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FILTERING OF EMG SIGNALS

Jørgen Rischel[1] and Birgit Hutters

Abstract: One of the ways to eliminate different kinds of disturbances in EMG signals is by filtering in the frequency domain. This procedure requires both a knowledge of the frequency content of the disturbing components and a knowledge of the frequency range of the relevant signal. Therefore, the frequency characteristics of an EMG material of various internal laryngeal muscles recorded by bipolar hooked-wire electrodes have been examined. We conclude that the highpass cutoff frequency normally proposed in the literature - i.e. 100 Hz or lower - is generally not sufficient to eliminate microphony and especially the movement artifacts. But the choice of filtering frequency will often be a compromise between the cutoff that is optimal with respect to removal of spurious components and the attenuation of the overall signal caused by the filtering. However, it is generally advisable to highpass filter the signal even at the expense of some overall attenuation, and the greatest improvement is often achieved by highpass filtering with cutoff frequencies well above the low range normally proposed.

1. The background of the present study

Over the past several years a very considerable amount of EMG recording has been made at the Institute of Phonetics. This research has been largely concentrated around a project involving several researchers and comprising investigations of the functioning of various internal larynx muscles in speech, particularly with a view to the production of various types of consonants and the production of Danish stød and word stress. These recordings from larynx muscles were all made with bipolar hooked-wire electrodes. Dr. Hajime Hirose[2] performed the insertions of the electrodes. (Information about the project as a whole will appear in a later report.)

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1) Institute of Linguistics, University of Copenhagen.
2) Institute of Logopedics and Phoniatrics, University of Tokyo, Japan.

The bulk of recordings made in 1974 exhibit occasional or, in some recordings, frequent or constant disturbances due to various factors external to the motor unit potentials being picked up. Typical disturbances encountered were: (I) hum, (II) other background noise of various kinds, (i.e. probably a summation of amplifier noise and background noise caused by fluctuations in the physiological properties of the tissue, the so-called "tissue noise", see Hayes 1960), (III) microphony (the EMG electrode functioning as a transducer picking up the periodic vibrations of voiced portions of the speech signal), and (IV) occasional aberrant spikes in the signal which are likely to be caused by movements in the tissue jerking an electrode back and forth, or even causing two electrodes to touch intermittently, i.e. the "movement artifacts" normally referred to in EMG work.

The identification of artifacts of type (IV) was in all cases done on the basis of the raw signal, which contains information both concerning the frequency content and the amplitude of the EMG signal. The main criterion for the identification of such artifacts is the presence of a dominant low frequency component at some point in the signal. Strong artifacts of this kind are normally visible also in integrated EMG curves, but for the identification of weaker artifacts these curves are not in themselves sufficient, and if one has access to integrated curves only, spurious energy due to artifacts may be erroneously identified as being a part of the useful signal, cf. Fig. 3a. - In most cases it does not seem to be very difficult to identify artifacts on the basis of their frequency content, but it must be admitted that we have no principled criterion for the decision.

All of the four factors mentioned above are very well known sources of trouble in EMG work. In the recordings made at the Institute, great care was taken to minimize such effects, and in fact the general quality of our recordings is high. In the design of the instrumentation a very low level of hum and noise was achieved, and thus the two factors ((I) and (II) above) are generally negligible. (They come to play a role only in cases of extremely low signal level, which is indicative of too large a distance from the motor units recorded. Such recordings are of dubious value anyway since, with the very small muscular structures of the larynx, the pickup area must be very close to some active muscle in order to achieve a signal that can be uniquely associated with that particular muscle.)

However, disturbances of types (III) and (IV) occur frequently enough to pose a problem in the processing and evaluation of the signals. As for "voice bar" microphony (III), which in the case of inner larynx muscles sometimes occurs with a magnitude comparable to a level of moderate EMG activity, the obvious way to eliminate this distortion is by filtering in the frequency domain. This procedure, of course, requires both a knowledge of the frequency content of the microphonic component, and a knowledge of the frequency range of the useful EMG signal, in order to see what kind of filtering (if any), can be applied successfully, i.e. without seriously degrading the useful signal.

As for (apparent or real) artifacts of type (IV), there are various possible solutions. The treatment of the problem partly depends on whether the appearance of the artifacts is "systematic" or random, and partly on where in the test sentence the artifacts appear. In the case of random appearance the averaged signal will be less dominated by such artifacts if the number of tokens included in the average is not too restricted - and for that purpose the median mean is preferable since it is less sensitive to random artifacts than the arithmetic mean. But if the appearance of artifacts is systematic, i.e., if it comes up several times at the same place in the test sentence, averaging will not help much. One may choose to disregard this kind of distortion if the artifacts occur outside the passage of primary importance. But whenever it appears essential to avoid this kind of averaged signals we have the possibility of eliminating artifacts in the time domain, i.e. by setting a window in the raw signal at the appropriate width (duration) and suppressing the part of the signal that is contained within the window.[1] In this case, too, information on the frequency characteristics of the various signal components is desirable, as a basis for the interpretation of a suspicious component as a relevant (though perhaps unexpected) signal spike, or as an artifact. But if a "systematic" artifact appears in the important part of the test sentence the tokens in question must either be eliminated - which in certain cases will result in a considerable reduction in the number of tokens to be averaged -

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1) An EDP programme for this kind of surgery is available at the Institute.

or it must be attenuated as much as possible by filtering, as in the case of "voice bar" microphony. Again, some kind of information on the frequency content of the various kinds of signals is a prerequisite.

