Surgery of Larynx and Trachea

Marc Remacle
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Surgery of Larynx and Trachea

Springer

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“To the memory of Prof. Dr. György Lichtenberger (1944–2009)”

Foreword

I have been honoured to write the foreword to this European Textbook on *Surgery of Larynx and Trachea.*

This multi-author textbook under the editorship of Professor Marc Remacle and Professor Hans Eckel is definitely a milestone in European laryngology and for the European Laryngological Society.

The editors and the chapter authors belong to the leading laryngologists in Europe. The book covers a broad field within larynx and trachea and represents the state of art within European laryngology today. The book covers physiology, phoniatrics, open, and endoscopic operative techniques in adults and in pediatrics. Even assisting drugs used in clinical practice as steroids, fibrin glue, mitomycin C, cidofovir, etc. have been covered.

The book is easy to read, but goes into depths of representative fields.

On the whole, the book is very well illustrated, not only with endoscopic photos, but also with a lot of illustrative drawings which complement and add to the quality of the chapters.

I am sure that this is a book that will be read, not only by laryngologists in Europe and outside, but also used in the teaching of residents and those superspecializing in laryngology.

As one of the founding members of ELS and President of EUFOS, I must congratulate all the authors and editors of this European Textbook on *Larynx and Trachea.* The book is an example of the standard and quality of European ORL-HNS and especially laryngology today. The book is definitely very promising for the future.

Jan Olofsson

Preface

Only 25 years ago, laryngology and laryngeal surgery mainly dealt with life-threatening conditions of the larynx, particularly those related to airway obstruction and laryngeal cancer. Endoscopic biopsies for diagnostic purposes, open laryngeal surgery to resect laryngeal tumours and tracheotomy for airway relief were the principal laryngeal procedures at most Ear, Nose and Throat departments throughout Europe and the world.

In the meanwhile, research into laryngeal anatomy and physiology, technical advances and pharmacological progress have provided us with an abundance of new insights into the basic laryngeal functions – protection of the lower airway during deglutition and voice production – and therapeutic options. During the same period, our attitude towards health and medical care has changed considerably. While cure was the only ambition of most medical and surgical interventions in the past, the preservation and improvement of physical function is now an equally important issue. Individuals in today's developed societies depend on communicative skills rather than on physical work, and laryngology has become a major medical subspecialty dealing with communication disorders.

Clinical pioneers, some of them are contributors to this textbook, have developed a wealth of new endoscopic and surgical techniques to improve the voice, to recover deglutition, to restore a laryngeal and tracheal airway and to treat cancer without sacrifice of laryngeal function. Refined diagnostic tools, to assess structural changes (endoscopy and imaging) or functional impairment (voice analysis) are available to identify both the origin and the consequences of laryngeal disease, and to direct symptom-related surgery. Different surgical traditions throughout the countries of Europe have developed into different solutions for clinical problems. This diversity of opinion and practice is part of this book. Each chapter reflects the personal experience and clinical skill of the contributing author. Differences in opinion may occur, and not all dilemmas in laryngology have been solved so far.

This textbook has been written to lay out the basic principles of contemporary laryngeal surgery from a European perspective. The description of these fundamentals of laryngeal surgery will not replace surgical atlases or detailed descriptions of individual laryngeal procedures. By providing context and perspective, the chapters of this textbook are meant to supply the reader with the fundamentals of laryngeal surgery.

The editors hope that this textbook may serve as a basis for future research, for discussion among laryngologists and as a source of inspiration to our readers.

We express our gratitude to Springer editors, who made this book possible, to the contributors to this project, and to our fellows, students and families.

September 2009

Mont Godinne and Klagenfurt
Marc Remacle and Hans Edmund Eckel
Editors

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Physiology of Voice Production

1

Antoine Giovanni and Suzy Duflo

Core Messages

- During phonation the respiratory cycle changes.
- The vocal fold is composed of the thyroarytenoid muscle, its fibrous tissue cover, and the facing mucosa.
- Cyclic repetition of closing and opening movements of the vocal cords results in vibration.
- Voice production depends on neuromotor coordination of all muscles involved in phonation.

Voice production corresponds to the physiological and physical processes by which vibration of the vocal fold is transformed into speech. The primary driving force for vocal fold vibration and voice production depends on conversion of aerodynamic energy to acoustical energy when the vocal folds are closed in the midline. The sound produced by vocal fold vibration is immediately modified and filtered in the cavities located between the vocal folds and the lips (buccopharyngeal resonator). Because a number of factors can affect phonation, voice production is a highly variable process, not only from person to person but also within the same person [24, 30].

1.1 Breath Stream

The diaphragmatic muscle, innervated by the phrenic nerve, is the most important inspiratory muscle. Contraction increases airway capacity, allowing a larger volume of air to be inhaled. During its relaxation, the air is exhaled from the lungs, which can go back to their initial volume owing to their elastic properties. During quiet breathing, inhalation is shorter than exhalation. Under some conditions (e.g., during phonation), accessory respiratory muscles may also be used. The accessory inspiratory muscles are the external intercostal muscles, scalene muscle, and sternocleidomastoid muscle. The expiratory muscles are the internal intercostal muscles and abdominal muscles, including the three oblique muscles and the right and dorsal large muscles [25, 27, 32].

During phonation, the respiratory cycle changes with shortening of inhalation and lengthening of exhalation. After closure of the vocal folds, blocking the airflow, and increasing subglottal air pressure, the speaker strives to maintain a constantly higher-than-normal expiratory pressure in the lungs and trachea (see reference to phonatory threshold pressure, below). After taking a deep breath during the prephonatory phase, the forces of elastic recoil are called into play. The diaphragm is not relaxed until the recoil forces diminish. The second phase corresponds to involvement of the internal intercostal muscles, which tend to decrease the size of the thorax and thus increase air pressure. The third phase corresponds to activation of the abdominal muscles, which constitute the most important active component. When singing, expiratory pressure, in the best case scenario, is controlled by contraction of the oblique abdominal muscles rather than by contraction

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of the right large abdominal muscles. Back muscles can also be used to stiffen the thorax.

1.2 Laryngeal Vibrator

The larynx sits on top of the trachea. The thyroid and cricoid cartilages, which are part of the larynx, provide reinforcement and prevent collapse of the airway. The other components of the larynx are mobile and form a closing mechanism that protects the trachea during deglutition. They include the arytenoid cartilage, epiglottis, and endolaryngeal muscles. For more information about the osteocartilaginous elements and the intrinsic and extrinsic muscles of the larynx, the reader is referred to classic anatomical descriptions [8, 33].

The vocal fold is a "multilayered" structure that exists only at the level of the anterior two-thirds of the fold (known as the "ligamentary" portion of the fold as opposed to the posterior cartilaginous portion, which corresponds to the vocal process). The vocal fold is composed of the thyroarytenoid muscle, its fibrous tissue cover, and the facing mucosa [7, 17, 18, 20] (Fig. 1.1).

The vocal fold features are specifically designed for vibration. The vibrating free edge is covered with squamous epithelium, which is more resistant to the mechanical constraints produced by vibration and contact than the pseudostratified respiratory mucosa that lines the rest of the larynx. In addition, the epithelium is covered with a mucus layer whose outer layer has a mucin film to prevent dehydration of the underlying serous layer, cilia, and cells. The free edge of the vocal fold is glaborous (i.e., totally devoid of glands that might hinder mucosal wave formation); and most blood vessels as well as elastin and collagen fibers run parallel to the free edge of the vocal fold. The basement membrane is attached to the underlying lamina propria by interlacing fibers whose density appears to depend on genetic factors. Thus, genetics could predispose patients to develop certain lesions, such as nodules. The lamina propria has traditionally been divided into three layers according to the histological composition regarding elastin and collagen fibers (i.e., the superficial layer that corresponds to Reinke's space in the classic description and the middle and deep layers that correspond to the vocal ligament). Interstitial proteins regulate vocal fold viscosity, which is an essential physical factor in vibration. Proteins also contribute to absorption of mechanical shocks caused by vibration. Hyaluronic acid is especially important for both viscosity regulation and shock absorption. The distribution of fibrous and interstitial proteins probably depends on the mechanical stress to which the vocal folds are subjected and may be genetically determined.

