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Inverse filtering as a tool in voice research and therapy

797

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This paper describes technical and practical aspects of inverse filtering applied to speech signals, with particular emphasis on the filtering of flow signals. Theoretical and practical methodological problems are discussed as well as the possibilites and limitations of the technique. Analysis of both sustained phonation and running speech is exemplified. Possible clinical applications are suggested.

Key words: inverse filtering, flow glottography, voice physiology, phonation.

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Introduction

The speech signal represents the product of the sound source and the vocal tract transfer function. This source-filter model is shown in Figure 1. This Figure also shows the signal in the time and frequency domains at different points during the production of vowel sounds where the source is the vibrating glottis. When the vocal folds are vibrating, the glottal area varies continuously between open and closed. In combination with a pressure drop across the glottis, the area variations result in a time-varying air flow through the glottis; this flow represents the glottal volume velocity waveform. The source consists of the fundamental and the higher harmonics. The spectral properties of the source depend on the glottal pulse.

The filter consists of the pharyngeal, oral, and nasal cavities. The speaker controls their acoustic properties by moving the tongue, the jaw, the lips and the velum. Finally, the radiation represents the load at the mouth; the acoustic effect of the radiation is that of a high-pass filter with a slope of +6 dB/octave.

Analysis of other source properties than fundamental frequency and overall amplitude requires some means of cancelling the effects of the filter, since it is technically difficult, and practically impossible, to make recordings of the source signal *in vivo*. One way of doing this is to make long-time averages of the output of the vocal tract (e. g., Löfqvist & Mandersson, 1987), where the effects of variations in the filter are averaged out. Another approach is to use a filter which has inverse properties of the vocal tract filter, i. e., an inverse filter.

The inverse filtering technique is based on the assumptions of the source-filter model, in particular that during the production of voiced vowels, sound is only generated in the glottis and the filter only changes the amplitude and the phase of the source components (see Fant, 1970, and Flanagan, 1972, for basic treatments of the source-filter theory). Although some of the assumptions underlying the source-filter model have been questioned (e. g., Kaiser, 1985; Teager & Teager, 1986, 1990; McGowan, 1988), in particular the idea that the only place of sound generation is in the glottis, the received view holds that any such effects are secondary.

Inverse filtering - Technical aspects

Inverse filtering of the speech signal can be performed on the acoustic signal or on the air flow through the mouth. If the acoustic signal is used, a microphone with a low-frequency response close to DC should be used for the recording and appropriate measures have to be taken to cancel noise and low-frequency pressure variations, e. g., those caused by the ventilation system. If a tape recording is made, an FM recorder should be used since it maintains the orginal phase relations of the signal; they are distorted on an ordinary tape recorder. When the analysis is made on the flow signal, the flow should be recorded with a system that has as wide a frequency response as possible. The system described by Rothenberg (1973) has an acceptable frequency response up to 1 kHz (cf., Badin, Hertegård & Karlsson, 1990) and is now widely in use.[1] The air flow is recorded through a face mask covered with a wire mesh that provides a linear flow resistance. The pressure drop

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[1] It is commercially available from Glottal Enterprises, 719 East Genesee Street, Syracuse, NY 13210, USA.

