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Abstract

Phonation requires a suitable balance between aerodynamic and myodynamic forces. The former include the pressure drop across the glottis and the transglottal air flow; among the latter are the tension and mass of the vocal folds. The present paper reviews some aspects of aerodynamic and myodynamic phonatory control mechanisms. In particular, we discuss variations in transglottal pressure associated with the control of speech prosody and the rapid fluctuations that occur during individual vibratory cycles of the glottis. We also discuss onsets and offsets of phonation and show how variations in the voice source at these transitions result in different source spectra. Finally, we exemplify transitions between different voice registers and the vibratory and aerodynamic changes associated with them.

AERODYNAMIC ASPECTS OF PHONATION

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1. INTRODUCTION

Phonation requires a pressure drop across the glottis and a resulting transglottal air flow. The aerodynamic forces combine with the myodynamic forces of the vocal folds in the control of phonation. The pressure drop across the glottis is controlled by active (muscular) and passive respiratory forces, whereas the myodynamic forces are controlled by the intrinsic and extrinsic muscles of the larynx (cf. Sonninen, 1968). In addition to these forces, recent theoretical and experimental work indicates that an acoustic coupling occurs between the source (the glottis) and the filter (the vocal tract). The magnitude and nature of this interaction is a matter of current debate (e. g. Rothenberg, 1981; Ananthapadmanabha & Fant, 1981). Another aspect of this interaction is the load imposed on the vibrating glottis due to fluctuations in the air pressure below and above the glottis during individual vibratory cycles.

The laryngeal control of phonation occurs principally along two dimensions. One involves the longitudinal tension of the vocal folds and is used for control of fundamental frequency. The other, frontal, dimension involves abduction and adduction of the vocal folds. This dimension is used to control voicing and aspiration as well as voice quality. Variations along the second dimension are found in many languages where voice quality has a linguistic function (cf. Henderson, 1977). They also occur as paralinguistic variations, since differences in voice quality between speakers, e. g., due to geographic and social factors, are often associated with differences along this dimension (cf. Laver, 1980). At the same time, this dimension can also be involved in pathological voice conditions such as excessive breathiness or creakiness.

The source characteristics of different types of phonation varying along the second dimension comprise the presence or absence of noise generation in the glottis, and also variations in the source spectrum. Similar variations are also found in normal running speech at the transitions between voiced and voiceless sounds and at onsets and offsets of phonation.

The aim of the present paper is to review some aspects of phonatory control and illustrate them with recordings of aerodynamic, vibratory, and acoustic parameters.

2.- METHOD

Pressure below and above the glottis were recorded with two different techniques. A hypodermic needle was passed through the crico-thyroid membrane and connected to a pressure transducer. Simultaneous records of oral pressure were obtained through a small catheter passed through the nose and connected to a transducer. With this technique, the frequency response of the recording system is limited to low frequencies due to the mass of air in the catheters connecting the subject to the pressure transducers.

In order to record the detailed characteristics of the pressure waveform, miniature transducers were used (cf. Kitzing & Löfqvist, 1975). One transducer was introduced through the nose and passed through the glottis under topical anesthesia of the laryngeal mucosa. The cable connecting the transducer to power supply and amplifier was positioned in the posterior commissure. Analysis of the voice under anesthesia and with the transducer in position revealed only small differences compared to normal conditions. For recording oral pressure, a second miniature transducer was placed in the pharynx above the glottis.

The output from the transducers was recorded on an FM tape recorder for subsequent processing.

Oral air flow was recorded with a pneumotach and a face mask covering the mouth and the nose of the subject. After amplification, the flow signal was recorded on another channel of the FM recorder.

Variations in glottal opening and electrical impedance across the glottis were recorded using a system described elsewhere (Kitzing, 1977). Briefly, light from a cold light source was directed to the surface of the neck at the crico-thyroid membrane through a flexible fiberoptics bundle. A phototransistor, placed in a small catheter, was introduced through the nose and placed about 3 cm above the glottis. The light modulated by the vibrating glottis was sensed by the transistor and recorded together with the output from an electro-glottograph on separate channels of the FM recorder. Conventional acoustic recordings were also made simultaneously. For processing, the signals were played back in an ink writer. Fundamental frequency was extracted using a hard-ware pitch extractor.

The subjects participating in the experiments all had a normal larynx and no known history of voice disorders.