Two of the most important cells of the lamina propria are fibroblasts and myofibroblasts. Fibroblasts play a key role in maintaining the integrity of the lamina propria. They allow replacement of proteins. Myofibroblasts are present only after trauma or damage requiring regeneration or repair of the extracellular matrix. This suggests that vocal folds are competent in repairing microscopic trauma within 36–48 hours. It has been reported that vocal rest is useful to give myofibroblasts time to act.

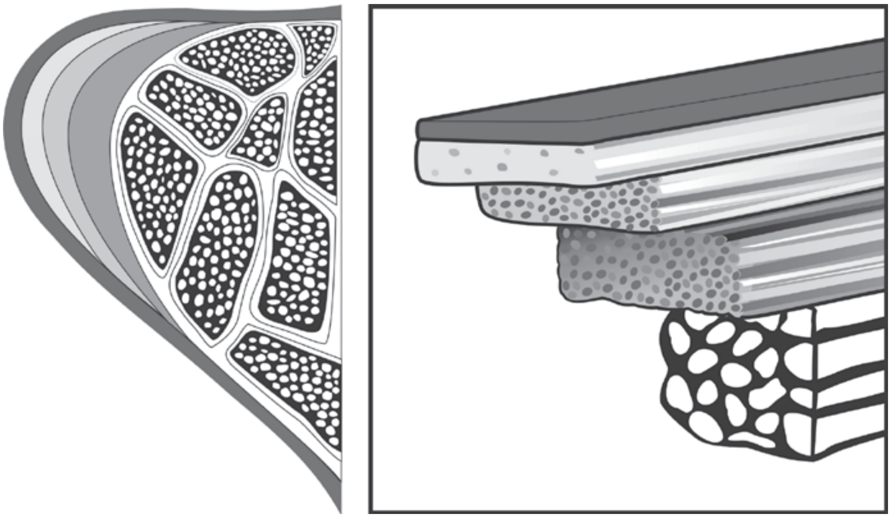

Fig. 1.1. Frontal section showing the multilayered structure of the vocal fold. (From Hirano [18], with permission)

1.3 Vocal Fold Vibration

All current theories and models of vocal fold vibration are based to some extent on the myoelastic-aerodynamic theory formulated by Van Den Berg. When the vocal folds are closed with appropriate tension on either side of the midline of the glottis (prephonatory attack position), airflow from the trachea is blocked and subglottic pressure increases. Vibration begins when subglottic pressure below the vocal folds exceeds fold resistance (phonation threshold pressure) and some air is released into the supraglottic region. As soon as the vocal folds separate, allowing some air to rush out, subglottic pressure decreases and the folds close back as a result of elastic recoil and the Bernouilli effect. Cyclic repetition of these closing and opening movements results in vibration [2, 6, 13, 16, 20, 23] (Fig. 1.2).

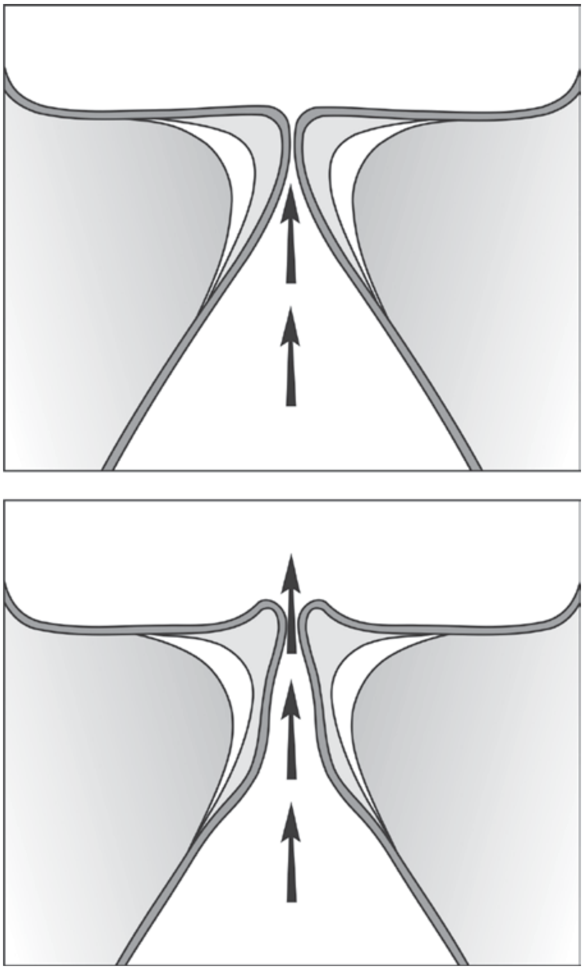

Fig. 1.2. Frontal section of the vocal folds shows resolution of the elastic conflict between subglottic air (*opening force*) and muscle and the elastic fold (closing force)

The mechanism underlying vocal fold vibration is comparable to that of a violin string. When the bow drags the string off the equilibrium point, countervailing elastic forces gradually build until they exceed the force of adhesion to the bow. At this point, the string “unhooks” and is free to oscillate (vibrate). When sufficient energy has been dissipated, the string adheres again to the bow. This is known as the stick–slip friction model involving alternation between a stick phase in which the string is dragged by the bow (“driving force”) and a slip phase in which the string is free to oscillate at a frequency determined by the mass of the string and the amount of tension applied. In the larynx, airflow over the free edge of the vocal fold serves as the driving force (instead of a bow) [6, 13, 15] (Fig. 1.3).

According to Titze, phonation threshold pressure (i.e., the minimum air pressure required to sustain vocal fold oscillation) is the “missing link” in understanding vocal fold physiology [31]. The phonatory threshold pressure depends on several parameters.

- Stiffness of the vibrating portion of the vocal fold
- Viscosity of the vocal fold
- Thickness of the free edge of the vocal fold
- Width of the glottal opening prior to phonation
- Transglottic pressure gradient

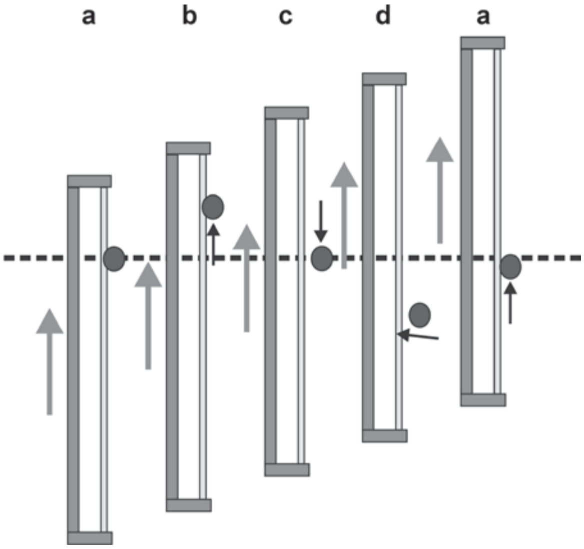

Fig. 1.3. Stick–slip friction model of fold vibration. (**a**, **b**) Stick phase. (**c**, **d**) Slip phase

Under normal conditions the phonatory threshold pressure is between 2 and 4 hPa and the subglottic pressure is around 7 hPa; however, higher pressures may be necessary when a louder voice is required. It has been shown that the increase of pitch has a relation with vocal fold tension, leading to higher phonatory threshold pressure. In disease states involving vocal fold lesions, mucosal stiffness leads to an increase in phonatory threshold pressure. In the case of unilateral laryngeal paralysis, the prephonatory glottic gap is too wide and the speaker must compensate by increasing the subglottic pressure. Increased phonatory threshold pressure is a fairly accurate indicator of voice strain in disease states.

There are numerous ways to decrease phonation threshold pressure. In general, decreasing the velocity of the tissues can be achieved by improving hydration, thereby decreasing tissue viscosity. Another way to decrease phonation threshold pressure is to decrease the mucosal wave velocity. This can be achieved by lowering surface tension (low-pitched voice) or by hydrating the surface mucus. The prephonatory glottic gap can be narrowed by tightening the muscles slightly. The goal of laryngoplasty in patients with laryngeal paralysis is to decrease the width of the prephonatory glottic opening. It can also be useful to increase the thickness of the vocal fold (e.g., by speaking in a lower-pitched voice or in some cases by changing the register: chest vs. head).

