Aerodynamic and Glottographic Studies of the Laryngeal Vibratory Cycle

Kitzing, Peter; Carlborg, Björn; Löfqvist, Anders

Published in:
Folia Phoniatrica

1982

Folia Phoniatrica

Editor: E. Loebell, Hannover

Publishers: S. Karger, Basel
Reprint (Printed in Switzerland)

Folia phoniat. *34:* 216–224 (1982)

Aerodynamic and Glottographic Studies of the Laryngeal Vibratory Cycle[1]

Peter Kitzing, Björn Carlborg, Anders Löfqvist

University Departments of Otolaryngology, Phoniatrics and Experimental Research, Malmö General Hospital, Malmö Sweden; Department of Phonetics, Lund University, Lund, Sweden

Introduction

During the last years, several computer-implemented models of the voice source have been developed and used as research tools for studying the phonation process and the laryngeal vibrations [*Ishizaka and Flanagan,* 1972; *Flanagan* et al., 1975; *Titze and Talkin,* 1979; *Fant,* 1979, 1980]. These models can be used for investigations and simulations of laryngeal vibrations under both normal and pathological conditions [*Ishizaka and Isshiki,* 1976]. Further development and refinement of such models require better and more complete knowledge of both the properties of the vocal fold tissues and the aerodynamic forces interacting with the myoelastic forces during each vibratory cycle of the glottis. The work reported here is concerned with the second of these aspects, i.e., measurements of pressure variations below and above the vocal folds during individual vibratory cycles.

In an earlier paper [*Kitzing and Löfqvist,* 1975], we presented some preliminary findings on transglottal pressure variations using a miniature transducer system. Since pressure recordings in themselves are ambiguous as to the temporal relationship between aerodynamic events and different phases of the glottal cycle, they should be supplemented with information on glottal vibratory movements. The aim of the present paper is to describe variations in subglottal pressure during single vibratory cycles of the glottis in relation to laryngeal vibratory movements recorded by simultaneous transillumination and electrical glottography.

Method

Subglottal air pressure was recorded with a microtip pressure transducer, Millar Instruments PC 350 5F, fitted into a Dacron catheter with an outer diameter of 1.67 mm. The frequency response of the transducer was DC-2 kHz, with a pressure range of −300 to +400 mm Hg, a sensitivity of 1.2–5 mV/V/100 mm Hg, and a combined linearity and hysteresis of ± 1.5 mm Hg of full scale. The output from the transducer was amplified through a custom-built amplifier and recorded on an FM tape recorder. An electrical calibration signal, tested against a water manometer, was used for calibration; calibration was made with the transducer in place and the subject holding his breath with an open glottis. During and after the recording session, the stability of the recording system was checked and any baseline shifts noted and corrected.

[1] This work was supported in part by a grant from the Wallenberg Foundation.

Before transducer insertion, topical anesthesia was applied to the pharyngeal and laryngeal mucosa. First, the subject gargled with 4% Xylocaine solution and was instructed not to swallow any of the liquid; second, the mucosa was sprayed with 1% Xylocaine; third, 1–2 ml 4% Xylocaine solution was applied on the glottis with a larynx syringe while the subject was producing a steady phonation as long as possible. The transducer was then inserted through the nose and passed through the glottis under indirect laryngoscopy. The catheter was positioned in the posterior commissure, with the transducer about 2 cm below the vocal folds.

Variations in glottal opening and electrical impedance across the glottis were recorded simultaneously using a system described elsewhere [*Kitzing,* 1977]. Briefly, light from a cold light fountain was directed to the surface of the neck at the cricothyroid membrane through a flexible fiberoptics bundle. A phototransistor, placed in a small catheter, was introduced through the nose and placed at the level of the uvula. The light modulated by the vibrating glottis was sensed by the transistor and recorded together with the output from an electroglottograph on separate channels of the FM recorder. Conventional acoustic recordings were also made through a close caption microphone. For processing, the signals were played back at reduced speed on an ink writer.

A male with a normal larynx and no known history of voice disorders served as the subject and produced various types of phonatory patterns.