3. RESULTS AND DISCUSSION

Figure 1 shows aerodynamic and acoustic records during the production of a Swedish declarative sentence without any extra heavy stress. In the record representing subglottal pressure, four kinds of variations can be seen. The pressure below the glottis shows an overall falling pattern with pressure being higher at the beginning than at the end of the utterance. This is the basic pattern found in normal declarative utterances. Overlaid on this pattern are local increases in subglottal pressure that occur on stressed syllables, i.e. /ba/ in "badade" and /is/ in "iskalla". This is

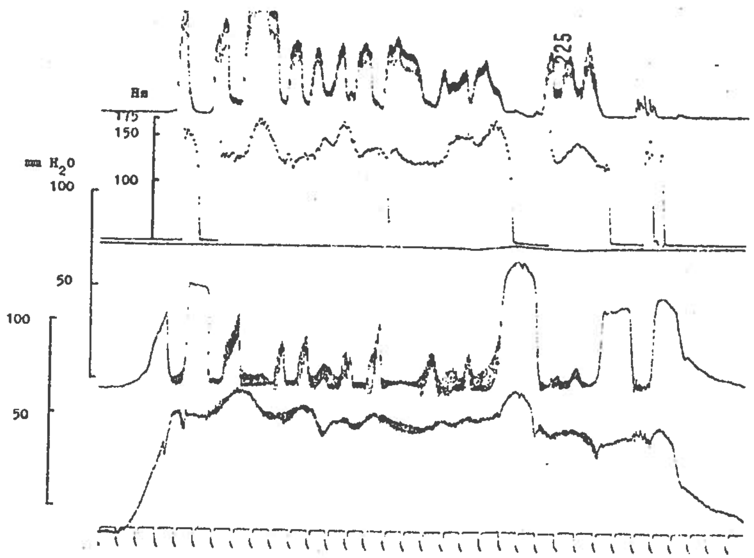

Figure 1. Record of the Swedish utterance "Pappa badade hela dagen i det iskalla vattnet". The curves represent from top to bottom, rectified and integrated audio signal, fundamental frequency, oral air pressure, subglottal air pressure, and time marker.

also a general finding: stressed syllables have an increased subglottal pressure. A third type of variation occurs at the release of stop consonants, where there is a local and rapid drop in subglottal pressure. This drop can be 10-20 % of the mean pressure (Löfqvist, 1975) and is due to a reduction in flow resistance in the larynx and vocal tract. Immediately after the release of the oral closure in voiceless aspirated stops, the glottis is open and also the passage in the the vocal tract. During this period of decreased upper air way resistance, a drop occurs in subglottal pressure.

Finally, we also see in Figure 1 rapid fluctuations in subglottal and oral pressure during individual vibratory cycles. These fluctuations are shown in more detail in Figure 2. This figure shows the pressure below and above the glottis as well as the variations in glottal opening recorded in

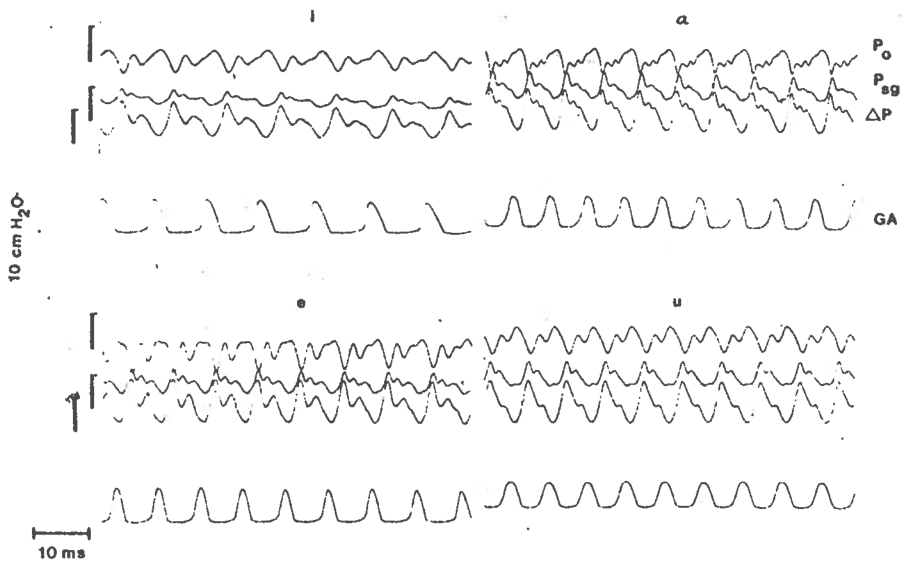

Figure 2. Aerodynamic and glottographic records of four different vowels: /i/ (top left), /ɑ/ (top right), /e/ (bottom left), and /u/ (bottom right). The curves within each panel represent from top to bottom, oral pressure, subglottal pressure, transglottal pressure (subglottal pressure minus oral pressure), and photoglottogram (glottal opening displayed upwards).