During a cycle of vibration, the vocal folds are not similar. This difference can be heard; but the coupling and adduction of the vocal folds has the effect of synchronizing the vibrating masses. This process is effective so long as differences between the two vocal folds stay within a certain range. Beyond the effective range, however, various abnormalities can appear, including biphonation, which corresponds to synchronization every other cycle. Another, more complex phenomenon is reciprocal modulation of the folds characterized by the presence of subharmonics and bifurcations (i.e., sudden state changes). This problem is frequently observed in patients with unilateral laryngeal paralysis, which is often associated with sudden voice shifts (bitonal voice) [4, 15, 22].

1.4 Pitch Control

The pitch of the human voice is related to the fundamental frequency (F_0) of vocal fold vibration. As shown in Table1.1, pitch depends on the length of the vocal folds and the sex, age, and weight of the person. Vocal fold thickness has also been shown to affect pitch, which increases with thickness in both men and women [3, 9, 10, 14, 29] (Table 1.1).

Pitch control depends on adjusting the F_0 of vibration. This adjustment can involve regulation of mass or tension, which can be done actively by contracting the intralaryngeal muscles or passively by contraction of the perilaryngeal muscles. Basically, pitch control involves the combined actions of two muscles: the cricothyroid (CT) muscle, which acts on vocal ligament tension, and the thyroarytenoid (TA) muscle, which acts on the muscle mass of the fold. This adjustment mechanism can be viewed as bipolar, according to the "body-cover" theory described by Hirano and Titze. If the TA muscle is contracted and the CT muscle is relaxed, the total length of the vocal fold increases; moreover, the overall stiffness of all layers increases, so the F_0 increases. Conversely, if the TA muscle is contracted and the CT muscle is relaxed, the stiffness of the muscle mass and the F_0 increase. Accordingly, these two muscles with different sources of innervation—superior laryngeal nerve (SLN) (for the CT) and recurrent laryngeal nerve (RLN) (for the TA)—can be seen as exercising differential control over the F_0 (Fig. 1.4).

Another mechanism that can be used for pitch control involves increasing the cover tension by decreasing the depth of the vibrating tissue. This strategy is used to produce higher pitches, such as a falsetto sound. Decreasing the effective depth can lead to

Table 1.1. Voice pitch as a function of age and sex [1]

Subject	Weight (kg)	Height (m)	Fold length (mm)	Arytenoid length (mm)	F_0 (Hz)
Newborn	3.5	0.50	2	2	500
Eight-year-old	30	1.20	6	3	300
Adult woman	60	1.60	10	4	200
Adult man	75	1.80	16	4	125

F_0, fundamental frequency

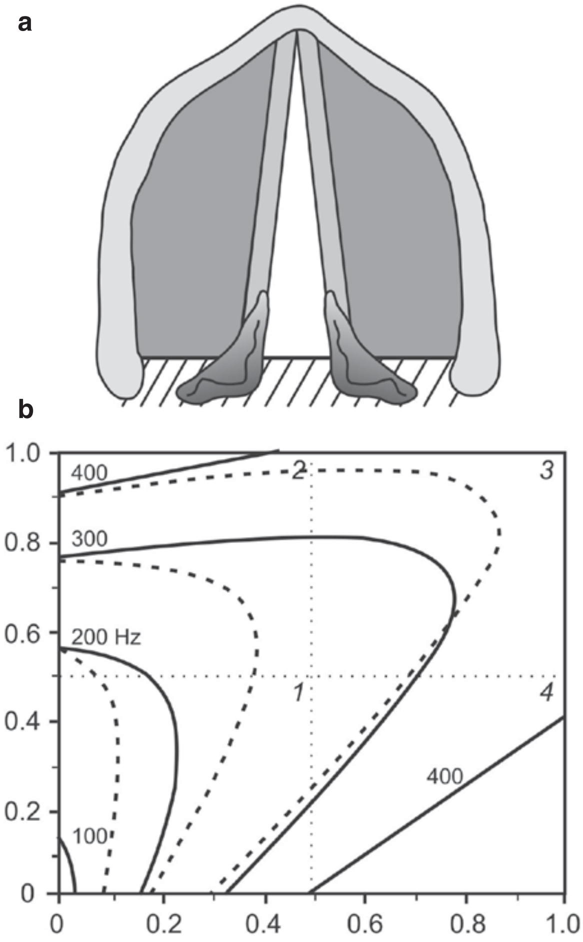

Fig. 1.4. Differential control of the fundamental frequency (F_0) by contracting the cricothyroid (CT) and thyroarytenoid (TA) muscles. (**a**) Action of the muscles. (**b**) Map of muscle activation. (From Titze [32], with permission)

changes in F_0 in the same way as changes in fold tension or length. The depth of the vibrating tissue can be regulated using the TA muscle. Although no accurate quantitative data are currently available, it can be speculated that the vocal fold ligament absorbs most of the elongation at high frequency so the remaining mucosa stays fairly loose. A taunt vocal ligament with a "free," loose tissue edge appears to represent the optimal condition for high-pitched phonation. For lower and middle-range frequencies, the muscle portion of the body can be used for elongation and tensioning. The vocal ligament can remain loose, providing a greater depth of vibration in the modal register [5, 26, 28].

The complex action of the TA on the F_0 is related to differences in tension and biomechanical properties of the tissue layers. According to Hirano, contraction of the TA muscle should be associated with an increase in body tension and a decrease in cover tension. If the vibrating tissue is composed only of mucosa, contraction of the TA muscle leads to lowering of the F_0. Conversely, if the vibrating tissue is composed mainly of muscle, contraction of the TA muscle leads to a rise in the F_0. Correlation between the F_0 and TA activity becomes more and more positive as the depth of vibration increases.

Each layer of the vocal fold has distinct biomechanical properties, depending on what is known as the length–tension ratio (i.e., tension induced in the material by changes in length, known as the stress–strain curve). In this regard, it has been shown that collagen fibers are more resistant to elongation than elastin fibers. Variations in the concentration of collagen and elastin in each layer of the lamina propria explain differences in behavior during elongation. A stress–strain curve can be obtained for the whole vocal fold. Total fold strain (tensile strain) corresponds to a combination of various active and passive actions that occur during tensioning.

1.5 Intensity Control

Current research indicates that the optimal glottic configuration for phonation is achieved when the vocal folds are in virtual contact and the vocal muscles are fairly relaxed. A slight gap should be established between posterior ends of the two vocal folds by balancing the activity of the adductor (interarytenoids and lateral cricoarytenoids) and abductor muscles. Under these conditions a quasi-sinusoidal signal with low harmonic content can produce a "pure voice" [11, 26, 28].

Intensity is controlled by combined regulation of subglottic pressure and glottic configuration. Higher intensity is achieved by simultaneously increasing vocal fold adduction and subglottic pressure. Because increased vocal fold adduction leads to longer contact time between the vocal folds, higher intensity is accompanied by a shortened open phase of the vocal folds cycle [19]. This raises the issue of the optimal adduction configuration. If the vocal folds do not touch, the voice is weak and of poor quality. Conversely, excessive contact leads to vocal straining, resulting in a tight, pressed voice quality. The ideal configuration appears to occur when the vocal folds are almost in contact before phonation (decreased prephonatory glottic width). In this configuration, the vocal folds are almost completely free and can express the full range of vibration modes. The signal produced is practically sinusoidal. This mode of functioning corresponds to what some singing teachers refer to as a "free-floating voice." According to this analogy, glottic resistance is adjusted to ensure the best possible yield from the conversion of aerodynamic to acoustical energy with minimal effect on vocal fold vibration. To increase the intensity, the glottis operates on a more "open–shut" than "wave" basis. However, glottal efficiency decreases, and a large amount of energy is dissipated at the vocal fold level in the form of friction, which can cause local inflammation and even fold lesions. These lesions, called dysfunctional lesions, are preferentially in the zone where contact of the vocal folds is the strongest (i.e., the middle third).