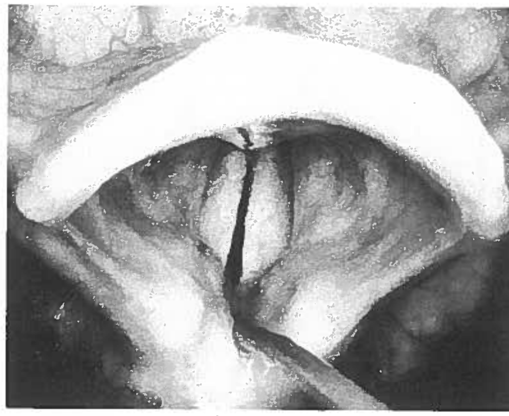

Fig. 1. Photograph showing the placement of the catheter in the posterior commissure during phonation in comfortable chest register. Picture taken during open phase of the vibratory cycle. Exposure time 1/400 s.

Results and Discussion

The pressure recordings required anesthetization of the laryngeal mucosa and the introduction of a catheter through the glottis, both of which may affect the phonation process. As shown in figure 1, the catheter was positioned in the posterior commissure between the arytenoid cartilages. Thus, it did not interfere with vibrations of the membraneous part of the glottis, nor did it prevent a complete glottal closure.

Application of surface anesthesia affects the sensory innervation of the larynx. It is well known that there is a rich supply of different types of sensory receptors in the larynx [*Wyke,* 1967, 1974], although their role in phonation is largely unknown. Investigations of the effects of anesthetization of the laryngeal mucosa or sensory laryngeal nerves [*Gould and Okamura,* 1974; *Gould and Tanabe,* 1975; *Mallard* et al., 1978; *Leonard and Ringel,* 1979; *Sorensen* et al., 1980] generally report small changes in airflow, vocal jitter, or in subjects' ability to follow frequency-modulated tones. In the present case, the only noticeable effect of the experimental procedure was a slight reduction in fundamental frequency after anesthetization and transducer placement. Mean fundamental frequency during reading of a short passage of running text, recorded by a procedure described in *Kitzing* [1979], decreased from 114 to 104 Hz. No breathiness or hoarseness was observed, as illustrated by spectrograms in figure 2. This figure also includes spectral analysis of an organically hoarse voice for purposes of comparison.

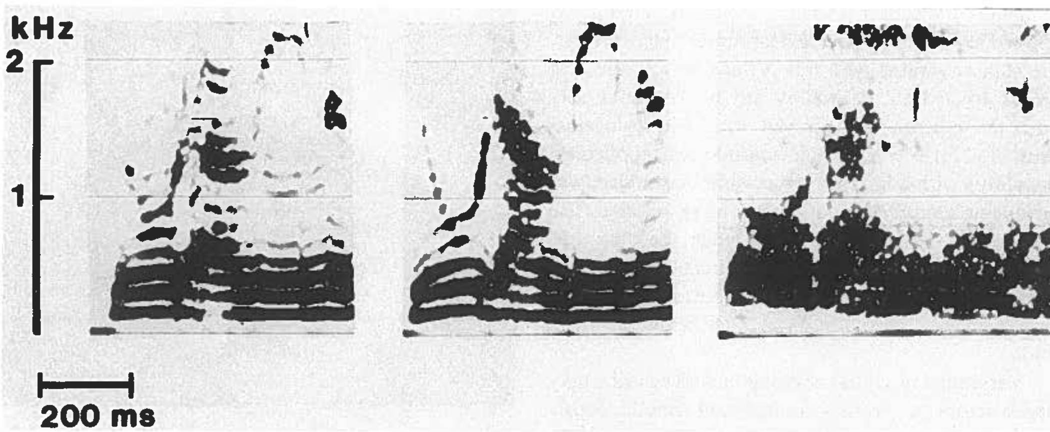

Fig. 2. Narrow-band spectrograms of the utterance 'Nordanvinden'. The left and middle panels show productions of the experimental subject before and after anesthetization and transducer placement, respectively. The right panel presents analysis of a production by a male speaker with organic hoarseness. Note, in particular, absence of noise components between harmonics in the left and middle panels, and the presence of such components in the hoarse voice.

Figure 3 displays records obtained during steady phonation of two different vowels. In the photoglottogram, glottal opening is displayed upwards. This is also true for the electroglottogram, where the onset of glottal closure is defined by a sharp negative drop in the signal. The identification of this point is easy and reliable. It corresponds in time with the point at which the transillumination signal returns to the baseline indicating glottal closure. The point of glottal closure is also related to the main excitation of the vocal tract resonances. In figure 3, a delay of 0.62 ms is found between onset of glottal closure and excitation of the vocal tract as shown in the audio signal. Assuming a speed of sound of 340 m/s, this delay corresponds to a distance of 21 cm, i.e., the distance from the glottis to the microphone in front of the mouth.

