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# Glottography, the electrophysiological investigation of phonatory biomechanics*

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## SUMMARY

*Some details of phonatory biomechanics, meaning the vibratory movements of the vocal folds during phonation, are described in the introduction. Here a special emphasis is laid on the multicomponent structure of the vocal folds. Glottography is a general term used for methods to monitor the vibrations of the vocal folds. Four different types of glottography are generally recognized (fig. 2),* viz. *photoglottography, electroglottography, ultrasound glottography and glottography by inverse filtering the acoustic or laryngeal air flow signal. In the main part of the communication the four methods are described and their applicability is discussed.*

Clinical investigations of laryngeal function tend to focus on the gross ad-/abductory or respiratory movements of the vocal folds. Most methods available for such investigations are in the optical dimension like mirror and direct laryngoscopy ; laryngeal endoscopy by rigid, angled optics or fiberoptics ; or X-ray examinations such as (computer-)tomography, xeroradiography or laryngography (= examination using a radioopaque contrast medium, Landmann, 1970).

Clinical investigations of the vibratory or phonatory function of the larynx have so far mainly been practised by speech pathologists and voice therapists, whose main concern usually are acoustic criteria, like the auditory evaluation of voice quality. One important exception to this is laryngeal stroboscopy, which has been used for several decades by

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phoniatricians as well as the small minority of phoniatrically interested laryngologists, and which offers the possibility of a combined auditory and visual examination of phonatory function.

None of the afore mentioned methods of investigation yields results, which can be expressed numerically, and all of them depend on evaluations made by experienced examiners, thereby introducing a factor of subjectivity. All of them are suitable for reproducible documentation : optical findings can be photographed or (video-)filmed, acoustical findings can be recorded on tape. However, most laryngologists prefer to rely only on optical documentation, probably because the terminology and practice of voice quality evaluation is not an integral part of traditional training in laryngology. Actually, laryngological services practising phonosurgery, i.e. surgical interventions aiming at an amelioration of voice quality, may very well lack routines for standardized documentation of the voice before and after surgery by high quality tape recordings. A comparable lack of audiological hearing tests in connection with otological surgery would be inconceivable. By mainly depending on visual findings, a number of laryngologists seem to emphasize morphological abnormalities of the vocal folds, whereas deviations of function may pass unrecognized.

One way to bridge the gap between morphologically orientated laryngologists and clinical voice specialists, interested in voice function and relying mainly on acoustical investigations, would be to promote the understanding in both parties of the vibratory behavior of the vocal folds during phonation and how this can be examined. The present outline of phonatory biomechanics and how they can be monitored by different glottographical methods will hopefully add to such an understanding.

## Phonatory biomechanics

The vibratory pattern of the vocal folds during phonation is of interest to the laryngologist as well as to the voice specialist. By aid of stroboscopic investigations of the vocal fold vibrations the laryngologist can obtain important information concerning the condition of the larynx, especially when he suspects laryngeal paresis or cancerous invasion of the mucosa (Kitzing, 1985). To the voice specialist the glottal vibratory pattern is of interest in studies of the laryngeal sound source. The dependence of the vocal source sound spectrum on the configuration of the glottal vibratory cycle will be commented on somewhat in the final part of this paper.

Generally, three different vibratory patterns of the vocal folds can be distinguished depending on the voice register. In the falsetto, the vocal folds are stretched, mainly by contraction of the crico-thyroid muscle.

In the frontal projection they appear thin and with a sharp angle between their upper and lower surface. Their vibratory amplitude in the lateral direction is usually restricted. The typical vocal fold vibratory pattern in falsetto is characterized by a high frequency, small amplitudes, and a just momentary or even missing contact between the folds. In the modal (or chest) register, the vocal folds appear more obtuse and rounded in the frontal projection. Between their upper horizontal and subglottal oblique surfaces a vertical margin, measuring several millimeters, can be clearly made out. The characteristics of the vibratory pattern in modal register are rather wide amplitudes, a moderate frequency comparing to the pitch of normal speaking, and distinct phases of contact between the folds causing complete vibratory closure of the glottis during about one third of the entire period. In creaky voice quality, also called vocal fry register, the amplitudes are small, the vibratory frequency is extremely low, and the phases of vibratory closure comprise the greatest part of the period time.