For the reasons stated above we found it essential to examine the frequency characteristics of the various EMG recordings. This was done mainly by highpass, lowpass and (to a more limited extent) bandpass filtering, the cutoff frequencies being varied stepwise within a frequency range chosen in accordance with the properties of each individual recording, and the effect on the signal shape and level was examined by visual inspection of mingograph tracings.

Since, in general, information on the frequency characteristics of EMG signals is very scanty, to say the least, the overall results of our filtering experiments may be of some interest to others, specifically as information on the properties of signals from very small muscles. We must, however, emphasize the limitation of the present study, viz. that we have confined ourselves to a qualitative appraisal of the effects of filtering (rather than performing quantitative measurements on frequency spectra) in accordance with our immediate goal: that of evaluating how much frequency limitation - especially in the form of highpass filtering - various kinds of EMG signals can stand, and how effective such filtering is in removing spurious components of the signal.

2. Previous research on the frequency characteristics of EMG signals and its relevance to the present study

The literature on EMG techniques and EMG research being by now extensive, we have found surprisingly little space devoted to questions having to do with the frequency characteristics of EMG signals and especially with the artifact problem. Several researchers touch upon the question of frequency filtering of EMG signals, however, and we refer to some of the more important statements below.

As for the possibility of improving the signals by filtering, Hayes (1960) finds that tissue noise and movement artifacts tend to be concentrated at low frequencies, and he recommends the use of band limited amplifiers with a lower cutoff frequency at about 20 Hz and a higher cutoff frequency in the range 100-200 Hz. Such band limiting also reduces amplifier noise, and it is applicable, according to Hayes, because the muscle action potentials exhibit sharply peaked spectra (he reports that biceps voltage is reduced by only about 3 dB when passing through a 35-75 Hz bandpass filter). Hayes' reasoning presupposes that movement artifacts etc. are indeed characterized by a preponderance of very low frequencies (ideally below the cutoff of some 20-30 Hz!). This is in disagreement with Geddes (1972), who briefly states that movement artifacts caused by disturbance of the electrical "double layer" are in the frequency range of many of the bioelectric events, and that for this reason "filtering techniques can seldom be employed with success" (p. 211).

Hayes' findings are of little direct relevance to our project since they are based mainly on EMG recordings from a large muscle by means of surface electrodes. Scott (1967), however, calculated power density spectra for signals measured with subcutaneous wire electrodes inserted in four large muscles, and he found "significant energy only in the frequency range from approx. 30 Hz to approx. 200 Hz" (p. 303), i.e. a result similar to that of Hayes as regards the frequency spectrum of the useful signal. He concludes that "methods of reducing mains frequency interference by using high pass filters are relatively inefficient" (p. 303), and also that "amplification of frequencies in excess of 200 Hz is likely to degrade the signal-to-noise ratio of a myo-electric system" (p. 303).

Trimble et al. (1973) performed a frequency analysis of single motor unit potentials recorded from a very small muscle (the medial rectus muscle of the eye) by means of a concentric needle electrode. They found energy at a much higher frequency range than found for other muscles by most other investigators, the predominant frequency band extending from 470 Hz to 1400 Hz (-3 dB points). They explain this surprisingly high frequency band by the very fact that a single motor unit was involved, whereas in other cases entire electromyograms have been analysed, which might be expected to reflect algebraic summations of asynchronous signals from different motor units. Such summation causes a lowering of the predominant frequency. With signals in which a single motor unit may predominate, the amplifier bandwidth must of course correspond to the resulting high frequency emphasis in the power spectrum for faithful reproduction of the single motor unit potential. This situation may well obtain in the case of EMG from larynx muscles.

If we look at the EMG processing employed for speech research a highpass filtering at 100 Hz or lower is normally proposed in order to eliminate movement artifacts and hum.

Fromkin (1965), in her EMG-investigation of the facial muscles using surface electrodes, states that the lower roll-off frequency of 40 Hz introduced by the tape recorder "gets rid of artifacts due to movements of the electrode" (p. 66). For the upper frequency limit she suggests a cutoff frequency at 10.000 Hz. Approximately the same bandwidth is proposed for research on muscles in the lips, tongue, and larynx by Hubler (1967), who mentions that "movement artefacts are minimized by rolling off the preamplifier at 40 Hz" (p. 27).