Increased tension in the voice apparatus can leads to "voice straining" on the part of the speaker. In the English-language literature, voice straining is often referred to as vocal misuse or abuse. In fact, the straining concept goes beyond vocal fold function and applies to all physiological components involved in communication. When striving to attract attention, the speaker increases muscle tension to produce a stronger, more effective ("projected") voice. This behavior, characterized by stiffening of the body, has been shown to result in increased muscle activity throughout the body. The breathing pattern changes in association with voice straining. Inhalation is deeper to increase subglottic pressure (prephonatory attack phase). Some subjects have trouble relaxing muscles sufficiently to inhale deeply and may need to use their accessory inspiratory muscles ("thoracic breathing" in place of the normal "abdominal breathing"). Stiffening is also observed in all posturing muscles including not only those of the neck and larynx but also those of the calves and back. Increased muscle activity in relation to increased vocal intensity requires more energy. If subjects do not or cannot rest sufficiently to offset the excess energy expenditure, they may develop complications such as dysfunctional laryngopathy (vocal overuse). Because voice straining affects all these components, rehabilitation should not be limited to changing the glottic configuration. Management must include a wide range of aspects, including general muscle tension, stress level, posture, and prephonatory respiration.

A number of factors promote synchronization of the vocal folds [12]. The first is symmetry of shape and tension of the vocal folds in the normal resting state. In this regard, unilateral laryngeal paralysis represents the worst possible condition. It should be noted that acceptable fold vibration can be obtained if contact is reestablished between the vocal folds, as can be observed during speech therapy or laryngeal manipulation. Another factor promoting synchronization is the Bernoulli effect, which applies equally to the two vocal folds and so tends to have the same effects as a function of glottic configuration. The most important synchronizing factor is the tissue mass-combining effect of direct contact between the vocal folds. The quality of contact is highly dependent on the vocal fold cover mucosa, with viscosity playing a major role. In vitro experiments on excised larynx models in our laboratory showed that the frequency of the vibration directly correlated with the viscosity of the artificial lubricant applied. The higher the viscosity of the lubricant used, the more the vibration frequency decreased when the vocal fold "closure" time increased. It has also been shown that more viscous mucosa increases the phonation threshold. Conversely, the greater the degree of asymmetry and freedom tend to be, the greater is the need for "forced" synchronization. It can thus be understood that the mechanism underlying "voice straining," used to increase loudness, is similar to the mechanism used to compensate for abnormalities in laryngeal vibration.

1.6 Vowel Production in the Vocal Tract

Human speech production depends on sound transformation in the vocal tract. According to the source-filter theory, the source sound is a pulsed airstream from the glottis containing numerous frequencies. Filtration consists of selecting certain frequencies for transmission through the mouth. The vocal tract acts as a resonator by suppressing the transfer of some frequencies. The concept of resonance in a tube is based on interference between waves submitted to multiple reflections. Like a wind instrument used to make music, the human vocal tract resonates at various source frequencies depending on the anatomical features that determine production of speech sounds (phonemes) [21, 30].

The resonance frequencies (formants) of the vocal tract are commonly numbered consecutively upward from the lowest frequency (F1–F5). Low-pitched formants correspond to the pharynx and high-pitched formants to the oral cavity. Vowels' formants are the lowest-pitched formants at F1 and F2. Thus, for vowel perception, the filtering process simplifies the code presented to the listener. In traditional phonetics, vowels are classified in regard to how the tongue is positioned in the mouth from top to bottom and from front to back. The tongue is placed at the bottom and back for the French /a/ vowel sound, at top and front for the French /i/ vowel sound, and top and back for the French /u/ vowel sound. These three vowels determine the vowel triangle on a F1 and F2 orthonormal representation.

To produce the French /eu/ vowel sound, the vocal tract is almost tubular with an almost constant cross section due to the neutral position of the tongue. The frequencies are about 500 Hz for F1 and 1500 Hz for F2. On the same diagram we can see the position of F1 and F2 with the tongue in different positions. For the French /a/ vowel sound, the vocal tract can be modeled as a narrow tube for the pharynx and a larger tube for the oral cavity.

Formants can be modified by articulatory movements. In general, the frequencies of all formants decrease evenly as the length of the tube increases. The length of the vocal tract can be changed by lowering the larynx or by projecting or retracting the lips. Because these movements cause frequency sliding without changing the interval between formants, there is no change in vowel identification. The sound of vowels can be modified by rounding the lips to reduce the mouth opening. Horn players sometimes cover the ends of their instruments to achieve this effect. The acoustical effect of obturation is the same as that of lengthening the tube (i.e., frequency sliding to a lower register). With the combination of adjusting the height of the larynx and the position and shape of the lips, it possible to enhance or muffle the pitch of the voice. Singers use several techniques to adjust pitch. Some sopranos can lower pitch by dropping the jaw. Using this technique, F1 can be brought into contact with F0; and acoustical power can be increased. By increasing acoustical power, contraction of the mouth lowers F1 and increases F2 to produce vowels with a wider spectrum (e.g., for the French /i/ vowel sound). Conversely, contracting the pharynx increases F1 and decreases F2 to produce a more compact vowel (e.g., for the French /a/ vowel sound).

Singers frequently talk about voice placement and claim that some vowels have exact locations in the vocal tract. The sensation that some vowels have precise locations could be related to the localization of pressure maxima of the standing waves in the vocal tract. Thus, there would be places where the sensations must be maximum (e.g., high pressure at the palate level for the French /i/ vowel sound, high pressure in the velar region for the French /u/ vowel sound, and high pressure in the pharyngeal region forthe French /a/ vowel sound). It is likely that some singers are able to use this sensation to customize vowel production. Other singing techniques based on sensations such as singing in a mask, using the jaw as a resonator, or directing the note at the level of the palate just behind the upper incisors may also be related to pressure maxima at precise locations in the vocal tract.

1.7 Nervous System Control

Voice production depends on neuromotor coordination of all muscles involved in phonation, ranging from posture and respiratory muscles to the muscles of the larynx, pharynx, and buccolabial articulatory apparatus [34].

1.7.1 Sensory Innervation of the Larynx

Sensory innervation of the larynx is provided mainly by the SLN, which receives fibers from the laryngeal vestibule and the laryngeal margin. These fibers merge with the vagus nerve at the level of the inferior vagus ganglion. Innervation of the vocal fold and subglottic region is also provided by fibers that merge with the RLN. There are sensory mucosal receptors in contact (mechanoreceptors) that induce the cough reflex when stimulated. They are mainly located at the vestibular level. In addition, intrinsic and extrinsic muscles present several types of articular and intramuscular mechanoreceptors (corpuscular, neuromuscular bundles, spiral) that supply nerve centers with proprioceptive information concerning vocal fold tension and elongation. The fibers penetrate the bulb of the vagus nerve and run in the direction of the nucleus of the solitary bundle.

1.7.2 Nerve Centers

The brain areas responsible for motor control of the pharynx and larynx are located in the lower part of the ascending frontal convolution (or precentral gyrus) of both hemispheres. When all or parts of these areas are stimulated, an overall larygeal response is observed with vocalization, inhibition of the posterior cricoarytenoid muscle, and bilateral activation of one or several adductor muscles. Cerebral damage in this area leads to unilateral paralysis.

There are many connections in the brain, particularly with language-related centers (e.g., the gyrus supramarginalis). The associative pathways between pharyngolaryngeal motor regions and cortical and subcortical auditory zones are especially noteworthy.

1.7.3 Reflex Control

Articulatory adjustment during phonation takes place during the prephonatory period and during sound production. Prephonatory adjustment is independent of audiophonatory control. This explains how singers produce sounds at a predetermined pitch and intensity. Prephonatory regulation in the cortex depends on input supplied by laryngeal mechanoreceptors concerning tension and position of the various muscles and articulations. During phonation, this input allows the adjustments necessary to maintain the glottic configuration to be made instantaneously. It is likely that other reflex arcs involving the abdomen thorax, neck, and tongue, among others, provide the feedback needed for continuous adjustment of the larynx during phonation.