The further description will concentrate on the vibratory biomechanics in the modal register as this is the physiological register of speech. Two different components of movement can be discerned in the vibratory pattern of this register. One of them is a to and fro movement in the lateral direction similar to that of a string on a violin, reminding of the older terminology of vocal « cord » (= string). The other component is vertical from below upwards. It arises by a phase difference in the opening and closing movements between the upper and the lower edges of the earlier described medial vertical margin. In the literature about stroboscopy, the two components of movement have been called « amplitudes » and « (mucosal) travelling waves » (in German « Randkantenverschiebung » = marginal edge displacement), respectively.

The general vibratory pattern of the folds resulting from the combination of the amplitudes and travelling waves is so complicated, that it is impossible so far to predict quantitatively from a set of given parameters, such as data on the aerodynamics of the vocal tract and the shape of the folds. The mathematical derivation of the glottal period configuration from such parameters is a major issue of current research on voice physiology.

The classical, widely accepted theory of phonation is the myoelastic-aerodynamic theory, presented by van den Berg (1958). According to this theory, the vocal fold vibrations are produced by an interaction between muscular and elastic forces within the vocal folds and aerodynamic forces active from their outside. At a maximum open position in the vibratory cycle of the glottis, the traversing air current reaches such a velocity as to cause an intraglottal pressure drop due to the so called Bernoulli effect. The marginal mucosal lining of the folds is sufficiently lax to be sucked medially, narrowing the glottis until complete closure takes place, beginning in the inferior aspects of the glottis. The air current is momentarily interrupted and a subglottal pressure builds up against the closed glottis. When the subglottal pressure is high enough to overcome the closing forces, the vocal folds are blown apart, also beginning at the inferior part of the glottis, and the cycle starts over again (fig. 1).

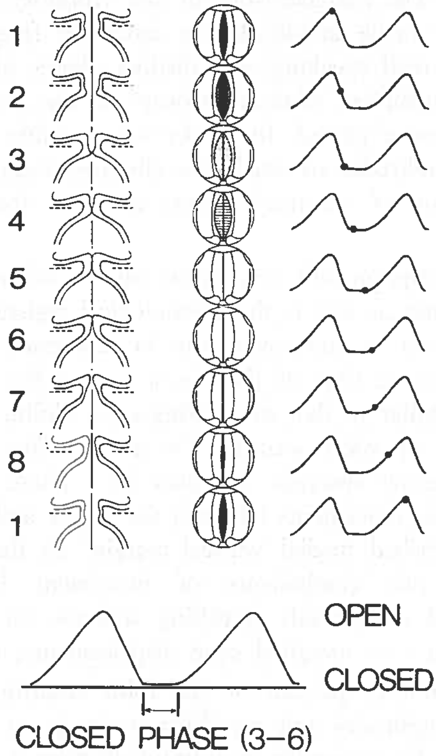

FIG. 1. — *The vocal fold vibratory pattern during phonation in normal chest register.*
Left column : frontal section (according to Hirano, 1981).
Middle column : view from above as perceived in the laryngeal mirror.
Right column and bottom : area function of the glottis.

The importance of the pressure drop due to the Bernoulli effect, implying medially directed aerodynamic forces as a cause of vibratory closure of the glottis, has been questioned by Titze (1985) on the basis of computer model experiments. According to these experiments, intraglottal pressure variations may be sufficient to cause vocal fold vibrations even if the pressure never becomes negative (i.e. inversely directed) during the cycle, on condition that the pressure varies in phase with the vibrations. This may be accomplished by varying configurations of the glottis during the vibratory cycle, from the form of a cone (called « convergent ») during the opening phase of the cycle to the form of a funnel (« divergent ») when closing (Titze, 1985).