From the photoglottogram, the duration of the open and closed portions of the glottal vibratory cycle can be measured. The open quotient is conventionally defined as the ratio between the open portion and the total period time. For the phonations shown in figure 3, the open quotient is 0.5 in both cases

The pressure below the glottis varies as a function of glottal opening. That is, it has a maximum after glottal closure and a minimum shortly after the occurrence of peak glottal opening. Overlaid on this pattern are smaller pressure variations most likely related to resonances of the subglottal system.

For the two vowels presented in figure 3, the open quotient and the fundamental frequency (140 Hz) are identical. The maximum subglottal pressure during each vibratory cycle is also the same, 14.5 cm H_2O. There is, however, a small but consistent difference between the two vowels in the minimum pressure during the cycle, 9.5 and 8.8 cm H_2O for /e/ and /a/, respectively. This difference may be related to differences in supralaryngeal impedance due to the vocal tract resonances associated with the two vowel articulations. It is only seen when the glottis is open during the cycle

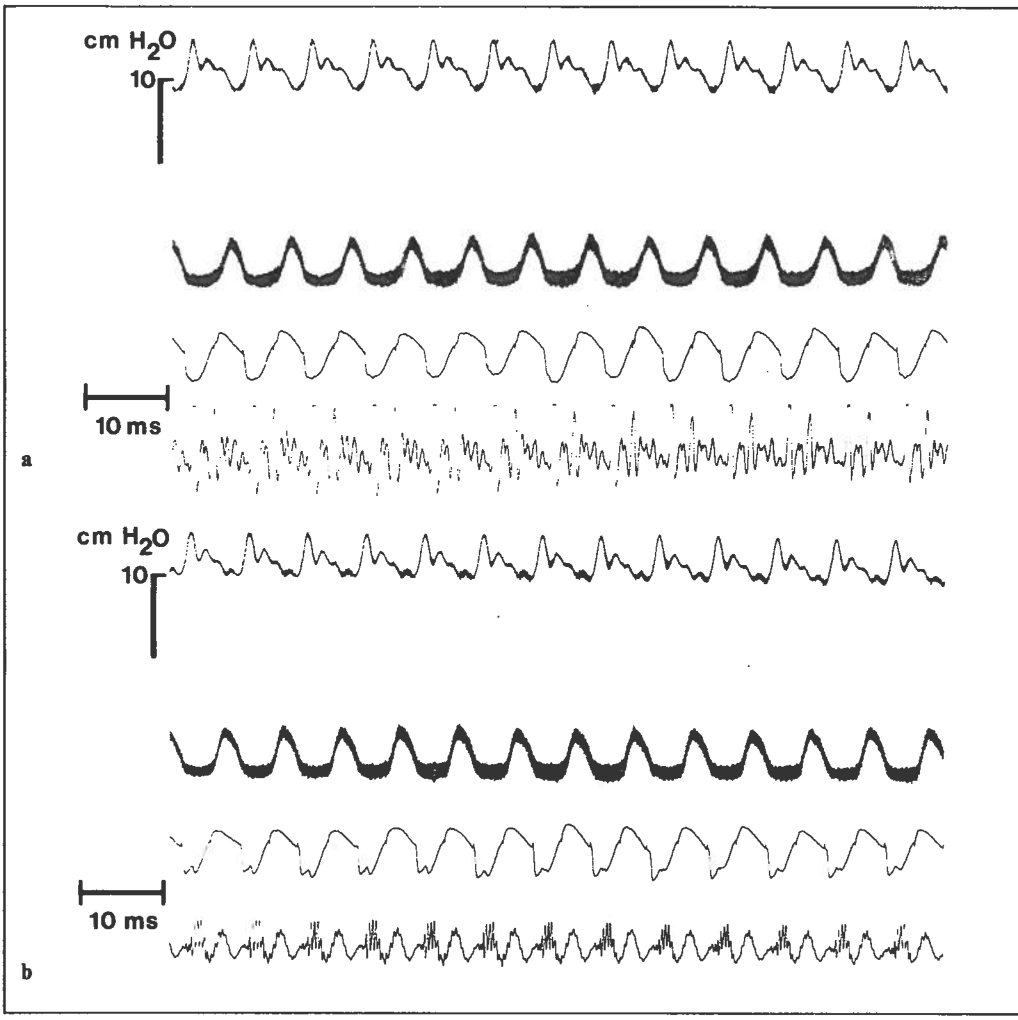

Fig. 3. Registrations of sustained phonation of two different vowels, /a/ (**a**) and /e/ (**b**). The signals represent, from top to bottom in each record, subglottal pressure, photoglottogram, electroglottogram, and audio signal. Glottal opening is displayed upwards in both the photo- and electroglottogram.

and the greatest amount of coupling occurs between the sub- and supraglottal systems. This problem will be taken up in more detail in subsequent publications.