A higher HP cutoff frequency is proposed by Hirano et al. (1967) in their presentation of the hooked-wire equipment. In some of their recordings of various speech muscles they have noted the occurrence of low frequency movement artifacts, and according to the authors, recordings containing these artifacts can be highpass filtered at about 80 to 100 Hz, "which will completely eliminate the movement artifacts without diminishing the overall signal strength by too great a factor" (p. 23). The same highpass frequency is employed by Hirano and Smith (1967), using bipolar hooked-wire electrodes inserted in external tongue muscles, in order to eliminate movement artifacts. Furthermore, they find it necessary to lowpass filter the signal at 1500 Hz in order to eliminate some extraneous high-frequency noise, and they find no noticeable loss of "strength" due to this bandpass filtering. Also at the Haskins Laboratories a highpass filtering at 80 Hz is employed in order to reject movement artifacts and hum (Kewley-Port 1977).

In order to find out what the contributions of various frequency components to the total amplitude of the EMG signals are for typical speech gestures, Mansell (1979) has made a frequency band analysis of EMG signals provided via a surface monopolar derivation from the lower lip of one subject. The frequency bands exmined were 56-560 Hz, 560-1000 Hz, and four bands in the higher frequency range comprising frequencies from 1000 Hz to 4700 Hz. He finds that although the signal is attenuated when rejecting the components of the EMG signal below 560 Hz in favour of the frequency band ranging from 560 Hz to 1000 Hz, the signal-to-noise ratio is maintained because of attenuation of a band of EMG activity in the region below 560 Hz which appears to be relatively undifferentiated with respect o the segmental gestures of the EMG signal. This "cleaning" of the signal results in a small drop in peak variance and a greater distinction between linguistic types. Furthermore, Mansell finds a much better alignment of individual traces and a better differentiation of multi-modal gestures, exemplified by the two-phase nature of the average signal for the labial gesture in the German word Pute.

Various authors have approached the possibility of using the frequency spectrum (profile) in the diagnosis of various aspects of the behaviour of the muscles involved. Thus it has been found that the frequency spectrum of the signal changes with the level of contraction and with fatigue (Kaiser and Petersén 1965; Kadefors, Kaiser and Petersén 1968; Kwatny, Thomas and Kwatny 1970). It has been repeatedly observed that "when the levels of contraction rise, the motor unit potentials become synchronized, which results in augmented potential duration and amplitude" (Herberts 1969, p. 21). Such synchronization, if causing broader activity spikes, necessarily affects the power spectrum, with the effect of boosting the lower frequency region (cf. above). However, there is probably no simple, uniform statement applying to all muscles under all conditions. Thus, according to Kaiser and Petersén (1965, p. 234), the spectral change accompanying increased muscle contraction intensity may take different courses depending on the intensity level in question. Kadefors, Kaiser and Petersén (1968) decompose the spectral change under fatigue into a smooth increase in low-frequency content, and a rapid decrease in high-frequency content, and they suggest that "the dropping-out of small motor-unit potentials as fatigue develops might cause part of the high-frequency decay" (p. 71). Kwatny, Thomas and Kwatny (1970) find that "fatigue tends to place more emphasis on lower frequency components, indicated by a rise in the mean frequency of the spectrum" (p. 311). In their investigation the effect of fatigue on the EMG spectrum seems to override that of increasing contraction level.

These findings, which relate to sustained contraction of muscles of a much larger size than those of the larynx, are in themselves hardly applicable to the study of speech production. However, it is noteworthy that the spectrum of the EMG signal may vary under varying conditions of muscular behaviour, and it would seem advisable not to base an appraisal of the effect of filtering on a single type of speech gesture.

As for the question of large versus small muscles, Kadefors and Petersén (1970) report on earlier studies according to which the decrease in high-frequency activity accompanying fatigue is "considerably different in different muscles, minor muscles showing steeper decrease (and lower recovery rates) than major ones" (p. 46). In the study under consideration they consider the frequency spectrum of two sphincter muscles as well as a levator muscle, and they find that "the static frequency spectrum of EMG from the two sphincter muscles studied contains much more high-frequency energy than muscles of the extremities in general..." (p. 63). The sphincter muscles in question agree in this respect with another sphincter muscle: the orbicularis oris. The sphincter muscles also generally exhibit less change in the spectra of EMG under maximal voluntary effort than do muscles of the extremities previously studied (p. 64). The authors attribute the greater amount of high-frequency energy of such muscles "to short duration of the motor-unit potentials and to small size motor-units" (p. 66), and they also establish some association between more high-frequency emphasis and faster muscle contraction.

All of this strongly suggests that one should not rely on generalized statements concerning the useful frequency range of EMG signals, and that one should be particularly aware of the possibility of a preponderance of higher frequency energy in the case of small and fast acting muscles such as the larynx muscles, as compared to the much larger muscles which have been most studied by physiologists.