For the understanding of glottographical methods, two conclusions may be drawn from this very brief and superficial outline of phonatory biomechanics. One is the overwhelming importance of aerodynamics for voice generation, a factor which is not monitored but in one of the four glottographic methods to be described, viz. acoustical glottography or inverse filtering of the glottal air flow. The second conclusion should be to realize, that the pattern of vibratory movements of the vocal folds is far too complicated to be completely monitored by any single electrophysiological or glottographical method. Four glottographical methods have been presented in the literature and will be described in some detail presently.

## Photoglottography

In photoglottography (PGG, fig. 2 B), also called photoelectric or optical glottography, the glottis is transilluminated by bright light shining either from the anterior of the neck through the tissues and the subglottical space upwards, or from the nasopharynx through the laryngeal entrance downwards. The modulations imposed on the light beam by the vibratory openings and closings of the glottis are monitored and transformed to variable voltages by a photosensor placed in one of the just named positions opposite to the light source. In modern applications of the method, the light usually is supplied by a flexible fibre glass cable, often in combination with a fiberoptical laryngoscope, which can be used to control the placement of the light source and the gross appearance of the larynx. The advantage of the light shining in the opposite direction would be that the photosensor placed in the pharynx can measure the light modulations directly without interference from diffusion in the neck tissues. Dejonckere (1981) carried out a comparison of the two variants of the method without finding any noteworthy differences.

The method of photoglottography was originally developed by Sonesson (1960). It can be understood as an indicator of the area variations of the glottis during phonation. The configuration of a typical PGG-curve in chest register (fig. 1, bottom) is characterized by a horizontal, a rising and a falling segment, called the closed phase (C), the opening phase (CO) and the closing phase (OC), respectively. The sum of the opening and closing phases is the open segment (O) of the period. For the analysis of PGG curves it has been common to calculate certain ratios, namely the open quotient (OQ) and the speed quotient (SQ). OQ is the open segment divided by the entire period, and varies inversely with the vibratory closure. Its maximum value is 1.o, when the glottis does not close at all during the cycle. Typical values for OQ are 0.50 - 0.65 for normal speakers in chest register and at comfortable pitch and loudness. SQ is the opening phase divided by the closing phase, telling the velocity of the glottal opening compared to the closing, a normal value being around 1.o. Theoretically it can vary from zero to infinity. Recently, Hirano (1981) has proposed to exchange the SQ for a speed index (SI), defined as a quotient between the difference of the opening and the closing phases and their sum (CO — OC) / (CO + OC), and variable only between —1.o and 1.o. Another advantage would be that the wave form is easier to visualize from SI values. Computerised recordings and measurements of glottograms becoming increasingly accessible, there has

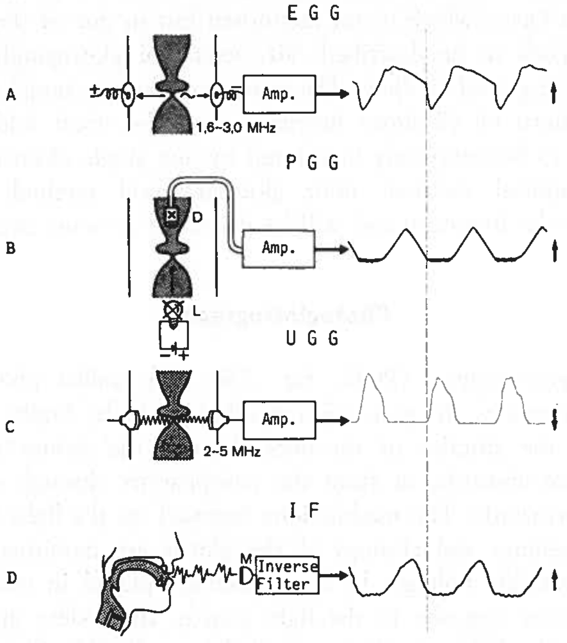

**FIG. 2.** — *Schematic presentation of the four different kinds of glottography.*

A. Electroglottography.
B. Photoglottography.
C. Ultrasound glottography.
D. Acoustic glottography by inverse filtering of microphone (M) signal.
(From Schultz-Coulon, 1980 by permission.)

been a growing interest to indicate speed changes of the vibratory movements by derivations of the curves. In the same way it has been convenient to perform measurements of mean pitch as well as of period and amplitude perturbations (Childers and Krishnamurthy, 1985, Gerratt *et al.,* 1985).