1.7.4 Audiophonatory Control

Auditory feedback is a necessary component of voice control. This is demonstrated by the disordered, unmodulated voice produced by people with congenital deafness. Audiophonatory control probably depends on voluntary commands produced by corticobulbar pathways in response to acoustic input arriving in the auditory cortex as well as a range of acousticolaryngeal reflexes. However, these control mechanisms act in synergy with proprioceptive control, allowing prephonatory tuning.

During the first months after deafness, the proprioception input explains the almost normal voice of people who became deaf.

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Assessment of Voice and Respiratory Function

2

Philippe H. Dejonckere

Core Messages

- Voice is multidimensional.
- Audio recording is the most important basic requisite for voice quality assessment.
- Once a high-quality complete recording has been attained, it can be stored and remains available.
- Existing research does not support the complete substitution of instrumental measures for auditory perceptual assessment.
- To be valuable, however, perceptual assessment should follow a standard procedure, as does the voice recording. A currently used scale for making perceptual judgments is the GRBAS scale.
- Videolaryngostroboscopy is the main clinical tool for diagnosing the etiology of voice disorders, but it can also be used to assess the quality of vocal fold vibration and thus evaluate the effectiveness of a treatment.
- The simplest aerodynamic parameter of voicing is the maximum phonation time (MPT), in seconds. It consists of the prolongation of an /a:/ for as long as possible after maximal inspiration and at a spontaneous, comfortable pitch and loudness.A reduction of possible bias (e.g., supportive respiratory capabilities compensating for poor membranous vocal fold closure) is possible by computing the ratio or quotient : Averaged phonation airflow or PQ = VC (ml)/MPT (s).
- Accurate estimation of subglottal pressure can be achieved by measuring the intraoral air pressure produced during the repeated pronunciation of /pVp/ syllables (i.e., a vowel between two plosive consonants).
- Among Voice Range Profile parameters, the highest and lowest frequencies and the softest intensity (decibels, or dBA, at 30 cm) seem most sensitive for changes in voice quality.
- Although subjective by definition, self-evaluation is of great importance in clinical practice. Careful quantification is needed for self-evaluation to be compared and correlated with the objective assessment provided by the voice, an important adjuvant technique, laboratory. The Voice Handicap Index is a largely diffused, validated protocol.
- Electromyography (EMG), an important adjuvant technique, is an electrophysiological investigation of neuromuscular function.

2.1 Introduction

The voice laboratory is considered an essential tool for the assessment and treatment evaluation of voice patients and for clinical research on voice disorders. Several specific questions may be answered from the information obtained in the voice laboratory.

1. Is a given voice or voice function measurement considered normal (within normal limits) or pathological?
2. If the voice or voice function is considered pathological, how severe is the alteration?

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3. Which aspects or mechanisms of voice production are involved with the voice disorder? How does the primary (medical) etiology or lesion explain the components of voice production that are perceived or analyzed as deviant (e.g., by limiting vocal fold closure or by eliciting irregular vibrations related to vocal fold asymmetry)? How do they account for the patient's complaints (e.g., voice fatigue or compensation mechanisms)?
4. What is the result of a comparison of voice production two or more times (e.g., before and after therapy), in two or several situations or voicing conditions (spontaneously vs. louder, when doing an Isshiki maneuver, or when applying a defined therapeutic technique)? Have the changes returned the voice to normal function as indicated by voice measurement [1]?

2.2 Prerequisite: Recording a Voice Sample

Audio recording is the most important basic requisite for voice quality assessment. Once a high-quality recording has been performed, it can be stored and remains available—as a document—for performing additional investigations at a later time (e.g., blind perceptual evaluation by a panel or sophisticated acoustical analyses) [2]. A sampling frequency of at least 20,000 Hz is recommended. Ideally, the recordings are made in a sound-treated room, although a quiet room with ambient noise permanently < 45 dB is acceptable. The mouth-to-microphone distance needs to be held constant at 10 cm. A (miniature) head-mounted microphone offers a clear advantage. Off-axis positioning (45°–90° from the mouth axis) reduces aerodynamic noise from the mouth during speech [3, 4].

In regard to voice/speech material, examples of protocol for standard recording are as follows.

- /a:/ at (spontaneous) comfortable pitch/loudness, recorded three times to evaluate variability of quality [5]
- /a:/ slightly louder to evaluate the possible change in quality (plasticity) and the slope of the regression line frequency/sound pressure level [6, 7]
- A single sentence or a short standard passage

Phonetic selection can be useful, such as a short sentence with constant voicing (no voiceless sounds and spoken without interruption) and no fricatives. Such a sentence (e.g., "We mow our lawn all year") can be analyzed by a computer program for sustained vowels; and because it contains no articulation noise, there is no biasing of harmonics-to-noise computations. Computation of the percent voiceless (normal in this case is 100%) is useful for neurological voices or spasmodic dysphonia [9]. Furthermore, it allows easy determination of the mean habitual fundamental speaking frequency.

Another example of a criterion for phonetic selection is a multiplication of voice onsets, as they are critical in disturbed voices [10]. Such criteria are not language-linked.

A standard reading passage should also be recorded whenever possible. Two classic, often used reading passages for English-speaking persons are "The Rainbow Passage" (a phonetically selected passage including all the speech sounds of English) and "Marvin Williams" (an all-voiced passage) [3].

2.2.1 Perception

Existing research does not support the complete substitution of instrumental measures for auditory perceptual assessment. To be valuable, however, perceptual assessment must follow a standard procedure, as does voice recording. A currently used scale for making perceptual judgments is the GRBAS scale, which rates grade, roughness, breathiness, asthenicity, and strain on a scale of 0–3 [11]. The rating is made by assessing current conversational speech or when reading a passage. The severity of hoarseness is quantified under the parameter "grade" (G), which relates to the overall voice quality, integrating all deviant components. There are two main components of hoarseness, as shown by principal component analysis [12].

1. Breathiness (B): an auditive impression of turbulent air leakage through an insufficient glottic closure, including short aphonic moments (unvoiced segments)
2. Roughness or harshness (R): an impression of irregular glottic pulses, abnormal fluctuations in fundamental frequency, and separately perceived acoustic impulses (as in vocal fry), including diplophonia and register breaks. When present, diplophonia can also be noted as "d."

These parameters have shown sufficient reliability (inter- and intrarater reproducibility) [13, 14]. A reliability analysis provided further evidence to support the GRBAS scale as a simple, reliable measure for clinical use [15]. The behavioral parameters asthenicity (A) and strain (S) appear to be less reliable. The remaining simplified scale, GRB, then becomes similar to the RBH scale used in German-speaking countries [16].

For reporting purposes, a four point grading scale is convenient (0 = normal or absence of deviance; 1 = slight deviance; 2 = moderate deviance; 3 = severe deviance). However, it is also possible to score on a visual analogue scale (VAS) of 10 cm, possibly with anchoring points [14, 17].

It is proposed that the term "dysphonia" be used for any kind of perceived voice pathology. The deviation may concern pitch or loudness as well as timbre or rhythmic and prosodic features. "Hoarseness" is limited to deviant voice "quality" (or timbre) and excludes pitch, loudness, and rhythm factors. A limited number of voice pathology categories—such as those related to mutation or transsexuality—are specifically concerned with pitch and register. Rhinophonia is a specific abnormality of resonance and if present needs to be reported separately. Tremor is a characteristic temporal feature and when present must also be reported separately. A special protocol is required for substitution voices [19, 77].

Perceptual evaluation—if averaged among several blinded raters—is very well suited to demonstrate treatment efficacy in voice pathology [21].

2.2.2 Vocal Fold Imaging

2.2.2.1 Videolaryngostroboscopy

Videolaryngostroboscopy is the main clinical tool for diagnosing the etiology of voice disorders, but it can also be used to assess the quality of vocal fold vibration and thus evaluate the effectiveness of a treatment. Stroboscopy involves a video-perceptual series of judgments and ratings (e.g., glottic closure, regularity, symmetry, mucosal wave). The pertinence of stroboscopic parameters is based on a combination of reliability (inter- and intraobserver reproducibility), no redundance (from the factor analysis), and clinical sense (relation to physiological concepts) [23].