Two different types of phonation are shown in figure 4, breathy voice and creaky voice. In both cases, phonation was made during articulation of the vowel /e/. The most salient difference between the two conditions is seen in the open quotient. It is 0.79 and 0.35, respectively, for breathy and creaky voice. Fundamental frequency is also different, 159 and 90 Hz, with breathiness showing the higher value. Mean subglottal pressure is

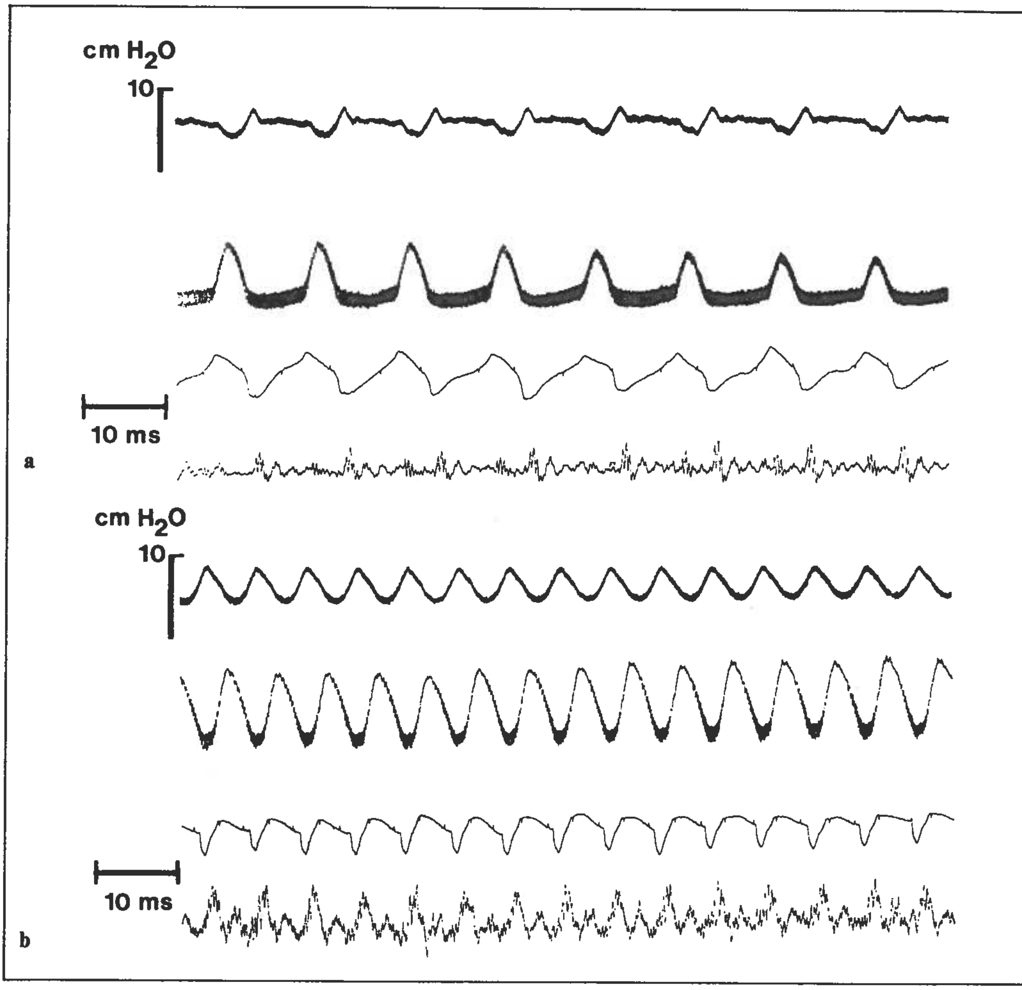

Fig. 4. Registrations of creaky voice (**a**) and breathy voice (**b**). Signals as in figure 3.

about the same, 6.3 and 6.6 cm H_2O. The pressure variations follow the changes in glottal opening rather closely in both cases. For creaky voice, in particular, pressure decreases and increases rapidly during the opening and closing movements of the glottis, and then stays level during the closed portion of the cycle. A short lag, about 0.5–1 ms, is found between the vibratory movements and the accompanying pressure variations.