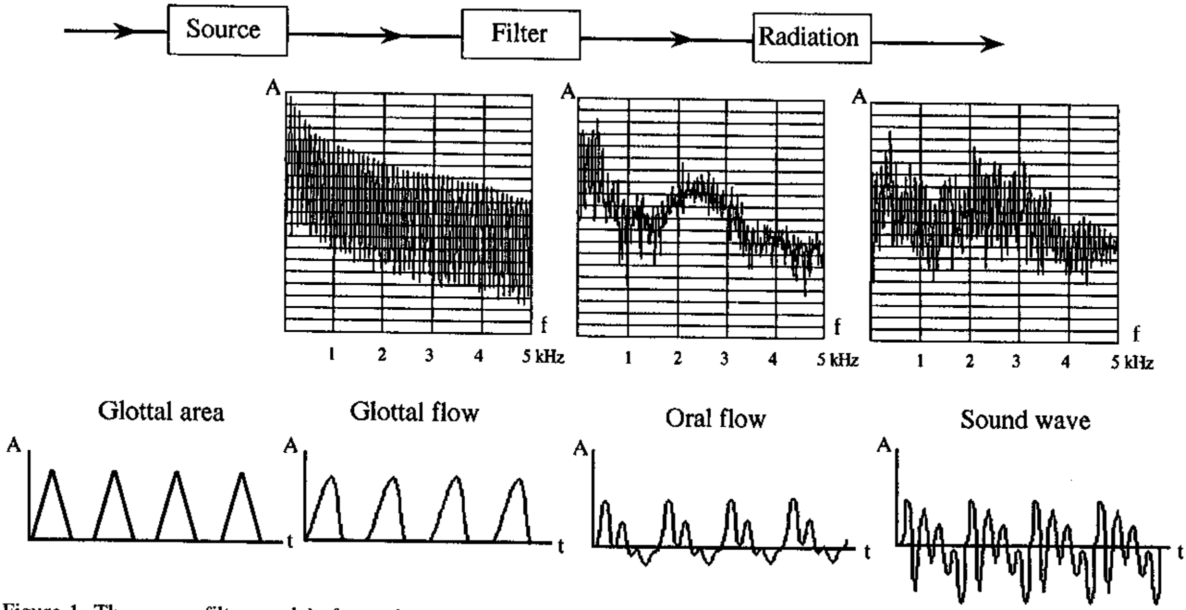


Figure 1. The source-filter model of speech.

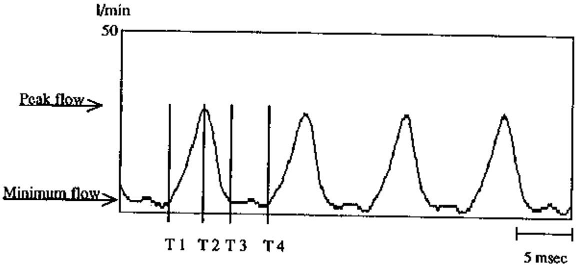
across the mesh is recorded using a differential pressure transducer and this pressure drop is proportional to the air flow through the mask. The use of the flow signal allows calibrated measurements of flow and also of measurements of the DC component of the flow, if present. At the same time, the bandwidth of the recording system for flow signals is considerably reduced compared to that for acoustic recordings (cf., Ananthapadmanabha, 1984 for a discussion). The following presentation will be limited to inverse filtering of flow signals.

The purpose of inverse filtering is to cancel the effects of the vocal tract transfer function and recover the glottal flow. This means filtering out the contributions of the formants and the radiation; if a mask is used to record air flow, the mask cancels the effects of the radiation. In practice, this is usually done on sustained phonations of vowel sounds. For the filtering to be effective, the fundamental and the first formant should be widely apart in frequency; thus, vowels with a high first formant such as [ɑ] and [æ] are most suitable. Given this requirement, it may sometimes be difficult to inverse filter female voices due to the higher fundamental frequency of the female voice.

The filtering may be peformed interactively using a hardware filter, where the frequency and bandwidth of the first and second formants are adjusted until the output signal, displayed on an oscilloscope, is free from ripples due to the formants. A real-time spectrum analyzer allows simultaneous monitoring of the derived source spectrum and may be useful.

Alternatively, the signal may be digitized, stored on disk and the filtering performed interactivly on a computer using a software filter (e. g., Javkin, Antoñanzas-Barroso & Maddieson, 1987). In the latter case, spectral analysis of the signal helps in selecting the appropriate values for formant frequencies and bandwidths. Since the "true" glottal flow is unknown, some kind of criterion has to be applied to decide when the "correct" result is obtained. The minimum ripple criterion mentioned above is commonly used in combination with a horisontal signal during the closed phase. Variations during the closed phase may, however, be due to the compliance of the vocal tracts walls, since the acoustic model assumes rigid walls (cf., Milenkovic & Mo, 1989).

Analysis of running speech presents some special problems. If only a limited material is to be analyzed, the analysis can be performed interactively on a period by period basis (e. g., Gobl, 1988; Gobl & Ní Chasaide, 1988). If, however, one is interested in collecting large amounts of data, this procedure can be prohibitively time consuming. Therefore, Löfqvist & McGowan (in press) resorted to a different procedure. They used reiterant speech, i. e., speech where the normal segments are replaced with reduplicated CV syllables; the vowel was always [ɑ]. A hardware inverse filter was set at a constant setting during the recording session to cancel the formants during the steady state portion of the vowel. This left traces of the first and second formants in the filtered signal. In order to remove the remaining effects of the formants, the signal was digitally low-pass filtered with a linear phase low pass filter after sampling at a suitable rate. This additional filtering effectively removed all but the first four or five harmonics in the signal. Since one is thus dealing with a heavily low-pass filtered signal, care is needed in choosing the appropriate measurements.