the photo-glottogram. The variations in subglottal pressure during one glottal cycle can amount to 50-60 % of the mean pressure, with pressure increasing during the closed phase of the cycle and decreasing during the open phase of the cycle. The lowest resonance of the trachea is also seen in the waveform with a frequency of about 600 Hz. Similar variations are also found in the pressure above the glottis. These variations have the opposite phase of the subglottal fluctuations, and the lowest resonance of the vocal tract is clearly visible in the waveform, differing for different vowels. No higher formants can be detected in this waveform, partly because the radiation effect of the lips is not found in the signal recorded in the pharynx. The radiation effect increases higher frequencies with a factor of 6 dB per octave.

The magnitude of these pressure variations is in accordance with theoretical calculations presented by Fant (1979a, b). These fluctuations would affect the pressure drop across the glottis and hence the air velocity

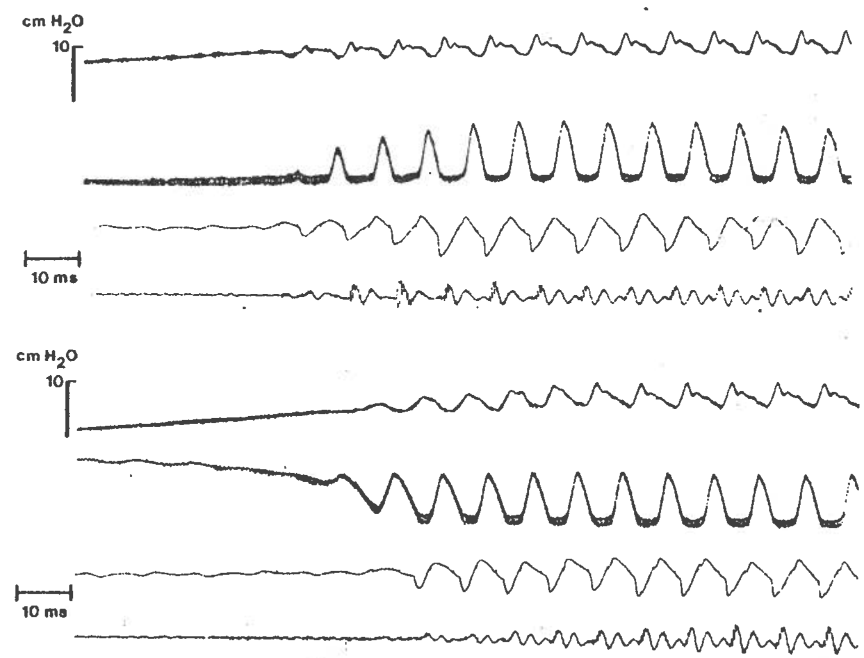

Figure 3. Records of hard attack (top) and breathy attack (bottom). The curves represent from top to bottom in each graph, subglottal pressure, photoglottogram, electroglottogram, and audio signal.

in the glottis. Since the velocity has an influence on the pressure in the glottis (the Bernoulli effect), the pressure variations could thus influence the magnitude of the Bernoulli effect. This would affect the vibratory pattern of the glottis and the glottal volume velocity waveform which could possibly result in different source spectra for different vowels. Further theoretical and empirical work is needed to clarify these phenomena and their consequences for the human voice.

Figure 3 shows the pressure below the glottis, glottograms and the acoustic signal for two different types of vocal attacks, breathy and hard. The main difference between the two types is due to different patterns of coordination between respiratory and laryngeal adjustments. In the breathy attack, expiration leads glottal adduction, and the vocal folds are adducted against an egressive air flow. During this transition, the amplitude of the acoustic signal will be rather small at the onset of voicing. Furthermore, the shape of the vibrations is characterized by a rather large open quotient indicating that the glottis is open during a large portion of the cycle.

In the hard attack, the folds are adducted before the increase in subglottal pressure and then blown apart by the increasing pressure. At the onset, the vibrations have a rather short open quotient and the amplitude of the sound increases rapidly.

A transition from voicing to no voicing is shown in Figure 4. The vibrations mirror those occurring in the breathy attack with the folds being abducted while a transglottal flow still occurs.