The basic parameters are the following:

1. Glottal closure. It is recommended that the type of insufficient closure also be recorded and categorized.
    - Longitudinal. It is important to consider that a slight dorsal insufficiency—even reaching into the membranous portion of the glottis—occurs in about 60% of middle-aged healthy women during normal voice effort. Fifty percent of the women close the glottis completely during loud voice.
    - Ventral.
    - Irregular.
    - Oval. It is over the whole length of the glottis but with a dorsal closure.
    - Hour-glass shaped.

Rating glottal closure has been found highly reliable [24, 25]. Objective quantitative measurements are also possible [26]

2. Regularity: quantitative rating of the degree of irregular slow motion, as perceived with stroboscopy [27].
3. Mucosal wave: quantitative rating of the quality of the mucosal wave, accounting for the physiology of the layered structure of the vocal folds [11].
4. Symmetry: quantitative rating of the "mirror" motion of both vocal folds. Usually asymmetry is caused by the limited vibratory quality of a lesion (e.g., diffuse scar, localized cyst, leukoplakia) [28].

For each stroboscopic parameter, a four-point grading scale can be used (0 = no deviance; … 3 = severe deviance), but a VAS may also be useful [23, 28]. Videostroboscopy can be documented on hard copy and thus be archived. Rating *a posteriori* is possible.

It is classically recommended to observe and record videostroboscopic pictures under various voicing conditions. For example, the degree of glottal closure usually increases with increased loudness [24, 25]. However, this basic rating concerns a comfortable pitch and loudness. Laryngostroboscopic ratings and measurements have been found relevant for documenting therapeutic effects [20–22, 29].

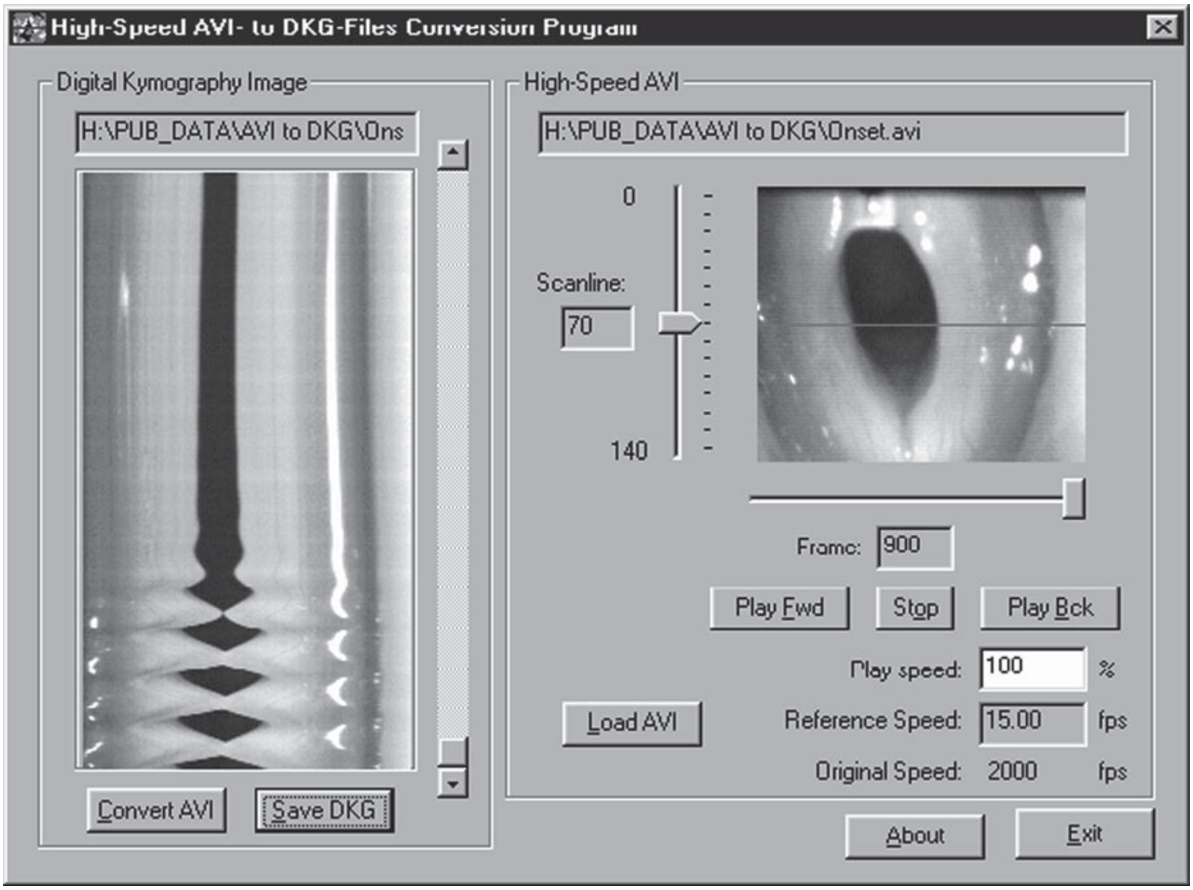
2.2.2.2 Digital High-Speed Pictures

With modern technology, it has become possible to capture and store digital vocal fold images at a rate of 2000 (and more) per second with sufficient definition (several hundred pixels) and to display the image sequence at a rate of, for example, 20/s immediately after capture. This procedure does not seem to be appropriate for routine use in the diagnosis of voice problems as a long review time is needed for a short sequence without simultaneous sound. A specific indication for digital high-speed cinematography is to analyze and understand the vibratory characteristics in aperiodic voices, during voice onsets or accidents (breaks), or in case of diplo- or triplophonia [30, 31].

2.2.2.3 High-Speed Single-Line Scanning (Video-Kymography)

High-speed single-line scanning (video-kymography) is an imaging technique for investigating vocal fold vibration, especially when the vibration is irregular and when the focus is on accidents or short events in this vibration, making conventional stroboscopy unsuitable. A modified video-camera selects a single horizontal line from the whole image and monitors it at high speed (8000/s). The displayed image shows successive high-speed line images below each other, thereby demonstrating the vibration of the selected ventrodorsal level of the vocal folds over time. An important practical advantage is that the display is in real time. This type of imaging provides relevant, timely information e.g., for comparing the vibration amplitude of both folds or for understanding diplophonia [32, 33]. It also clearly demonstrates the mucosal wave phenomenon and its absence or asymmetry.

Single-line scanning can also be performed on a high-speed video recording (Fig. 2.1). If several lines are displayed, phase shifts between different ventrodorsal segments of one or both vocal folds—as



H:\PUB_DATA\AVI to DKG\Ons

H:\PUB_DATA\AVI to DKG\Onset.avi

Scanline: 70

Frame: 900

Play speed: 100 %

Reference Speed: 15.00 fps

Original Speed: 2000 fps

Fig. 2.1. Single-line scan (video-kymography) obtained from a high-speed video recording in a normal subject (Kay System; Kaypentax, Lincoln Park, NJ, USA). *Right* Vibrating vocal folds and the *single line* that was selected. *Left* Oscillation pattern at that specific level during a voice onset

frequently occurs in case of a vocal fold cyst—can be demonstrated [34].

2.2.3 Aerodynamics

Aerodynamic analysis of voice production includes measurement of airflow and air pressure, and their relation during phonation. Using appropriate instrumentation, a number of derived measurements can provide information regarding vocal efficiency, although for certain measurements only a stopwatch is needed.