Photoglottography has been used to study how the glottal area function varies with different kinds of voicing. The open quotient generally increases with rising pitch and weakened intensity and the speed quotient tends to increase with increasing intensity (Sonesson, 1960 ; Kitzing and Sonesson, 1974). At the quality of vocal straining or hyperfunction of the voice there is generally an increase of the closed phase of the period resulting in a decrease of the open quotient (fig. 3 A). As a rule the closing phase, OC, is reduced at strained quality, which causes the speed quotient or speed index to increase (Kitzing and Löfqvist, 1977 ; Kitzing, 1983). The photoglottographical method is especially well suited to illustrate different glottal vibratory patterns at the start of phonation such as a hard vs. a soft glottal attack, and to monitor the different vocal registers and voice breaks between them (Kitzing, 1977 and 1982). Gerratt *et al.* (1985) applied PGG on subjects with different kinds of abnormal motor control of their larynx. In a patient with unilateral (flaccid) paresis of the recurrent laryngeal nerve they observed an increase of the opening speed and a decrease of the closing speed of the glottis, resulting in a substantial decrease of SQ. On the other hand, in a patient with muscular rigidity due to Parkinson's disease, most likely also affecting his vocal folds, the results were opposite, with an increase of the opening time relative to the closing duration, resulting in an increase of SQ. The authors concluded that specific neuromuscular deviations of laryngeal function seem to effect glottographic wave form characteristics in ways that are consistent with the suspected pathophysiology of the lesions. In particular they found their results suggesting that SQ may be related to vocal fold myoelasticity, a reduction being associated with a decrease of SQ and vice versa.

Besides the physiological and clinical applications described so far, PGG has also been successfully used by phoneticians to monitor laryngeal articulation (for references cf Baer *et al.,* 1983). However, the method does not lack disadvantages and some possible sources of error have been pointed out. The necessity to place either the light source or the phototransducer in the throat defines the method as semi-invasive. Even if the discomfort of the subject can be minimized by topical anaesthesia and by the use of soft catheters for insertion of the transducer (Kitzing and Löfqvist, 1977) at least in some cases the investigation will not be feasable for lack of cooperativeness or because of too narrow anatomy of the