Different types of transitions from voicing to no voicing and from no voicing to voicing commonly occur in running speech. They occur, in

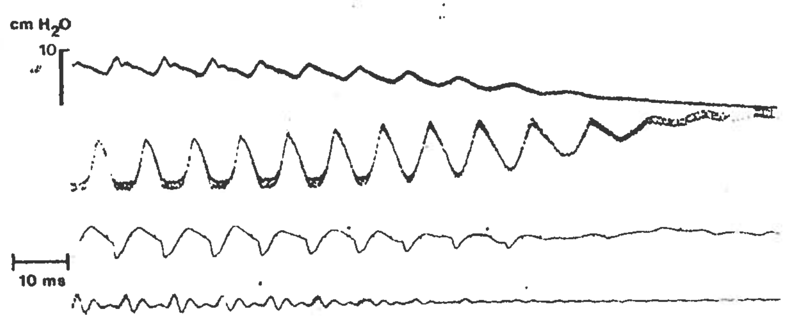

Figure 4. Record of offset of phonation. Curves as in Figure 3.

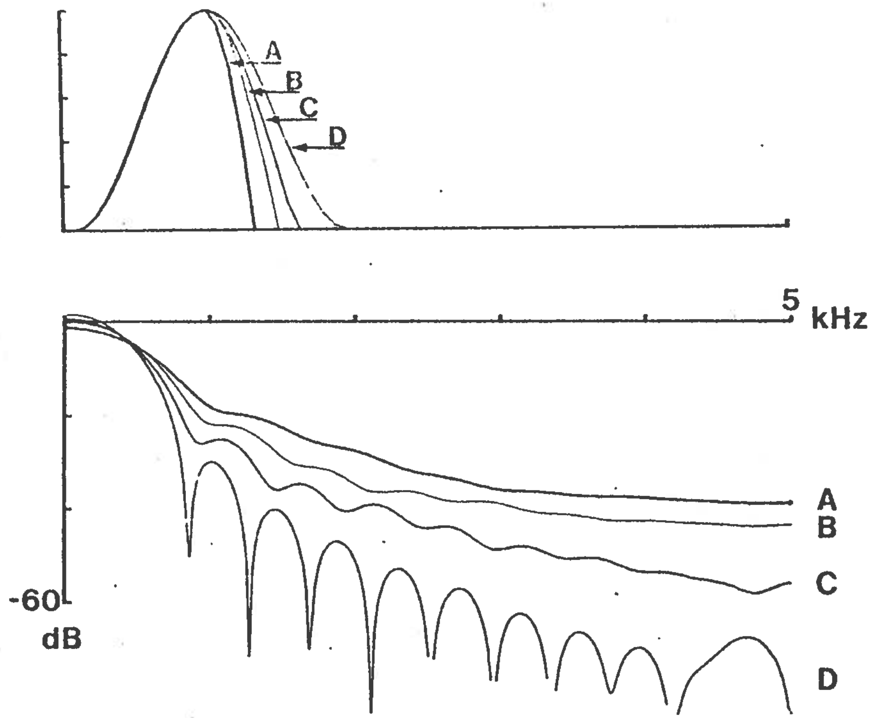

Figure 5. Different computed glottal waveforms and their associated spectra. See text for further discussion.

particular, for voiceless stops and fricatives where an abduction gesture of the glottis is made to stop vibrations and create favorable aerodynamic conditions for the transient and fricative noise source (cf. Löfqvist & Yoshioka, 1981). The changes in the glottal volume velocity waveform that occur at these transitions will affect the source spectrum. This is illustrated in Figure 5 using a computer simulation of the glottal volume velocity waveform adapted from Fant (1979a). The top graph shows different waveforms and their corresponding spectra are shown in the lower graph. The waveforms differ in the steepness of the trailing edge and thus in the sharpness of the discontinuity at the cessation of air flow at glottal closure. The most striking spectral difference occurs in the higher harmonics. Their level can differ as much as 30 dB. One practical implication of the source changes at transitions such as these concerns speech synthesis. One might improve the naturalness of synthetic speech by incorporating these source variations into the synthesis.