Variations in phonatory patterns somewhat similar to those just discussed are shown in figure 5, presenting aerodynamic and glottographic records during hard and breathy attacks. Generally, the differences between the two types of attack are due to different patterns of coordination of respiratory and laryngeal adjustments. In the hard attack, the glottis is firmly closed during the buildup of subglottal pressure. This tight

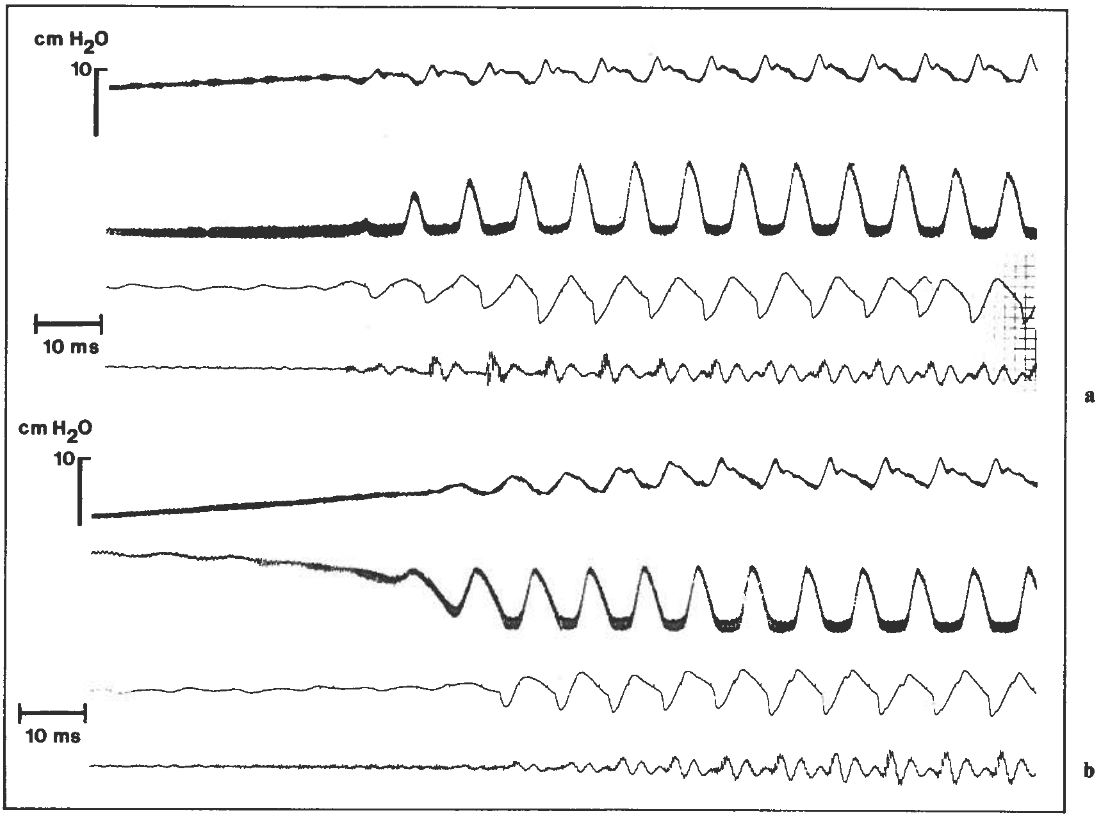

Fig. 5. Registrations of hard (**a**) and breathy (**b**) attacks.

glottal closure, brought about by increased activity in laryngeal adductor muscles, notably the lateral cricoarytenoid [*Hirose and Gay,* 1973], is then released and the folds blown apart. The transition from the tight glottal closure immediately before phonatory onset and during the first glottal cycles is evidenced by the upward shift in the baseline of the photoglottogram indicating glottal closure.

In the breathy attack, expiration precedes glottal adduction and the folds are brought together against an egressive airflow. Vibrations start with an inward movement of the folds.