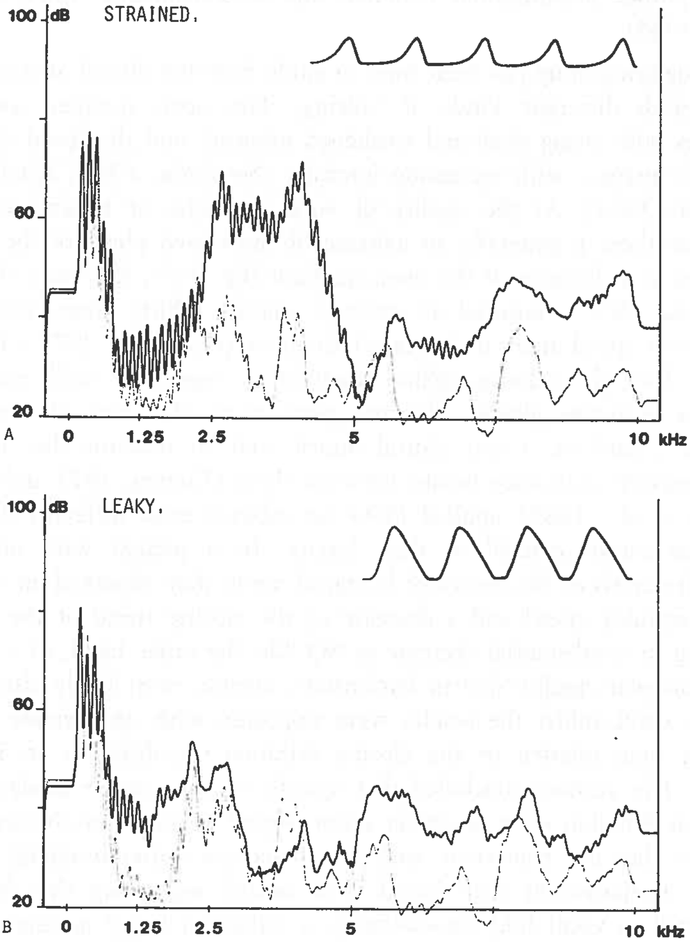

FIG. 3. — *Glottal area function curves obtained by photoglottography and corresponding acoustic spectra of the microphone signal. Male speaker, conversation intensity, pitch about 120 Hz.*

A. Strained, hyperfunctional voice quality.

B. Leaky, hypofunctional voice quality.
The spectrum of normal voice quality is shown with a thinner line for comparison.

nose or throat. Another drawback is the general impossibility to use back vowels causing the pharyngeal cavity to become obstructed by the posterior placement of the tongue with the retroflected epiglottis closing most of the laryngeal entrance. Possible sources of error may be variable light reflexes from the laryngeal mucosa and the changing cross-sectional area of the folds causing uneven transillumination ; the variable light-density distribution within the vocal folds, so that the light may shine through the thin mucosal edges, indicating an open glottis, even if it is still aerodynamically closed ; and the impossibility to control the distance between the transducer and the glottis because of vertical movements of the larynx during phonation, which would be desirable as the placement of the transducer influences on the configuration of the PGG cycle. Furthermore, there seems to be no practicable way to calibrate the amplitude of the O-segment relatively the vibratory amplitude of the glottis, rendering impossible speed measurements of the glottal vibrations. Finally, the start moment of glottal opening may not appear distinctly in the PGG, as the glottis usually opens more gradually than it closes.

On the other hand, recent comparisons between high-speed films of vocal fold vibrations and PGG recordings showed a good agreement. Photoglottograms were shown to represent a weighted sum of the widths along the length of the glottis, the weighting function depending on the location of both the light source and sensor with respect to the glottis. At the same time PGG was shown to give essentially the same information as high-speed film about the peak glottal opening and glottal closure in normal phonation (Baer *et al.,* 1983). Of the glottographic methods available, PGG is the only one to monitor the point of maximum glottal opening. As this is necessary for estimation of SQ, recently shown to be of clinical importance (Gerratt *et al.,* 1985), PGG may attract more clinical interest in the near future than has been the case during the more than two decades since the method was first described.

To the present author's experience, the most reliable and least invasive way to practise PGG is to transilluminate the glottis from below and to use a miniature light sensor mounted in front of a rigid, 90° angled, laryngeal endoscope so the placement and direction of the aperture of the sensor can be controlled by sight as well as the quality of the light shining through the glottis. In recent applications of the method (Kitzing, 1977 ; Baer *et al.,* 1983 ; Gerratt *et al.,* 1985) it has been common to combine the PGG with the next glottographic method to be described here, namely electroglottography. Such a combination is highly recommendable. Childers and Krishnamurthy (1985) found that the PGG and EGG waveforms complement one each other and greatly increase the utility of both.

## Electroglottography

In electroglottography (EGG) two metal electrodes, sized about 3 $cm^2$, are placed in direct contact with the skin of the neck on each side of the larynx. A weak (microampère) alternating current is applied to the electrodes from a signal generator, which may be either of the constant voltage or constant current type. The frequency of the current is typically in the magnitude of several MHz, and the voltage level is about 0.5 V, depending on the tissue impedance and the current. A small part (about 1 %) of the current passing through the tissues is modulated by the vocal fold vibrations. These modulations can be detected and amplified to obtain the electroglottographic curve (fig. 2 A).