Different voice registers are used in the control of fundamental

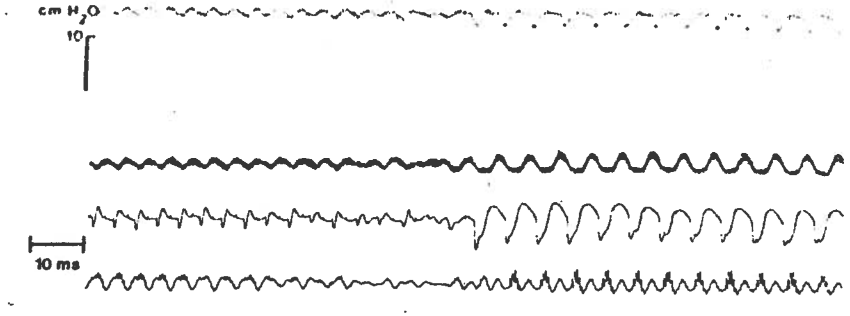

Figure 6. Record of register shift from falsetto to chest at descending pitch. Curves as in Figures 3 and 4.

frequency. A transition from falsetto to chest, or modal, register is shown in Figure 6. The most conspicuous change in the vibratory pattern of the folds concerns the very short duration of the closed phase in falsetto. Here, the glottis may never close completely during the vibratory cycle. At the transition, the open quotient is reduced rapidly, and as a further consequence of the change in the vibratory mode the amplitude of the higher harmonics increases; this is evident in the acoustic signal. The most direct physiological change associated with the register transition appears to be the activity of the vocalis muscle. This muscle is active in chest voice but has very reduced activity level in falsetto (Hirano, Vennard & Ohala, 1970).

Aerodynamic variations associated with a similar transition from falsetto to chest voice are illustrated in Figure 7. From the aerodynamic records, we see that air flow appears to be similar in falsetto and at high fundamental frequencies in chest voice. At the transition, air flow increases momentarily and then returns to the same level as before the transition. This increase at the transition is related to a decrease in the flow resistance of the vibrating glottis. This is shown in the top graph in Figure 7. The values of mean glottal resistance have been calculated by dividing the pressure drop across the glottis (subglottal pressure minus oral pressure) with the transglottal flow. The values plotted for this parameter show the mean resistance at selected instances during the register shift. Glottal resistance varies between 15 and 50 cm water/liter/second and is generally higher during falsetto than during chest voice. In chest voice, glottal resistance is proportional to the intensity level of the voice (Isshiki, 1964), whereas no such dependancy appears to exist in falsetto.

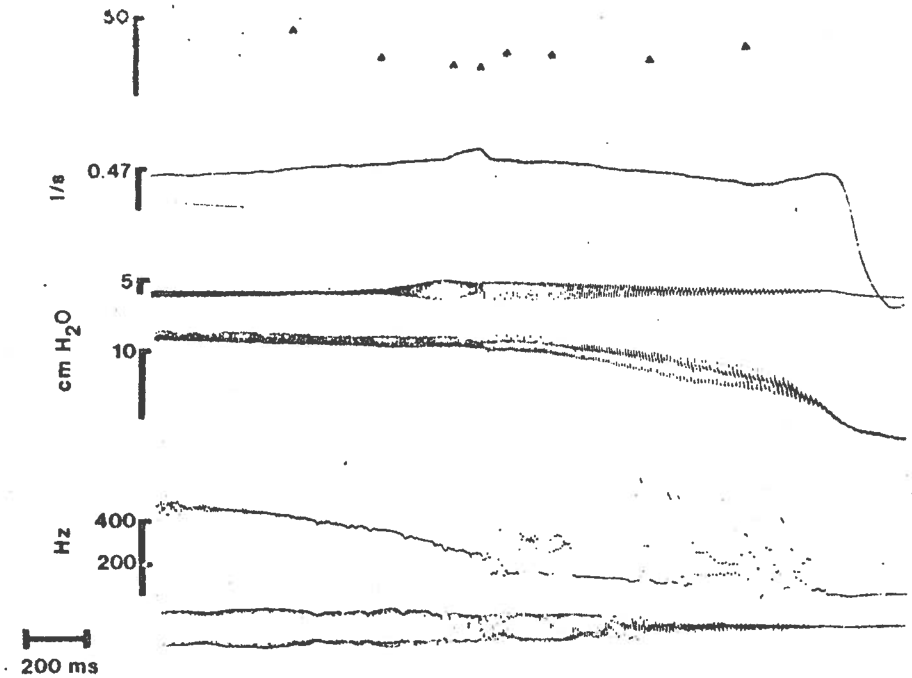

Figure 7. Acoustic and aerodynamic records of register shift from falsetto to chest. The curves represent from top to bottom, mean glottal resistance, oral air flow, oral air pressure, subglottal air pressure, fundamental frequency, and audio signal. See text for further discussion of glottal resistance.

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