As stated by Abbs and Watkin (1976), there appears to be little agreement by electromyographers as to the frequency band necessary for EMG signal recordings. Needless to say, comparisons of findings concerning different muscles make sense only if the same setup and exactly the same electrodes are used. Ideally, even the number of motor units involved and their distances from the electrode should be similar. This makes it very difficult to arrive at valid generalizations beyond the particular muscles studied and the particular technique employed. Generally speaking, surface electrodes pick up from a more diffuse area and at a greater distance from the motor units under investigation than do needle or hooked-wire electrodes, and they are expected to yield signals with more low-frequency emphasis than the other types of electrodes. As the larynx muscle potentials are picked up by hooked-wire electrodes which are placed (hopefully) closely adjacent to the muscle fibres, the output is a priori likely to have a relatively high amount of high-frequency energy, although this would depend very much on the distance from a motor unit. The presence of strong high-frequency components in the signal makes the possibility of signal improvement by frequency filtering more promising than with many other types of EMG signals. At the same time there is a particular need for such signal processing because the electrodes are placed in a small-size region of which all parts move almost continuously, so that the likelihood of movement artifacts here is extremely high.

3. Filtering approach in the present project

In the filtering experiments various types of filters were employed. The results reported on here were based almost exclusively on two types, viz. active RC filters (FJ-Electronics) coupled as lowpass, highpass or bandpass filters, and a passive LC filter for highpass filtering only. The former type of filter had an attenuation slope of 36 dB/octave; the latter type had a much steeper roll-off, the attenuation at 1/2 octave above the cutoff frequency being at least some 50 dB. The range of available cutoff frequencies for the active filter covered the entire frequency range of possible interest, whereas the passive filter could be set at cutoff frequencies only from 200 Hz upwards. The use of one type or the other was not found to make any essential difference in the effect of highpass filtering on the EMG signals (strictly speaking, the results were not exactly comparable because of differences in the nominal cutoff frequencies for the two filter types, but this was of no consequence because of the rather narrow spacing of the available cutoff frequencies for each type).

The EMG recordings were played back on an FM multi-channel tape recorder (Lyrec), viz. the one on which they had been recorded. The filters were connected to the output of the tape recorder via suitable high quality pre-amplifiers set to a gain minimizing the background noise caused by the instrumentation. The outputs from the filters were rectified and smoothed and recorded on a mingograph (with or without interstage amplifiers). Whenever filtering attenuated the signal so much that its characteristics were no longer clearly discernible, the gain of the interstage amplifiers was raised by a suitable amount (the gain being varied in calibrated steps, so that the real changes in signal level as a consequence of filtering can be observed by comparison of the various mingograms).

The total range of cutoff frequencies used was from 22 Hz to 2000 Hz in the case of highpass, and from some 4700 Hz to 22 Hz in the case of lowpass filtering. Bandpass filtering[1], if performed at all, was made within the frequency region 22 Hz - 12000 Hz. (The bandwidth of the amplifying and recording equipment greatly exceeded the range within which filtering was performed.)

We did not, however, perform filtering at closely spaced cutoff frequencies across these total ranges for all subjects. The filter settings were often varied in large steps at first, i.e. a recording specimen was filtered at various rather widely spaced frequencies, closer spacings (or an extension of the frequency range of the filter settings) being used especially if the signal turned out to be clearly sensitive to filtering in a certain frequency region.

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1) The signal was bandpass filtered by setting a highpass filter and a lowpass filter (coupled in cascade) at the same nominal cutoff frequency, so that the pass band consisted of only a narrow peak with attenuation slopes of 36 dB/octave on either side of the center frequency, the point in bandpass filtering being to locate particularly prominent frequency components of artifacts. In this setup, an additional 30 dB amplification was used.

By this more or less selective use of filtering, a considerable amount of informative data concerning a variety of EMG signals could be produced. However, even with this attempted minimization of redundant and excessively detailed information, the filtering was a laborious task. The frequency range from about 30 Hz to some 500 Hz, in particular, was important, and in virtually all cases most of this range required detailed analysis for a full description of the relationship between the frequency contents of artifacts versus useful signals.

4. Material

The EMG signals studied comprised specimens from recordings of 12 subjects: 8 males (PM, BM, BF, LG, JJ, NR, JR, JPF) and 4 females (MF, BH, HU, MW). One of these subjects was French (JPF), one was German (MW), the rest were Danish. All subjects spoke test sentences, i.e. frame sentences plus test words, in their own language. In this paper we have not taken language differences into consideration.

The recordings (made with bipolar hooked-wire electrodes, as mentioned earlier) were from the following muscles of the larynx: the cricothyroid muscle (CT), the vocalis muscle (VOC), the posterior crico-arytenoid muscle (PCA), and the interarytenoid muscle (INT).