Subglottal pressure is higher at onset of vibrations for the hard attack, 8.3 cm H_2O compared with 6.2 cm for the breathy attack. Fundamental frequency at onset of phonation is almost identical in the two conditions, 121 and 124 Hz, whereas the open quotient is higher for the breathy than for the hard attack, 0.67 and 0.46, respectively. In both cases, about five vibratory cycles are required for the glottis to reach a stable mode of vibration. The differences in laryngeal and respiratory adjustments before and during vocal initiation between the two types of attack cause higher airflow rate for the breathy attack [*Koike* et al., 1967].

Control of fundamental frequency of phonation involves changes in the length, tension, and mass of the vocal folds. These changes are controlled by the intrinsic laryngeal muscles, in particular the cricothyroid and the vocalis. Extrinsic muscles of the larynx may assist in pitch control, although their role is not very well understood at present. In general, the activity of the cricothyroid and the vocalis show a positive correlation with fundamental frequency, at least in the chest register. A register shift from chest to falsetto is usually accompanied by a reduction in vocalis activity [*Hirano* et al., 1970]

Figure 6 shows the aerodynamic and vibratory changes associated with register shifts on rising and falling pitch. In the upward shift, fundamental frequency is 162 Hz on the extreme left of figure 6, increasing to 190 Hz just before the shift. Over three glottal cycles the pitch then rises to 249 Hz and continues to increase, being 270 Hz on the extreme right of the figure. During the same time, the open quotient changes from 0.65 to 0.83. Subglottal pressure does not change appreciably with the register shift, and stays at 13.9 cm H_2O. The only salient quantitative difference is found in the minimum pressure during each cycle, which increases from 11.2 to 12.3 cm H_2O during the shift. The reason behind this change may possibly be related to a smaller glottal opening in falsetto phonation. At the same time, the pressure wavefrom also changes. Although it is premature to discuss these changes in detail, one could argue that they are related to changes in the vertical position of the larynx accompanying the pitch changes. Variations in the vertical position of the larynx would change the resonances of the subglottal system. On the assumption that the glottal opening decreases in falsetto, one might also argue that this leads to a smaller amount of coupling between the supra- and subglottal system.

The register shift made on a descending pitch is more abrupt in the present case (fig. 6). The pitch drops from 249 to 175 Hz at the transition, and the corresponding change in the open quotient is from 0.85 to 0.62. Again, the most conspicuous change in the pressure below the glottis concerns the minimum pressure during the vibratory cycle, which decreases from 13.9 to 12.6 cm H_2O, whereas the mean pressure is constant at 14 cm H_2O. In this respect, then, the effects of the register shift are identical in the two cases illustrated in figure 6, and are also consistent with measurements of other cases of register shifts. We should also note that the quite drastic change in the mode of glottal vibrations during the register shift occurs over three to four vibratory cycles.

Finally, figure 7 presents recordings during a termination of phonation. Mean subglottal pressure is 8.2 cm H_2O on the left in the figure, falling to 2.1 cm H_2O at the end of phonation. The fundamental frequency is 112 Hz. The rising baseline of the photoglottogram indicates that the glottal opening increases successively towards the end. At the same time, the vocal folds continue to make contact even though they are being abducted. This is most clearly shown in the electroglottogram. This pattern is most likely due to the fact that the membraneous part of the glottis continues to vibrate while the opening in the posterior portion is being made by the arytenoids moving apart. At the very end, the modulation of the light passing through the glottis and visible in the photoglottogram is probably caused by vibrations of the edges of the folds. Here, no contact occurs between the folds, as indicated by the disappearance of the electroglottographic signal.