The EGG curve is understood as an indicator of the size of the contact area between the vibrating vocal folds by most investigators, even if it has been impossible so far to confirm this by independent measurements, and the factors causing the depicted changes in laryngeal impedance are not known in detail.

The relation of the EGG curve to the vocal fold vibratory cycle can best be understood by comparison with the area function or a PGG (fig. 1 and 2 B). The most conspicuous deflection occurs at vibratory closure or the beginning of the C-segment in the PGG (position 3, fig. 1). Investigators, used to combine the EGG with other registrations of the vocal fold vibrations (like PGG, volume flow inverse filtering or scanning from high speed films), therefore prefer to display the EGG closure deflection directed downwards in their curves. On the other hand, those concentrating on the fact that the curves represent conductance variations prefer to have the maximum directed upwards as is the rule in most displays of electrical signals. The rapidly occurring point of maximal deflection represents the moment of maximum vocal fold contact (position 5, fig. 1). Then the vocal folds peel apart from below more slowly, as shown in the more gradually rising part of the EGG illustration in figure 2. The EGG-representation of the open phase normally lacks details as the impedance is equally maximal whether the air gap between the vocal folds is narrow or wide. The slope of the upper part of the EGG in figure 2 is partly due to electrical filtering. It should be noted, that it is impossible to find out the point of maximal glottal opening by aid of the EGG.

The EGG method was originally described by Fabre (1957). Even if there seems to be no obvious correspondence between vocal sound generation and the size of varying contact between the folds, EGG has attracted a widespread interest as an altogether non-invasive method for tracing glottal vibrations, easy to handle also by non-medical personal.

The literature about EGG is abundant. For detailed information the reader is referred to the thesis of Lecluse (1977) regarding the earlier research, and to the most comprehensive and informative state of the art review by Childers and Krishnamurthy (1985) taking into consideration also the latest trends. The one single research group having gathered the most extensive and diverse experience developing the EGG-method is probably that at University College, London, which prefers a differing terminology such as laryngography and Lx for EGG and EGG-curve, respectively (cf. Abberton and Fourcin 1984, and the there cited literature).

In spite of extensive clinical research on EGG during the last 10 to 15 years, no consistent results have been obtained from analysis of the EGG wave form. It is generally consented, that the steep (in figure 2 downwards directed) part of the EGG cycle represents the increase of vocal fold contact area from its beginning to its maximum, but where on that line one should put the acoustically relevant point of glottal closure is not entirely certain. One reasonable position is the starting point of the inflexion. Measuring from that point horizontally to the opposite (rising) part of the inflexion, the present author found an agreement within 10 % in comparison with measurements of the C-segment from simultaneous PGG : s, permitting acceptable calculations of the OQ. On the other hand, pertinent measurements of the C-segment were possible in only 60 % of the 252 cycles' under observation, due to an all too continuous change of the EGG curve for making out a distinct point for measuring (Kitzing, 1983). Summing up these findings with the fact, that the point of maximum glottal opening cannot be seen in the EGG, it has to be stated that EGG does no seem to be a reliable method to obtain either OQ or SQ (SI). Hopefully, computerized analysis including differentiation of the curves as proposed by Childers *et al.* (1982, for reference cf. Childers and Krishnamurthy, 1985) will change this state of affairs in a more satisfactory direction.

If the EGG-wave does not seem appropriate for detailed and secure monitoring of the glottal vibratory cycle, its simple configuration with one steep deflection in every period makes it ideally suitable for measurements of the glottal period length, inversely related to the fundamental frequency of the voice. Such measurements of the fundamental frequency can be displayed either as intonation curves or as distribution histograms and statistics of the mean and range obtained by computerized calculations (Abberton and Fourcin, 1984 ; Kitzing, 1979). The intonation curves can be used in interactive visual feedback techniques in the speech remediation of profoundly deaf subjets, and the same signal has also been used for external electro-cochlear stimulation of subjects with acquired total deafness (Abberton and Fourcin, 1984). Finally, calculations of glottal period perturbations, signalling vocal fold pathology, can be based on measurements of the EGG cycle (Abberton and Fourcin, 1984).