AC flow = Peak flow - Minimum flow

Open quotient = (T3 - T1) / (T4 - T1)

Speed quotient = (T2-T1) / (T3-T2)

Figure 2. Four glottal pulses obtained by inverse-filtering. The events marked in the first cycle correspond to the rise in flow at the instant of glottal opening (T1 and T4), peak flow (T2), and offset of flow at glottal closure (T3). In addition to peak flow and minimum flow, the calculation of the AC flow, the Open quotient, and the Speed quotient are also shown.

Figure 2 shows an example of an inverse-filtered flow signal as well as some measures commonly applied. Peak flow and minimum flow represent the maximum and minimum flow during each pulse, respectively. While one might expect minimum flow to be zero for normal voices, this is not necessarily the case. A non-zero minimum flow might represent a constant, or DC, flow due to an incomplete closure of the glottis. The modulated flow, the AC component, is the difference between the peak flow and the minimum flow. The Open quotient represents the ratio of the open part of the cycle to the period time; an Open quotient of 1 indicates that the glottis is never completely closed. The Speed quotient shows the durational relationship between the rising and falling parts of the pulse. A Speed quotient of 1 indicates that they are of equal duration. When the Speed quotient is less than 1, the pulse is skewed to the left, whereas a Speed quotient greater than 1 indicates a skewing to the right.

The Open quotient and its relation to minimum flow merits some further discussion. It would seem that an Open quotient less than one is difficult to reconcile with a minimum flow greater than zero. Such a situation often occurs, however. There are several reasons for this. First, it is not clear that a constant DC flow during the "closed" phase is, in fact, caused by an incomplete glottal closure. Barring experimental error, other factors may cause such a pattern. Air remaining in the upper and middle part of the glottis after the lower margins of the folds have made contact will be expelled. The movements of the vocal folds also contain a vertical component that may induce air flow (e. g., Baer, 1981; Saito, Fukuda, Kitahara, Isogai, Tsuzuki, Muta, Takayama, Fujioka, Kokawa & Makino, 1985). Vertical movements of the larynx as well as movements of other articulators can also generate air flows (e. g., Barry and Kuenzel, 1975). Hence, it would seem unwise to draw conclusions about incomplete glottal closure from records of air flow. Such records should be supplemented with imaging techniques.

At the same time, there is accumulating evidence from studies making direct observations of the glottis that "normal" voices often do not have a complete glottal closure (e. g., Peppard, Bless, and Milenkovic, 1988; Biever and Bless, 1989; Bless, Biever, Campos, Glaze, and Peppard, 1989; Fex, Löfqvist, and Schalén, 1989; Södersten and Lindestad, 1990). This can take the form of either a constant opening in the posterior (cartilagineous) portion of the glottis or an incomplete closure in the anterior (membraneous) portion.

A further consequence of this is that measurements of the Open quotient using different measurement procedures may well give different results. For example, Childers and Krishnamurti (1985) provide an example (their Figure 6) of incomplete glottal closure, derived from high-speed films, where the Open quotient measured from the accompanying electroglottographic signal would be less than one (see also Childers, Hicks, Moore, Eskenazi, and Lalwani, 1990 for similar results). The reason is that as long as there are variations in vocal fold contact area, the electroglottographic signal will be modulated and the measured Open quotient less than 1, even though there may be no complete closure; for example, there may be a constant opening in the posterior part of the glottis while the anterior part is vibrating. This suggests that some caution is warranted in interpreting and comparing measures of the Open quotient obtained by different methods. Furthermore, if it is indeed the case that a complete glottal closure rarely occurs during phonation, the use of Open quotient in voice research would seem to be questionable. At least, its meaning has to be clarified.

Table I. Selected pulse parameters for the phonatory patterns shown in Figure 3; flow values are given in 1/sec.

	Modal	Hyperfunctional	Hypofunctional	Hyperfunctional+ breathy
Peak flow	0.27	0.2	0.36	0.42
Minimum flow	0.04	0.0	0.08	0.11
AC flow	0.23	0.2	0.28	0.31
Open quotient	0.65	0.55	0.75	0.75
Speed quotient	1.7	2.3	1.4	1.6