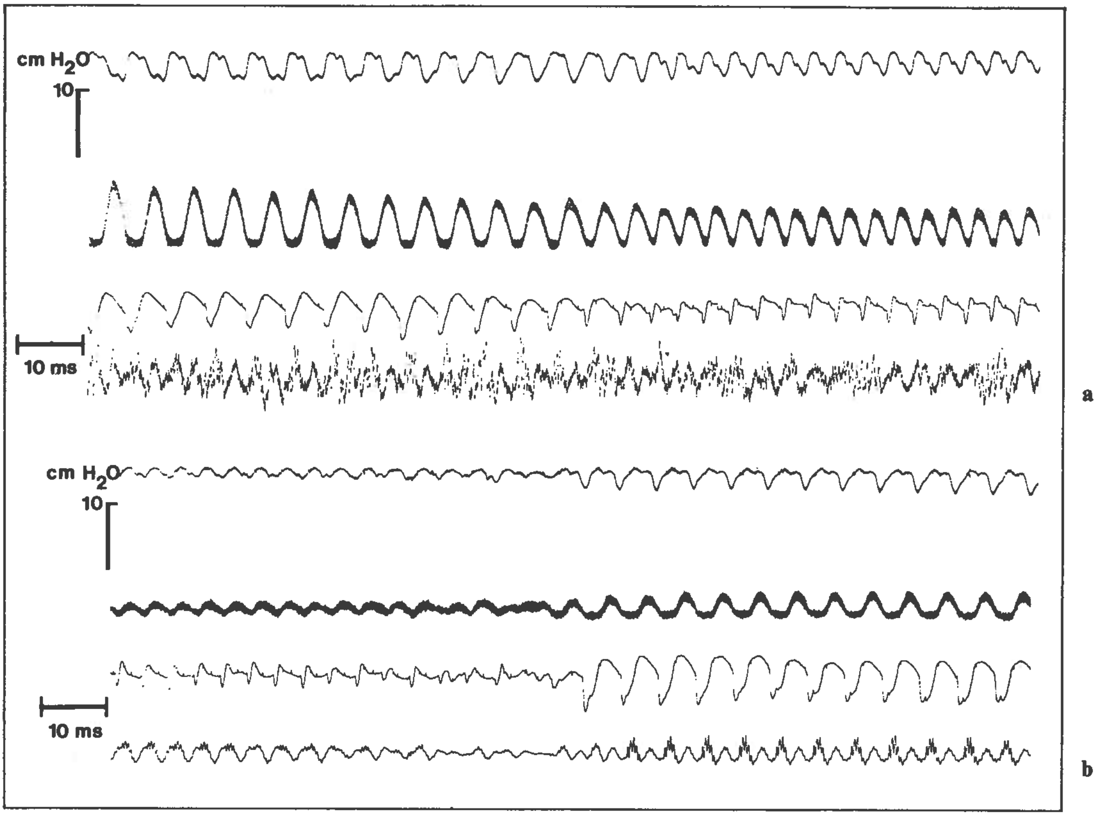

Fig. 6. Registrations of register shifts (voice breaks). **a** Transition from chest to falsetto on rising pitch. **b** Transition from falsetto to chest on descending pitch.

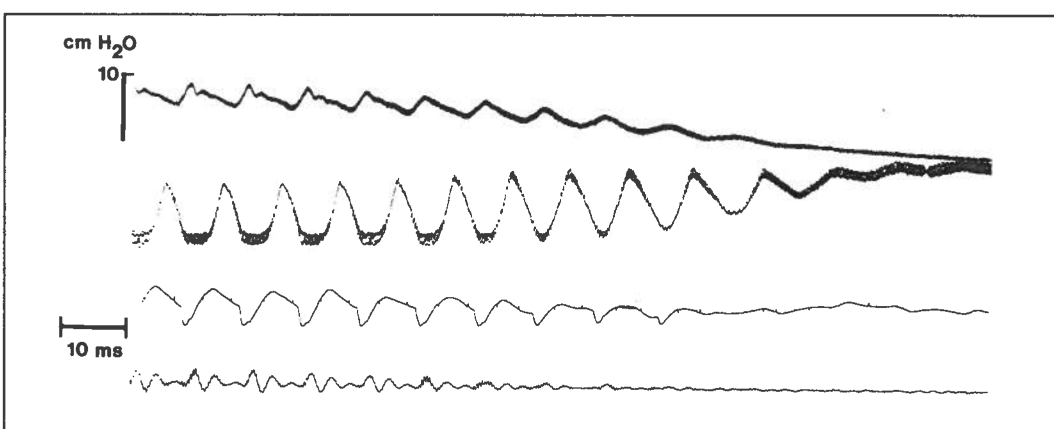

Fig. 7. Registration of termination of phonation.

Zusammenfassung

Diese Arbeit beschreibt simultane aerodynamische und glottographische Registrierungen von Phonationsprozessen. Ein Miniaturtransducer wird in die Glottis eingeführt, um den subglottalen Druck zu messen. Die Stimmlippenschwingungen werden simultan durch elektrische und photoelektrische Glottographie registriert. Diese experimentelle Methode verhindert die normale Phonation nicht; sie verursacht auch keine Heiserkeit. Registrierungen von verschiedenen Phonationstypen, wie Frequenz und Intensitätsvariationen, Stimmeinsätzen und Umkippen der Stimme werden diskutiert.