## Ultrasonic glottography

Especially in the fields of brain surgery, obstetrics and cardiology ultrasonic methods to map internal organs have shown to be most informative as well as safe and non-invasive. Beams of high frequency sound waves of the magnitude of several MHz are generated by piezo-electric transducers which can also function as receivers. The ultrasonic waves can travel through the body tissues but at each interface between organs of different acoustic impedance there occurs some reflexion, which can be detected and measured. As the impedance of air is considerably smaller than that of the tissues, the reflexion is almost total at the level of the vocal folds protruding into the vocal tract. Several methods of ultrasonic glottography (UGG) have been developed to make use of these almost ideal conditions to measure laryngeal vibrations, but the obstacles to a clinically practicable UGG are manyfold and none of the methods presented so far seems to have gained general acceptance.

Here, only a short and superficial account of the different methods can be given. The reader is referred to Holmer and Kitzing (1978) for an analysis of the principal restrictions to UGG and to Hamlet (1981) for a more detailed review of available ultrasonic methods to investigate the larynx. In *continuous UGG* (fig. 2 C) two transducers, preferrably mounted in a holder to face each other exactly (Holmer and Kitzing, 1978), are placed on each side of the neck in the region of the thyroid alae. Continuous ultrasound passes from one of the transducers through the laryngeal tissues and is received by the transducer on the opposite side. The ultrasound beam is modulated by the varying air gap in the glottis. Maximal modulation is an indicator of optimal placement of the transducer. If the transducer is placed too far anteriorly or too far back on the neck the ultrasound can pass through the tissues in front or behind the vocal folds even if the glottis is open and the signal will not decrease to zero. If the signal does not increase sufficiently when there is maximum contact between the vocal folds, some parts of the ultrasound beam may have hit other laryngeal structures than the vocal folds, most probably because of improper transducer positioning or beam direction, even if the size and the focussing of the transducer also are important. The correct placement of the transducer is not always easy due to anatomical asymmetries. However, it is critical, because UGG-amplitude modulations have been shown to occur even if the transducers are not level with the vocal folds. Such modulations must be discarded as artefacts representing passive vibrations in the vocal tract without relevance for phonatory function.

The information to be expected from continuous UGG is measurements of the varying area of contact between the vocal folds, i.e. principally the same as from EGG. The positioning of the EGG electrodes is less critical than for the UGG transducers, as the electrical field is much more diffuse than the ultrasound beam. Another reason to prefer EGG is that the instrumentation for ultrasound investigations is more complicated and expensive.

A different UGG method was developed by research groups in Japan and Sweden (for details see Hamlet, 1981), viz. *pulsed echo UGG.* In this method short pulses of ultrasound (pulse frequency 1 - 10 kHz) are emitted from one single transducer, which in the silent pauses between the pulses functions also as a receiver for the reflected pulse echoes. A practicable method according to this principle would be of utmost laryngological interest, as absolute measures of the vocal fold vibrations could be obtained. Moreover, using two transducers, such measurements would be possible from each single fold at the same time permitting comparisons between the sides, whereas other glottographic methods can depict only summation effects of the both folds vibrating together. However, focussing, placement and direction difficulties are just as great as with continuous UGG. In practice, echo UGG curves have shown to be most difficult to interpret, mostly because of the complicated varying configuration of the vocal fold edges during the vibrations.

Current development of ultrasound methods to investigate the larynx seems to focus mostly on a third method, array or sector *scanning,* providing images of larynx segments in so called B-mode display, but of inadequate temporal and spatial resolution to securely monitor the vocal fold vibrations, so far. As a final observation on UGG it should be pointed out, that ultrasound waves are scattered too much by cancellous bone to be able to penetrate. Insuperable difficulties can therefore be expected with any type of UGG in subjects with advanced ossification of their thyroid cartilages, i.e. predominantly aged males.

