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