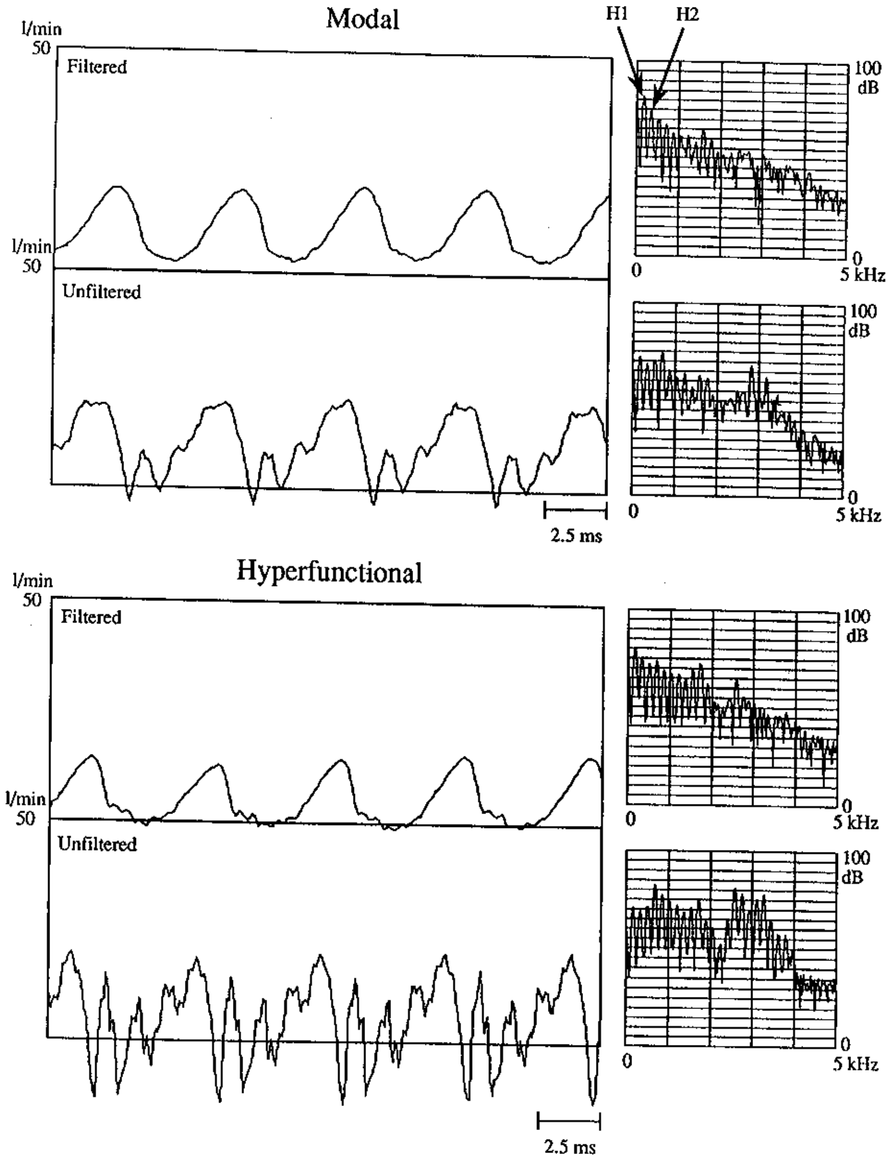


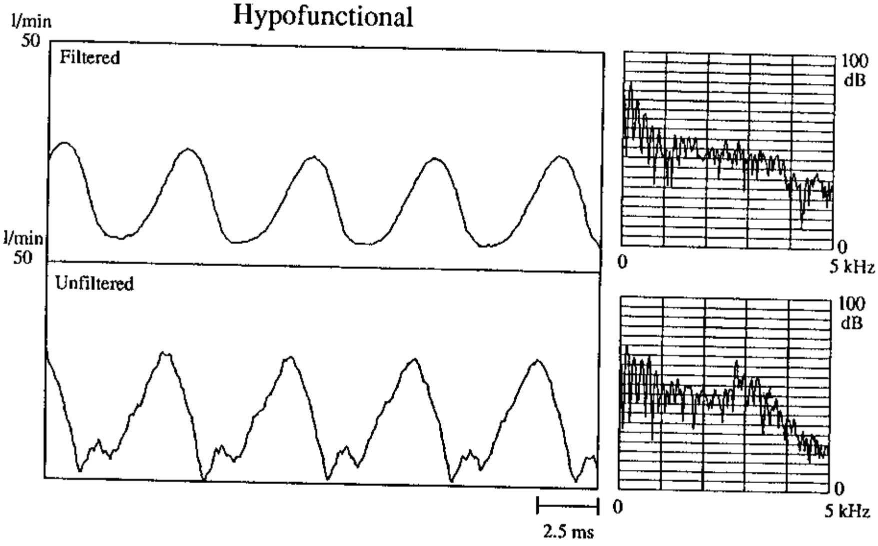
Figure 3 a,b. Inverse-filtered and unfiltered flow signals of four different phonatory patterns of a female voice: modal and hyperfunctional (a), hypofunctional and hypofunctional + breathy (b). Waveforms and spectra are shown.