2.2.3.1 Phonation Airflow

The simplest aerodynamic parameter of voicing is the MPT (in seconds). It consists of the prolongation of an /a:/ for as long as possible after maximum inspiration and at a spontaneous, comfortable pitch and loudness. It is one of the most widely used clinical measures in voice assessment worldwide [35]. A prior demonstration is necessary, and three trials are required, the longest being selected for comparison to the norm [36]. As it concerns an "extreme" performance, it has been shown to be extremely sensitive to learning and fatigue effects. Furthermore, in good voices the duration of "apnea" can become the limiting factor, rather than the available air. Children show significant lower MPT values as their lung volume is smaller [37]. A reduction of possible bias (e.g., supportive respiratory capabilities compensating for poor membranous vocal fold closure) is possible by computing the following ratio: (Phonation Quotient).

$$\text{Averaged phonation airflow or PQ} = \text{VC (ml)}/\text{MPT (s)}$$

Vital capacity (VC) is defined as "the volume change at the mouth between the position of full inspiration and complete expiration." It can be measured in a reliable way using a hand-held spirometer [38]. In normal subjects, the VC depends on anthropometric factors and is quite strongly correlated, for example, with height [39]. It is also sensitive to lung disease. As the VC is not directly related to voice quality, it is meaningful to take it into account, especially if a child is being investigated.

The mean airflow rate can also be measured using pneumotachography. This technique directly measures the mean airflow rate (ml/s) for sustained phonation over a comfortable duration, usually 2–3 s, at the habitual pitch and intensity level and following habitual inspiration. Pathophysiological backgrounds and normative values have been reported [11, 35, 40–43].

The variation of averaged phonation airflow varies considerably among normal subjects, and there is a large overlapping range of values in normal and dysphonic subjects, which limits its value for diagnostic purposes [44]. Nevertheless, when comparing glottal function before and after surgical intervention or nonsurgical voice training techniques, airflow measurement may be useful for monitoring therapeutic effects [45] (e.g., in the case of paralytic dysphonia [46–48] or when microlaryngeal phonosurgery is performed) [42]. The method is especially useful for demonstrating changes in a single test subject over time. For comparisons (pretreatment/posttreatment), it is recommended that the same technique (PQ or mean airflow rate measured by pneumotachography) be used for each measurement.

Flow glottography (FLOG) consists of inverse filtering of the oral airflow waveform. The basic tool is a high-frequency pressure transducer incorporated into an airtight Rothenberg mask [49]. The inverse filtering procedure removes the resonant effects of the vocal tract and produces an estimate of the waveform produced at the vocal folds. The special advantage of this technique is that it differentiates, and after calibration quantifies, leakage airflow (the DC component of the air flow) and pulsated airflow (AC component). Leakage airflow is an important concept: It assumes that there is an opening somewhere along the total length of the vocal folds through which air escapes. Calibration is critical for reliable measurements. FLOG can also be used to analyze voice onset.

2.2.3.2 Subglottal Air Pressure

Measurements of subglottal air pressure using esophageal balloons or pressure transducers, transglottal catheters, or tracheal puncture are semi-invasive or invasive and are limited to research situations. Subglottal pressure can be accurately estimated by measuring the intraoral air pressure produced during the repeated pronunciation of /pVp/ syllables (i.e., a vowel between two plosive consonants). A thin catheter is introduced into the mouth through the labial commissure, is sealed by the lips, and is not occluded by the tongue. If there is no closure of the vocal folds, the intraoral air pressure should be similar to the pressure elsewhere in the respiratory tract. During production of a voiceless consonant, the vocal folds are abducted and should not impose any significant obstruction to airflow from the lungs. Thus, the pressure behind the lips is the same everywhere and reflects the pressure available to drive the vocal folds if they were to vibrate [50, 51]. This technique also allows measurement of the phonation threshold pressure (PTP), the minimum pressure required to initiate phonation [52]. Pressure is usually reported in pascal units: 1 Pa = 1 N/m^2; and 1 kPa = 10 cm H_2O.

2.2.3.3 Efficiency of Phonation

Together with airflow and vocal intensity, subglottal air pressure can be used to estimate the efficiency of phonation. Obviously, reduced efficiency is expected to induce voice fatigue. Vocal efficiency—defined as the ratio of acoustical power to aerodynamic power—can be estimated by dividing the acoustical intensity of the utterance by the product of the air pressure and the airflow used to produce the utterance [54].

2.2.3.4 Flow Versus Volume Loops

Spirometry is important for investigating cases in which voice problems are associated with laryngeal obstruction, such as bilateral abduction paralysis, stenosis caused by extensive webs and scars, cancer, or even severe Reinke's edema. The flow–volume loop is generated when measurements of maximum forced expiration and maximum forced inspiration are plotted on a graph, with the flow rate on the ordinate and lung volume on the abscissa (Fig. 2.2). Lack of effort is easy to detect because there is reduced flow at the beginning of the expiratory curve, and the inspiratory curve is abnormal (Fig. 2.2b). Obstructive lesions of the larynx are easily detected and quantified because the morphology of the flow–volume loop is altered. Variable extrathoracic obstruction (as with bilateral vocal fold paralysis) manifests as a decrease in inspiratory flow only (Fig. 2.2c), whereas a fixed obstruction of the upper airway (e.g., extensive laryngeal cancer) is demonstrated and quantified by a symmetrical reduction of inspiratory and expiratory flow (Fig. 2.2d) [55–57].

2.2.4 Acoustics

Acoustical measures provide, in an objective and noninvasive way, a great deal of information about vocal function. Increasingly, these measures have become available at affordable cost and appear to have succeeded well in monitoring changes in voice quality across time (e.g., before and after treatment). Acoustical measures reflect the status of vocal function and do not relate specifically to certain voice disorders because basic biomechanical changes resulting in acoustical differences can be induced by various lesions and dysfunctions.

2.2.4.1 Visible Speech

Acoustical analysis can be used to make the voice and speech visible (e.g., in spectrograms) [50]. This visual representation may be a considerable aid to the perception and description of voice characteristics. Spectrograms are also useful for comparing normal phonation with phonation characterized by excessive noise. Commercially available software packages provide synchronized displays of the microphone signal and the spectrogram, showing the frequency distribution of acoustical energy over time. A choice can be made between narrowband filtering (frequency resolution, mainly demonstrating fundamental frequency, harmonics, interharmonic and high-frequency noise, subharmonics) and broadband filtering (temporal resolution, mainly demonstrating periodicity but also formant location). Voice characteristics such as the sound pressure level (SPL), fundamental frequency, and formant central frequency can also be displayed over time for analysis of the singing voice. Visualizing fast Fourier transform (FFT) graphics (power spectrum) and long-time average spectra (LTAS) is usually possible (Fig. 2.3). When visible speech is provided simultaneously with voice sound, the interrater consistency of the perceptual quality evaluation significantly increases [8, 9]. Martens WMAF, Versnel H, Dejonckere PH (2007) The effect of visible speech on the parceptual rating of pathological voices. Arch Otolaryngol Head Neck Surg 133 : 178–185.