In the survey of findings below, we have found it most useful to group the results according to the muscle studied (rather than according to the subject). It may be doubtful whether one can arrive at clear differentiations between the performances of these muscles as regards the frequency characteristics of the EMG signals. It is, however, interesting to distinguish between the set of muscles (CT and VOC) which were reached by insertion of a needle through the neck, and the rest, which were reached via the oral and pharyngeal cavities, since the conditions for movement artifacts may be expected to be somewhat different in the two cases. Moreover, it may be interesting to distinguish between VOC and the other muscles, since VOC is obviously more vulnerable to microphony ("voice bar" interference) than the others. The clearest presentation, then, is obtained by simply treating each muscle separately. The specimens chosen for analysis include artifact types (III) - microphony - and (IV) - movement artifact - if they appear at all in the recordings.

5. Survey of results from filtering

5.1 The crico-arytenoid muscle (CT)

The frequency characteristics of recordings from CT were examined for subjects BF, BH, HU, BM, JR, and JJ. All subjects are Danish.

Subject BF: two specimens were analyzed. One of these was highpass filtered in steps from 47 to 1600 Hz, and lowpass filtered in steps from 3300 to 100 Hz. The other specimen was filtered within the same range except for the highpass filtering which started at 200 Hz.

On visual inspection of the raw curves these look "clean", except that there appears to be mains interference in one of the specimens.

Results: the hum is obviously 50 Hz mains interference, which is easily removed by HP filtering, e.g. at 68 Hz. Otherwise, it is a signal which is very resistive to filtering, the overall shape being essentially constant at least in the frequency region 390 - 1600 Hz, and with rather evenly distributed energy in the region 390 - 800 Hz. LP filtering at 100 Hz is more detrimental to the output than is HP filtering, even at 1600 Hz.

Subject BH: two specimens were analyzed. One was highpass filtered in steps from 200 to 1000 Hz and lowpass filtered in steps from 1000 to 100 Hz. The other specimen was highpass filtered in steps from 250 to 1600 Hz and lowpass filtered in steps from 470 to 47 Hz.

On visual inspection the raw curves exhibit some (occasional?) hum as well as some apparent movement artifacts. It is likely that the electrodes had been misplaced in this recording, so that the muscle involved is in fact not CT (or there may be contamination from another muscle).

Results: the hum is easily removable by HP filtering at 250 Hz (the lowest cutoff frequency employed) without affecting the useful signal. The spurious spikes, which we identify as movement artifacts, are suppressed by HP 400 Hz and more completely by HP 630 Hz. The useful signal seems to have rather evenly distributed energy in a wide frequency region from 100 Hz upwards, although with considerable attenuation at HP filtering above 400 Hz.

Subject HU: one specimen was highpass filtered in steps from 200 to 2000 Hz and lowpass filtered in steps from 4700 to 47 Hz.

On visual inspection the raw curves do not seem to be contaminated by disturbances.

Results: the signal information is fairly constant over the frequency range from some 470 Hz upwards, but increasingly changed at lower frequencies. The low frequency component is relatively weak. It seems clear that a more well-defined signal is obtained by HP filtering at 470 Hz or even higher.

Subject BM: one specimen was analyzed. It was highpass filtered in steps from 200 to 1600 Hz, lowpass filtered in steps from 1000 to 470 Hz, and bandpass filtered with (exceptionally) a pass-band comprising the range 1000 - 1500 Hz.

On visual inspection the raw curves do not seem to be disturbed by artifacts of any kind.

Results: the result of the filtering was that only very minor changes occurred in the shape of the curves, and the signal has a very broad frequency spectrum, ranging from below 470 Hz to above 1600 Hz.

Subject JR: two specimens were analyzed. One of these was highpass filtered in steps from 22 to 2000 Hz, lowpass filtered in steps from 4400 to 82 Hz, and bandpass filtered with a pass-band comprising the range 22 - 330 Hz. The other specimen was highpass filtered in steps from 200 to 2000 Hz and lowpass filtered in steps from 4700 to 82 Hz.

On visual inspection the curves exhibit numerous spurious spikes and occasional microphony.

Results: microphony disappears by HP filtering at e.g. 200 Hz. The artifacts have a frequency spectrum which is most prominent at frequencies below 200 Hz, whereas the useful signal has its dominant spectral components at higher frequencies, apparently with most energy in the region 300 - 600 Hz. But the signal is well preserved, even at frequencies well above 1000 Hz. Thus it seems straightforward to improve the signal by HP filtering somewhere above 200 Hz, and it is probably safe to choose a cutoff frequency somewhere in the region of most spectral prominence (i.e. somewhat above 300 Hz).

Subject JJ: one specimen was analyzed. It was highpass filtered in steps from 22 to 1600 Hz, lowpass filtered in steps from 1000 to 47 Hz, and bandpass filtered in steps from 22 to 3300 Hz.

On visual inspection the raw curves seem free from disturbances except that there is microphony.

Results: BP and HP filtering showed that the microphony contains both the first and the second harmonic of the voice fundamental frequency, although the second harmonic does not do any harm at HP 200 Hz, since the total signal energy above this frequency completely overrides the microphony. At higher HP cutoff frequencies there are various changes in the shape of the curves, and the signal level becomes considerably weaker with HP cutoff frequencies in the vicinity of cutoff 1000 Hz.