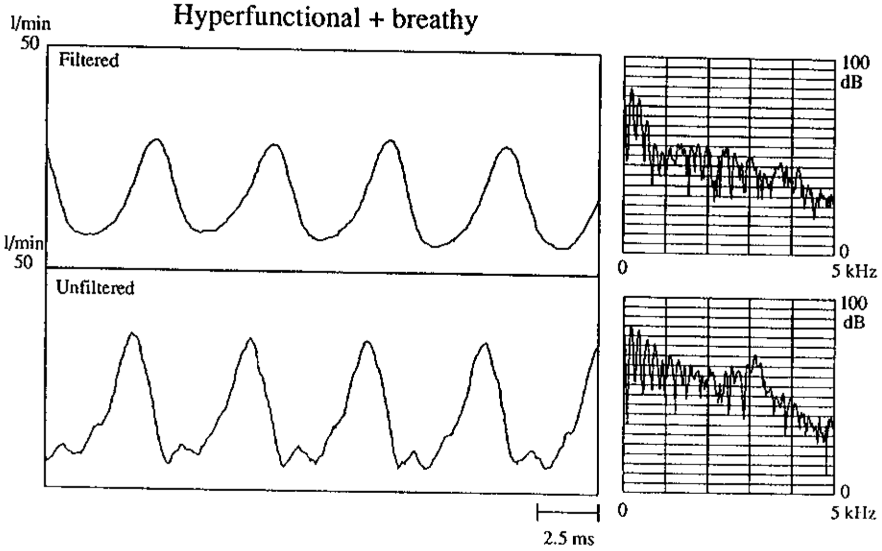
Inverse filtering - some examples

Sustained phonation

Figure 3 presents inverse filtered flow signals of different phonatory patterns in a female voice - modal, hyperfunctional, hypofunctional, and hyperfunctional + breathy; the speaker was instructed to focus on the phonatory pattern and no attempt was made to control fundamental frequency and intensity. For each mode of phonation, the waveform and spectrum of the filtered and unfiltered flow are shown. Pulse properties for these waveforms are listed in Table I.

Comparing these source pulses, we see differences between them that most likely can be rationalized by their associated muscular and myodynamic adjustments, in particular the degree of glottal adduction. Thus, hyperfunctional voice would have a higher degree of glottal adduction than modal voice. The higher degree of glottal adduction used in hyperfunctional voice would explain why this mode has lower values of peak, minimum, and AC flow as well as a smaller Open quotient and a larger Speed quotient compared to modal voice. Similarly, hypofunctional voice has a lower degree of glottal adduction than modal voice. This accounts for the higher values of peak flow, minimum flow, AC flow of the hypofunctional voice and also its higher Open quotient and lower Speed quotient compared to modal voice. In the hyperfunctional + breathy voice, we find the highest values of peak, minimum, and





AC flow. In this condition, we might expect the source to have strong aperiodic components due to turbulence created in the incompletely closed glottis.

These source properties determine the source spectrum, i. e., the quality of the produced sound (cf., Gauffin & Sundberg, 1989). One difference between the source spectra for the different modes of phonation that can be observed in Figure 3 is the tilt of the source spectrum, i. e., how rapidly the amplitude of the higher harmonics decreases. Conventionally, the tilt of the source spectrum has been taken as -12 dB/octave. It is important to note, however, that this value differs between different voices and also varies within a given voice, since the source properties are constantly changing during running speech.

One way of illustrating this difference is to compare the amplitudes of the first and second harmonics in the source spectrum. If we thus compare the spectra of the filtered waveforms for modal and hyperfunctional voice in Figure 3a, we see that the difference between the first and second harmonics (the leftmost peaks indicated by the arrows H1 and H2 in the spectrum at the top) is greater in modal than in hyperfunctional voice. Comparing modal and hypofunctional voice, we find that the difference is greater in hypofunctional voice. This implies that the spectral tilt increases in the order hyperfunctional, modal, and hypofunctional. The pulse measure most directly related to this spectral difference is the rate of flow decrease as the flow reaches its minimum value (i. e., the derivative of the flow) at point T3