Résumé

Dans ce rapport, des enregistrements aérodynamiques et glottographiques simultanés de la phonation sont présentés. Pour enregistrer la pression d'air sous-glottique un transducteur de pression miniaturisé a été introduit dans la glotte. Les mouvements vibratoires de la glotte ont été enregistrés simultanément par glottographie électrique et photoélectrique. Ce procédé n'a pas provoqué de distorsion sérieuse de la phonation normale. En particuler, il n'a pas causé de raucité. Des enregistrements obtenus pendant des activités phonatoires différentes telles que des variations de qualité, d'attaque et de registre sont discutés.

References

Fant, G.: Glottal source and excitation analysis. Q. Prog. Status Rep., Speech Transm. Lab., R. Inst. Technol., Stockh., No. 1, pp. 85–107 (1979).

Fant, G.: Voice source dynamics. Q. Prog. Status Rep., Speech Transm. Lab., R. Inst. Technol., Stockh., No. 2/3, pp. 17–37 (1980).

Flanagan, J.L.; Ishizaka, K.; Shipley, K.L.: Synthesis of speech from a dynamic model of the vocal cords and vocal tract. Bell Syst. tech. J. *54:* 485–506 (1975).

Gould, W.; Okamura, H.: Interrelationships between voice and laryngeal mucosal reflexes; in Wyke, Ventilatory and phonatory control systems, pp. 347–358 (Oxford University Press, London 1974).

Gould, W.; Tanabe, M.: The effect of anesthesia of the internal branch of the superior laryngeal nerve upon phonation: an aerodynamic study. Folia phoniat. *27:* 337–349 (1975).

Hirano, M.; Vennard, W.; Ohala, J.: Regulation of register, pitch and intensity of voice. Folia phoniat. *22:* 1–20 (1970).

Hirose, H.; Gay, T.: Laryngeal control in vocal attack: an electromyographic study. Folia phoniat. *25:* 203–213 (1973).

Ishizaka, K.; Flanagan, J.L.: Synthesis of voiced sounds from a two-mass model of the vocal cords. Bell Syst. tech. J. *51:* 1233–1268 (1972).

Ishizaka, K.; Isshiki, N.: Computer simulation of pathological vocal-cord vibration. J. acoust. Soc. Am. *60:* 1193–1198 (1976).

Kitzing, P.: Methode zur kombinierten photo- und elektroglottographischen Registrierung von Stimmlippenschwingungen. Folia phoniat. *29:* 249–260 (1977).

Kitzing, P.: Glottografisk frekvensindikering; diss. Lund University (1979).

Kitzing, P.; Lögqvist, A.: Subglottal and oral air pressures during phonation: preliminary investigation using a miniature transducer system. Med. biol. Engng *13:* 644–648 (1975).

Koike, Y.; Hirano, M.; Leden, H. von: Vocal initiation: acoustic and aerodynamic investigation of normal subjects. Folia phoniat. *19:* 173–182 (1967).

Leonard, R.J.; Ringel, R.L.: Vocal shadowing under conditions of normal and altered laryngeal sensation. J. Speech Hear. Res. *22:* 794–817 (1979).

Mallard, A.R.; Ringel, R.L.; Horii, Y.: Sensory contributions to control of fundamental frequency of phonation. Folia phoniat. *30:* 199–213 (1978).

Sorensen, D.; Horii, Y.; Leonard, R.J.: Effects of laryngeal topical anesthesia on voice fundamental frequency perturbation. J. Speech Hear. Res. *23:* 274–283 (1980).

Titze, I.R.; Talkin, D.T.: A theoretical study of the effects of various laryngeal configurations on the acoustics of phonation. J. acoust. Soc. Am. *66:* 60–74 (1979).

Wyke, B.: Recent advances in the neurology of phonation. Br. J. Disord. Commun. *2:* 2–14 (1967).

Wyke, B.: Ventilatory and phonatory control systems (Oxford University Press, London 1974).

Received: September 9. 1981
Accepted: October 15, 1981

Peter Kitzing, MD, Department of Phoniatrics, University ENT Clinic, Malmö General Hospital, S–214 01 Malmö (Sweden)