5.2 The vocalis muscle (VOC)

The frequency characteristics of recordings from VOC were examined for subjects BF, BH, HU, NR, JR, MW, JJ, and BM. All subjects are Danish except for MW, who is German.

Subject BF: five specimens were analyzed. These specimens were chosen from different parts of a long recording because the performance varied quite a lot during the recording. The signal level was good in the beginning and later, but low in an intermediate portion, the temporary weakening having to do with the fact that the electrode was touched and got into a less suitable position but apparently restored its original conditions at a later stage. One of the specimens was chosen to exemplify a passage with some strange spikes, viz. just before p and s.

Three of the specimens were highpass filtered in steps from 47 to 2000 Hz, lowpass filtered in steps from 3300 to 47 Hz, and two of these were bandpass filtered in steps from 47 to 1000 Hz. The other two specimens were highpass filtered in steps from 200 to 1000 Hz and lowpass filtered in steps from 3300 to 270 Hz.

On visual inspection the signals exhibit no disturbances, except for the specimen extracted from the intermediate portion of the recording, which is not only weak but also filled with spurious spikes and microphony.

Results: the noise and movement artifacts in the weak recording can be attenuated by HP filtering at 200 Hz, but the signal remains poor. The remaining specimens exhibit a very good signal with a relatively even distribution of energy in the region 100 - 1000 Hz, but with the most prominent energy in the middle of this range. It is hardly appropriate to process these different parts of the recording together in terms of filtering, since they differ widely in signal level and do not become similar in quality anyway.

Subject BH: two specimens were analyzed. One specimen was highpass filtered in steps from 200 to 1600 Hz, lowpass filtered in steps from 1000 to 47 Hz, and bandpass filtered in steps from 39 to 680 Hz. The other specimen was highpass filtered in steps from 200 to 630 Hz and lowpass filtered in steps from 1000 to 150 Hz.

On visual inspection the signal is characterized by spurious spikes, which are interpreted as movement artifacts.

Results: the frequency content of the spurious spikes covers a rather wide band with most prominence around 100 - 150 Hz. But as the wide frequency band of the spurious spikes overlaps with the prominent frequency band of the useful signal, they can hardly be eliminated completely by filtering, although HP 400 Hz seems a reasonable compromise between too little suppression of artifacts and too much signal attenuation. With high cutoff frequencies the curve becomes less smooth with rather prominent single spikes reflecting the action potentials.

Subject HU: two specimens were analyzed. Both specimens were highpass filtered in steps from 200 to 2000 Hz and lowpass filtered in steps from 4700 to 47 Hz. Moreover, one of the specimens was bandpass filtered in steps from 47 to 4700 Hz.

On visual inspection the curves exhibit mains interference, microphony and various spurious spikes.

Results: the mains interference is removed by HP filtering at 200 Hz (the lowest cutoff frequency employed). Removal of the microphony required a somewhat higher cutoff frequency. HP filtering at higher cutoff frequencies gradually changed the fine structure of the signal, and in some cases this change is rather considerable at high cutoff frequencies, while at the same time the overall signal gets weaker. However, the signal is in part well preserved even at HP 2000 Hz. The apparent artifacts are of varying frequency content, and they are not all easily removable by filtering.

Subject NR: one specimen was analyzed. This specimen was highpass filtered in steps from 22 to 2000 Hz and lowpass filtered in steps from 4700 to 47 Hz.

On visual inspection the curves appear to contain microphony and artifacts.

Results: microphony and artifacts can be at least partially eliminated by HP filtering in the vicinity of 150 Hz. Most of the artifacts have their strongest spectral energy below 100 Hz, but one (perhaps not a mere artifact?) has most of its energy at higher frequencies. Since the fine structure of the signal fluctuates quite a lot from one frequency band to another, it may not be advisable to eliminate too much of the signal by filtering, and hence a compromise must be found.

Subject JR: two specimens were analyzed. One of the specimens was highpass filtered in steps from 200 to 2000 Hz, lowpass filtered in steps from 4700 to 68 Hz, and bandpass filtered in steps from 22 to 330 Hz. The other specimen was highpass filtered in steps from 200 to 500 Hz, lowpass filtered in steps from 4700 to 68 Hz, and bandpass filtered in steps from 68 to 330 Hz.

On visual inspection this is a signal without much disturbance, so that there is not a priori a need for filtering.

Results: the most prominent frequency range is 100 - 500 Hz, but there is energy reflecting the action potentials even at much higher frequencies.

Subject MW: two specimens were analyzed. Both specimens were highpass filtered in steps from 200 to 2000 Hz, and lowpass filtered in steps from 560 to 27 Hz.

On visual inspection the signal seemed to be rather noisy and disturbed by movement artifacts.

Results: the movement artifacts are most prominent at some 220 Hz, but can be removed effectively only by HP filtering at a high cutoff frequency (some 800 Hz or more). At this frequency the useful signal is also attenuated a good deal, however. Still, HP filtering has the additional advantage of removing various noise components at relatively low frequencies. The "cleanest" looking signal is obtained by HP filtering above 1000 Hz.