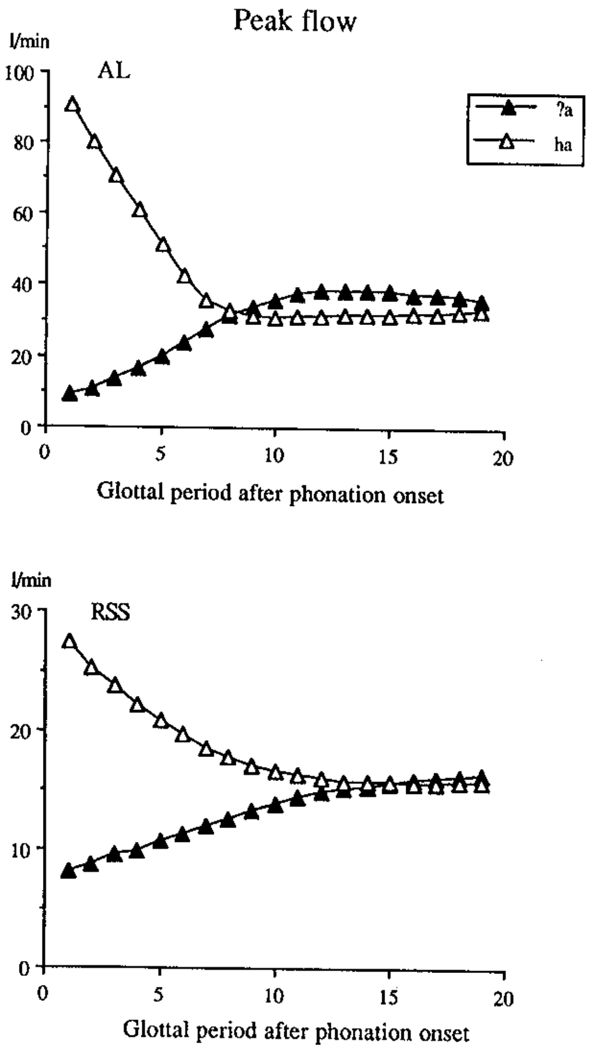


Figure 4. Peak flow during two types of glottal attack: a hard attack (?a), and a breathy attack (ha). The graphs plot the change in peak flow for 19 consecutive cycles after onset of glottal vibrations for a male (AL), and a female (RSS) voice; each data point represents the mean of 12 measurements.

in Figure 2. In the waveforms shown in Figure 3, a reflection of this is found in the skewing of the pulse, indicated by the Speed quotient, which decreases in the order hyperfunctional, modal, and hypofunctional.

Running speech

Figures 4 and 5 illustrate variations in the glottal pulse following a hard and breathy attack for a male (AL) and female (RSS) voice, respectively. Peak flow is shown in Figure 4 and minimum flow in Figure 5. The measurements have been made from inverse-filtered flow signals like the one shown in Figure 2. Nineteen consecutive glottal cycles after voice onset have been measured; each data point in these figures represents the mean of 12 measurements. The (mean) speaking fundamental frequency differs for the two subjects: 120 Hz for AL, and 210 Hz for RSS. Hence, the same number of glottal cycles does not correspond to the same temporal interval (see Löfqvist & McGowan, in press, for further details).

At the onset of glottal vibrations in Figure 4, peak flow differs considerably for the two conditions; it is higher for the breathy attack than for the hard attack. The two curves then converge as peak flow decreases for the breathy attack and increases in the hard attack. The plot of minimum flow in Figure 5 shows a similar pattern of variation for the two conditions. Minimum flow is thus higher in the breathy attack. In the hard