## Acoustical glottography. Inverse-filtering techniques

Voiced speech sounds are the product of the acoustic source signal generated in the glottis and the resonance and damping effects of the vocal tract. The transmission function of the vocal tract can be defined mathematically and it is possible to construct a set of filters with the opposite or inverse effect. By treating a speech sound emitted from the mouth with inverse-filter technique a residual signal can be obtained, representing the glottal volume velocity waveform or an acoustic glottogram.

Different inverse-filter techniques have been described. The most uncomplicated one is probably to supply the vocal tract with a pseudo-infinite termination. Such an effect can be accomplished by letting the subject phonate into a large (about 2 m long), metal or perspex tube made reflexionless by inserting a long conical wedge of a porous material (fiberglass, polyurethane) at the end opposite to the mouth. The glottal source signal can be picked up by a small electret condenser microphone inserted into the tube at some distance from the mouth end. The method was described by Sondhi (1975, cited in Monsen and Engebretson, 1977) and studied in some detail on normal speakers providing different types of phonation by Monsen and Engebretson (1977). Like this author (Kitzing, unpublished data shown at the oral presentation of this paper) at increasing intensity of the voice they commonly found a hump building up in the opening phase of the glottal wave, most probably representing uncancelled resonances in the frequency region of the first formant, whereas phonation types lacking a prolonged closed phase in their wave shape, like soft of falsetto voice, appeared quite regular and symmetrical.

Another, more intensity independent method of cancelling the resonances of the vocal tract is by electrically inversefiltering either the ambient microphone (pressure) signal (Miller, 1959) or the oral volume velocity (flow), which can be measured by means of a pneumotachograph mounted in a mask covering the nose and mouth (Rothenberg, 1972). Inverse-filtering the flow instead of the pressure wave form has the advantages of providing a reliable indication of zero flow and that it can easily be calibrated by a constant air flow.

The shape of inverse-filtered glottograms resembles the area function of the glottis or optical glottograms, so that closed segments as well as opening and closing phases can be distinctly discerned (fig. 2 D). As a rule, the glottal volume flow waveform is less symmetrical than the corresponding area function, the flow wave sloping more to the right. The causes of this asymmetry may be amongst others different relationships during the opening and closing phases between the area and flow, the inertia of the air flow and the compressibility of the air.

The reliable indication of zero flow in inverse-filtered (IF) glottograms is an obvious advantage, permitting to measure the amount of unmodulated air escaping through the vibrating glottis in cases of breathy (leaky) voice quality. Contrary to transillumination glottography (PGG) it is also possible to calibrate and measure the amplitude of the JF curves. Therefore, from measurements of glottal flow waves it is possible to obtain not only temporal parameters like the OQ and SQ but also information about the maximum amplitude and the velocities of the changes of flow.

Supported by theoretical considerations by Fant (1979), Sundberg and Gauffin (1980) succeeded in showing a close correlation between measurements of the glottal volume flow wave and certain characteristics of the resulting sound spectrum, which may be illustrated by PGG's of different voice qualities combined with the corresponding spectra (fig. 3). Sundberg's and Gauffin's findings can be summarized in the following way.

1. The amplitude of the volume flow determines the amplitude of the fundamental frequency in the source spectrum ; and

2. the velocity of the closing phase in the volume flow wave determines the intensity of the higher partials of the source spectrum : the higher the velocity, the higher the amplitudes of the overtones.

So, the acoustic parameter of the amplitude of the fundamental can be traced back to the biomechanical dimension of glottal vibratory amplitude, which, in turn, depends on the physiological quality of muscle tone in the larynx. Corresponding links can be established between the spectral level of the higher partials and thereby the intensity of the sound source, related to the biomechanical closing velocity of the glottis, back to the aerodynamic quantity of subglottal pressure, which ultimately depends on the physiological function of expiration.

To sum up, measurements of the glottal volume flow wave may be a means to close the conceptual gap between the vocal fold vibrations (controlled by subglottal pressure and the configuration of the glottis) and the resulting acoustic sound. It thereby seems to be the most promising form of glottography to study both normal and pathological phonation, and of equally high clinical interest to both laryngologists and voice therapists.

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