Subject JJ: three specimens were analyzed. One of these was highpass filtered in steps from 22 to 2000 Hz, lowpass filtered in steps from 1000 to 33 Hz, and bandpass filtered in steps from 22 to 680 Hz; another was highpass filtered in steps from 47 to 1600 Hz, lowpass filtered in steps from 1000 to 69 Hz, and bandpass filtered in steps from 47 to 1000 Hz. The last specimen was only highpass and bandpass filtered from 200 to 2000 Hz and from 68 to 1200 Hz, respectively.

Inspection of the raw curves reveals occasional hum and spurious spikes, of which at least some are interpreted as movement artifacts.

Results: the filtering showed that the spurious spikes were not eliminated to the same degree by filtering, but in most cases they are eliminated by HP filtering with cutoff 150 Hz (which also eliminates occasional hum). The signal has components at much higher frequencies, so it seems perfectly possible to filter somewhere in the range 200 - 400 Hz. The signal level at HP 400 Hz is not much below that at HP 200 Hz, and the removal of spurious spikes is better.

Subject BM: one specimen was analyzed. It was highpass filtered in steps from 200 to 2000 Hz, lowpass filtered in steps from 1000 to 47 Hz, and bandpass filtered in steps from 22 to 12000 Hz.

Inspection of the raw curves reveals microphony and hum.

Results: microphony and hum disappear with the lowest HP filtering attempted, viz. HP 200 Hz. The filtering showed that the signal was very resistive to filtering, its overall shape being essentially constant, irrespective of the choice of cutoff frequency in the range HP 200 - 1600 Hz, and BP from 680 Hz and upwards, although the signal was weakened very much at very high BP frequencies.

5.3 The interarytenoid muscle (INT)

The frequency characteristics of recordings from INT were examined for subjects JPF, MF, LG, and PM. JPF is French, the others are Danish.

Subject JPF: four specimens were analyzed. One of the specimens exhibited an unstable signal since the pickup of the signal by the electrode suddenly became very weak during this period; after the failure of this electrode, another one was inserted, and one specimen represents the signal from the new electrode.

The first recording was highpass filtered in steps from 22 to 1600 Hz and lowpass filtered in steps from 560 to 56 Hz. The second recording was highpass filtered in steps from 200 to 2000 Hz and lowpass filtered in steps from 560 to 39 Hz.

On visual inspection both recordings (the specimens with the electrode inserted at the start of the recording session versus the specimen with a new electrode inserted) are characterized by spurious spikes, although these are not very prominent except in the specimen showing a very weak signal. Altogether, the signal is not very "clean".

Results: by HP filtering the signal is gradually weakened; this effect is noticeable from about HP 100 Hz upwards and very pronounced with HP 340 - 500 Hz. Above 500 Hz the signal is very weak with only occasional peaks of activity. Conversely, LP filtering affects the signal very little until rather low cutoff frequencies (below LP 200) are reached; it is only with cutoff frequencies below 100 Hz that the signal is considerably weakened. The apparent artifacts are essentially eliminated by HP 250 Hz. These characteristics are shared by both recordings.

Thus, both recordings exhibit a not very "clean" signal, dominated by the frequency region around and just above 100 Hz. Only in the beginning of the first recording is the signal so much better that HP filtering at higher frequencies (e.g. 630 Hz) can be successfully applied. The signal-to-noise ratio is such that one cannot generally achieve any considerable improvement by HP filtering (HP 250 seems to be the upper practical limit).

Subject MF: one specimen was analyzed. The signal was highpass filtered in steps from 150 to 2000 Hz and lowpass filtered in steps from 1000 to 22 Hz.

On visual inspection this signal contains only few artifacts (there is occasional hum in other parts of the recording, which has been found to be easily removable by HP filtering).

Results: HP filtering practically removed a spurious spike at cutoff 200 Hz. The useful signal was rather resistive to HP as well as to LP filtering, except with LP filtering with very low cutoff frequencies (100 Hz or lower). The above mentioned artifact appears to have energy in the range 40 - 200 Hz; the useful signal is well represented throughout the spectral range from some 100 Hz to at least 2000 Hz, but apparently with most energy in the range 300 - 500 Hz.

Subject LG: two different recordings (with different electrodes) were made. These are treated separately below.

(1) One specimen was analyzed. The signal was highpass filtered in steps from 82 to 2000 Hz, lowpass filtered in steps from 1500 to 47 Hz, and bandpass filtered in steps from 22 to 220 Hz.

On visual inspection the signal appears to contain some artifacts, but the distinction between artifacts and the useful signal is not altogether clear.