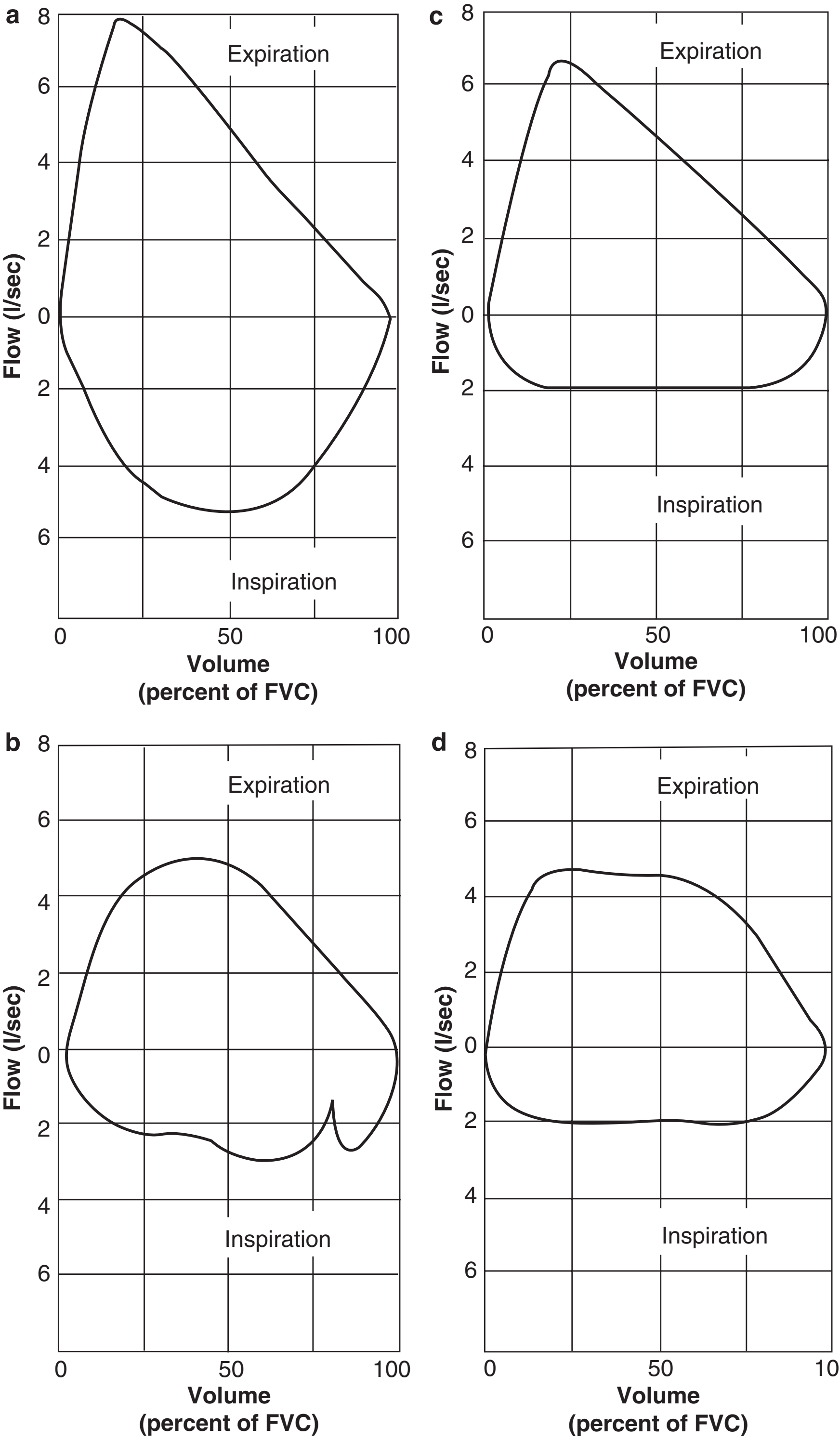


Fig. 2.2. Flow-volume curves. Measurements of a maximum forced expiration and a maximum forced inspiration are plotted on a graph with flow rates on the ordinate and lung volume on the abscissa. (**a**) During normal respiration the expiratory flow curve decays linearly. (**b**) When effort is poor, the initial slope of part of the expiratory curve is decreased, and the inspiratory curve is also abnormal. (**c**) A variable extrathoracic obstruction decreases only the inspiratory flow rate. (**d**) In case of fixed obstruction of the upper airway, inspiratory and expiratory flow rates are both reduced

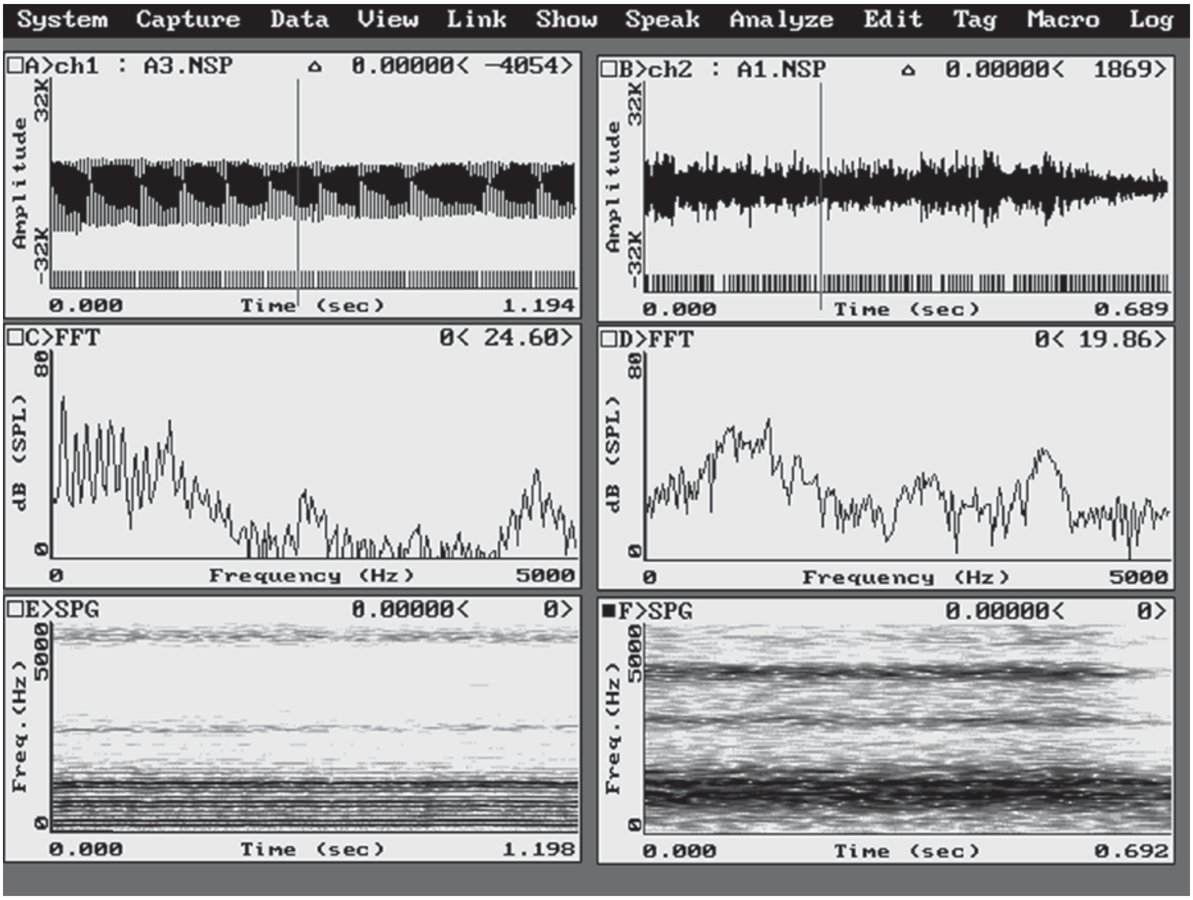


Fig. 2.3. Visible speech or sonagraphy, as displayed by the Computerized Speech Laboratory (Kay Elemetrics, Lincoln Park, NJ, USA). Sustained /a/: on the left by a normal voice and on the *right* by a breathy voice. *From top to bottom* : microphone signal), power spectrum (0–5000 Hz), and spectrogram (sonogram), frequency display 0–5000 Hz over time: about 1.2 s *left* and 0.7 s *right* , narrowband filtering 25 Hz with frequency (resolution). *Left panels*: in Power spectrum and spectrogram the harmonics are easy to identify, whereas they are lacking on the *right panels* . Here the power spectrum and spectrogram are replaced by aperiodic acoustical energy (noise). This kind of display also provides information about formant location

2.2.4.2 Acoustical Parameters

Acoustical analysis can also provide precise numerical values for many voice parameters, from averaged fundamental frequency to sophisticated calculations for noise components or tremor features.

Factor analysis allows the large number of acoustical parameters to be reduced to a limited number of clusters [14].

- Short-term fundamental frequency perturbation
- Short- or medium-term amplitude perturbation and voiceless segments
- Harmonics-to-noise ratio
- Long-term frequency and amplitude modulation
- Very long-term amplitude variation
- Subharmonics
- Tremor

Perturbation measures (in period and amplitude) and harmonics-to-noise computations on a sustained vowel (/a:/) at comfortable frequency and intensity appear to be the most robust measures and seem to determine the basic perceptual elements of voice quality: grade, roughness, and breathiness. Nevertheless, correlations with perceptual data remain usually moderate [14, 58]. *Jitter* is computed as the mean difference between the periods of adjacent cycles divided by the mean period. It is thus a fundamental frequency (F_0)-related measurement (Fig. 2.4). For *shimmer*, a similar computation is made on peak-to-peak amplitudes. Voice breaks must always be excluded. For pathological voices, the coefficients of