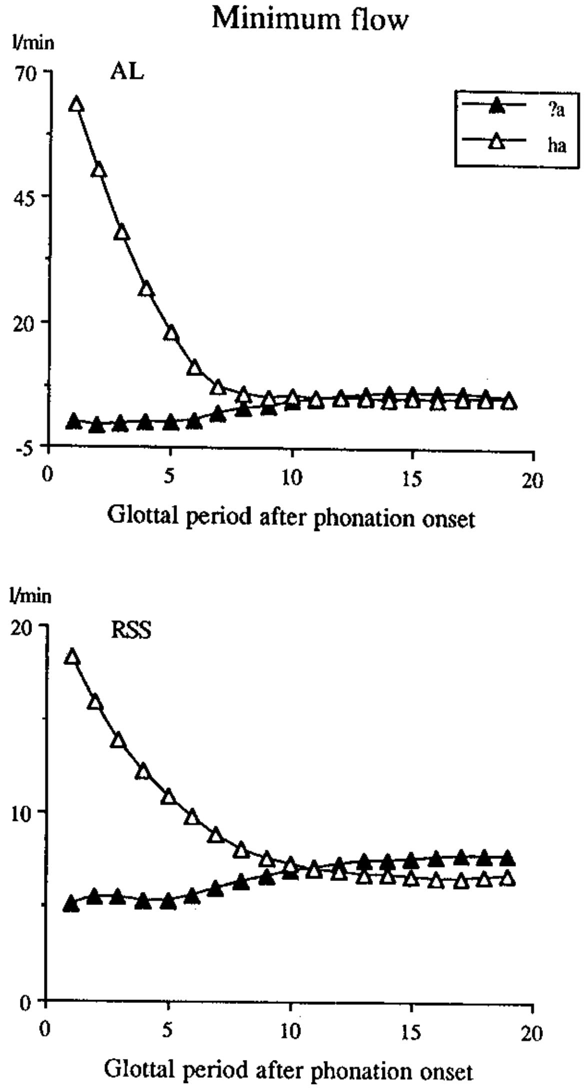


Figure 5. Minimum flow during two types of glottal attack: a hard attack (?a) and a breathy attack (ha). The graphs plot the change in peak flow for 19 consecutive cycles after onset of glottal vibrations for a male (AL) and a female (RSS) voice; each data point represents the mean of 12 measurements.

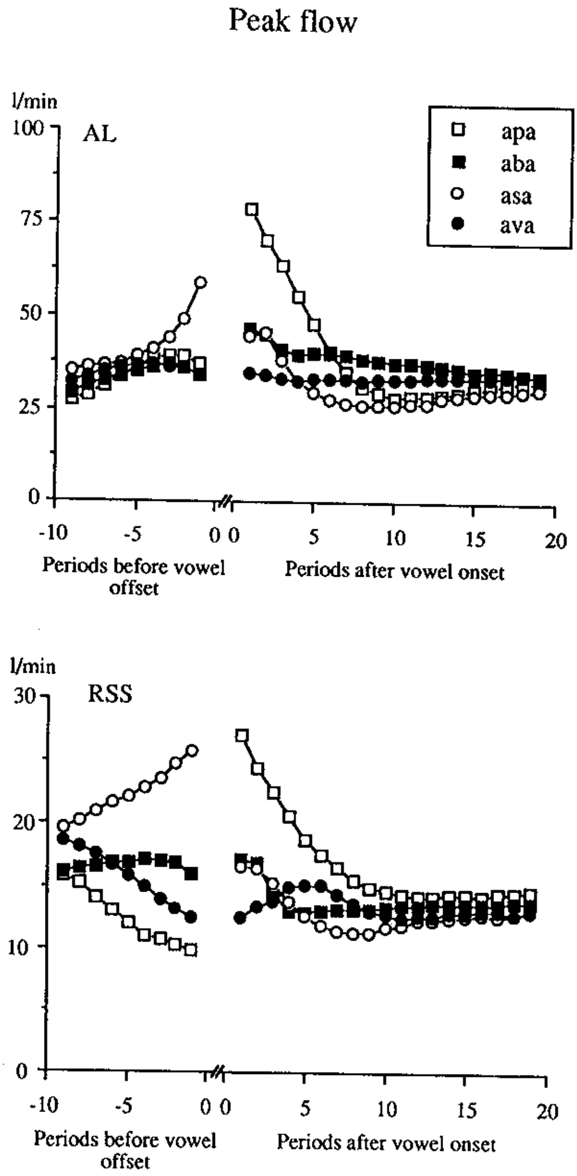


Figure 6. Variations in peak flow during vowel-consonant-vowel transtions for a male (AL) and a female (RSS) speaker; each data point represents the mean of 12 measurements.

attack, there is a small increase in minimum flow after the onset of glottal vibrations.

The source variations shown in Figures 4 and 5 can be rationalized with reference to the different laryngeal adjustments associated with the two types of attack (cf., Hirose & Gay, 1973). In the breathy attack, the glottis is open and the folds are being adducted while there is a high rate of air flow through the glottis; at the onset of vibrations, the source properties are thus similar to those of the hypofunctional voice shown in Figure 3b. In the hard attack, the folds are tightly adducted before the onset of vibrations and then forcefully blown apart by the subglottic pressure; here the source after voicing onset is similar to the hyperfunctional voice shown in Figure 3a. Consequently, both peak and minimum flow are higher in the breathy attack.

Figure 6 presents further examples of source variations in connected speech. In this case, the changes in peak flow are related to transitions between vowels and consonants and between consonants and vowels. The data are from the same male and female speakers as in Figures 4 and 5; the linguistic material consists of vowel-consonant-vowel sequences in running (reiterant) speech with stress on the second vowel. The leftmost part of the x-axis in Figure 6 presents the results for 8 periods before the offset of the first vowel. The rightmost part of the x-axis shows source variations during 19 periods following the onset of the second vowel (further details are given in Löfqvist & McGowan, in press).

Before vowel offset in Figure 6, peak flow increases in anticipation of the voiceless fricative /s/, whereas it shows a small decrease before the consonants /p, b, v/. At vowel onset, peak flow is very high following the voiceless stop /p/ and then decreases. Another feature is also evident after vowel onset in Figure 6. Following the voiceless consonants /p, s/, peak flow decreases to reach a minimum and then increases again. Let us, for example, concentrate on the curve for the sequence /pa/ of speaker AL. We find that it reaches a minimum at period 10 and then shows a small increase. The same also holds for the curve representing the sequence /sa/ of the same speaker, where the minimum occurs at period 9. The same pattern is also seen for speaker RSS. In her case, a minimum thus occurs at period 9 following the voiceless fricative /s/, and at period 12 following the voiceless stop /p/.

The source variations at the vowel-consonant-vowel transitions in Figure 6 are related to the coordination of the laryngeal and oral adjustments associated with the consonants, in particular the voiceless ones; the source changes in the sequences containing a voiced consonant are less marked. Voiceless consonants are produced with a glottal abduction gesture that has to be coordinated in time with the making and breaking of the oral closure/constriction for stops and fricatives, respectively (cf., Löfqvist & Yoshioka, 1981, 1984). For the voiceless fricative /s/, the phasing of the oral and laryngeal gestures is such that peak flow is high both at the voicing offset and voicing onset before and after the fricative in Figure 6. That is, the glottis begins to open before the oral constriction is made and is still being adducted when the constriction is released. Hence, the voice is most likely hypofunctional, or breathy, at voicing offset and onset.

At the release of the voiceless stop /p/ in Figure 6, the glottis is open since the stop is aspirated. There is thus a high rate of air flow through the glottis as the folds are being adducted. Voicing onset is thus similar to the breathy attack in Figures 4 and 5.

Following the voiceless consonants /p, s/ in Figure 6, peak flow shows a decreasing increasing pattern. That is, after an initial decrease during the first periods, there is a small increase. This pattern most likely reflects small changes in the degree of glottal adduction following the voiceless consonants. In particular, the glottis is open during the consonant and then adducted for the upcoming vowel. The adduction gesture makes the folds come forcefully together and the resulting tight glottal closure is seen in the reduction of peak flow. The degree of glottal adduction then returns to a value suitable for phonation during the vowel.

Male and female voices differ in other aspects than fundamental frequency. The values of peak flow in Figure 4 and 6 are higher for the male voice (AL). This is most likely due to the larger dimensions of the male larynx. Recent studies have also indicated that the AC flow is higher and the Open quotient is lower for male voices (Holmberg, Hillman & Perkell, 1988, 1989). The data presented in Figure 5 also show that the female spaker has higher minimum flow than the male speaker. This may well be a coincidence, however, since Holmberg, Hillman & Perkell (1988) did not fine any such differences. At the same time, it is important to note that the differences between male and female voices are not well understood (cf., Karlsson, 1988; Price, 1989; Titze, 1989; Klatt & Klatt, 1990).

Inverse filtering can also have clinical applications. For example, the technique can be used to document and monitor changes within a voice after surgery or during voice therapy. One drawback is that the analysis is most conveniently applied to sustained phonation which does not necessarily provide a reliable sample of voice function during normal use. The method could also be useful for biofeedback during voice therapy. Here, a visual display of the inverse-filtered signal can provide an additional channel of information besides auditory and kinesthetic feedback.

In summary, provided that the assumptions underlying inverse filtering are taken into account and the proper technique is applied, the procedure offers a valuable tool for voice studies.

Acknowledgments

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Sammanfattning

Artikeln beskriver tekniska och praktiska aspekter av inversfiltrering av talsignaler med tonvikt på filtrering av flödessignaler. Teoretiska och praktiska metodiska problem behandlas liksom metodens möjligheter och begränsningar. Tillämpningar på fonation och löpande tal illustreras. Kliniska tillämpningar diskuteras.

Yhteenveto

Käänteissuodatus työvälineenä äänen tutkimuksessa ja terapiassa

Artikkelissa kuvataan virtausmittaukseen perustuvan käänteissuodatusmenetelmän tekniikkaa ja käyttöä. Menetelmään liittyviä teoreettisia ja menetelmällisiä mahdollisuuksia ja rajoituksia pohditaan. Sekä sujuvan puheen että pitkien ääntöjen tutkimustuloksia esitetään ja hahmotellaan kliinisiä sovelluksia.