Results: HP filtering removes various spurious spikes, but they do not all disappear at the same cutoff frequency: some require only a cutoff frequency of 82 Hz to be sufficiently eliminated, others require HP 200 or 250 Hz. BP filtering shows that the former have their spectral energy below 100 Hz, but that the latter have most of their energy in the range 100 - 200 Hz. The useful signal is rather resistive to both HP and LP filtering: there is a discernible signal even at HP 2000 Hz and at LP 100 Hz (the latter strongly contaminated by the spurious spikes). However, most of the spectral energy is at relatively low frequencies: at HP 630 Hz the signal is very considerably weakened.

(2) One specimen representing the signal from the other electrode was analyzed. The signal was highpass filtered in steps from 200 to 2000 Hz, lowpass filtered in steps from 1000 to 33 Hz, and bandpass filtered in steps from 22 to 220 Hz.

On visual inspection this is a "clean" signal, though with apparent artifacts.

Results: the spurious spikes are at least in part artifacts; these are essentially eliminated by HP filtering with a cutoff of 200 Hz. The useful signal has a broad spectrum, ranging all the way from 27 Hz to above 2000 Hz, although it is considerably weakened towards higher frequencies.

Subject PM: one specimen was analyzed. The signal was highpass filtered in steps from 200 to 1000 Hz, and lowpass filtered in steps from 1000 to 100 Hz.

According to Dr. Hirose, this is not a very clear signal, but it must be INT, since there is not much possibility of contamination with other muscles (during insertion the needle pointed at the middle of the muscle). What we have here is an EMG interference pattern with different motor units involved, and it is hard to tell what information is present without averaging over several tokens.

Results: the signal is relatively constant over most of the frequency range studied, but the signal gets perceptibly weaker with LP 270 Hz (or lower), and with HP 630 Hz (or higher), i.e., the spectral energy is most prominent between these frequencies. There are artifact-like spikes which have most of their energy below 100 Hz, but the ratio between the remainder of the signal and these spurious spikes is improved by HP filtering at higher cutoff frequencies. The optimum is reached with HP 400 Hz, which does not weaken the useful signal very much.

5.4 The posterior crico-arytenoid muscle (PCA)

The frequency characteristics of recordings from PCA were examined for subjects MF, LG, and PM, all speakers of Danish.

Subject MF: two different specimens were analyzed. One of these was highpass filtered in steps from 47 to 2000 Hz, and lowpass filtered in steps from 1000 to 22 Hz; the other specimen was highpass filtered in steps from 200 to 1000 Hz and lowpass filtered in steps from 1000 to 100 Hz.

On visual inspection this signal is found to contain artifacts. There is occasional hum elsewhere in the recording, but not in these specimens.

Results: the signal is found to have a broad frequency spectrum but with particular prominence of a rather narrow region (the signal is considerably weakened both by LP filtering with cutoff 270 Hz and by HP filtering with cutoff 630 Hz). The artifacts are eliminated by HP filtering with cutoff 150 or 200 Hz (which also eliminates occasional hum), which can be done safely since the useful signal has its essential energy at higher frequencies.

Subject LG: one specimen was analyzed. It was highpass filtered in steps from 200 to 2000 Hz, lowpass filtered in steps from 1000 to 33 Hz, and bandpass filtered in steps from 47 to 2200 Hz.

On visual inspection this signal contains spurious spikes which are interpreted as artifacts, and it is also contaminated by microphony.

Results: around 47 Hz there is activity only in some of the spurious spikes. The microphony is narrow-banded: it is weakened by LP filtering with cutoff 100 Hz and eliminated by HP filtering with cutoff 200 Hz. The overall (useful) signal seems to have a broad spectrum ranging all the way from some 100 Hz to above 2000 Hz, but with a rather uneven distribution of energy in different frequency regions. As for the apparent artifacts, these are not all affected in the same way by filtering, but generally HP filtering improves the ratio between the useful signal and the spurious spikes. Some of the latter exhibit energy at relatively high frequencies, however. In this signal it is not very easily determined what is an artifact and whether it may be necessary to distinguish between different kinds of "artifacts" in a broad sense.

Subject PM: three different specimens were analyzed. These were highpass filtered within different ranges, together encompassing the range 22 - 1600 Hz, and (one specimen) lowpass filtered in steps within the range 1000 - 47 Hz.

On visual inspection the signal seems very weak, and it contains spurious spikes of the type interpreted as movement artifacts.

Results: suppression of various spurious spikes is obtained by HP filtering with cutoff 200 Hz, and in part even at 100 Hz. The signal itself seems to have a certain spectral dominance somewhere around 300 - 400 Hz: it is quite considerably attenuated by LP filtering with cutoff 270 Hz and likewise by HP filtering with cutoff frequencies above 400 Hz. HP filtering with a cutoff frequency in the range 100 - 200 Hz would seem advisable in such a case.

6. Discussion and conclusion

There is a great deal of variation within the material considered here. As regards the subjects for which two or more muscles have been recorded, i.e. most of the subjects, it is possible to see whether the frequency characteristics and general appearance of the EMG signals differ more characteristically from one person to another, or more characteristically from one muscle to another. However, on the basis of the results above, it seems hard to draw any such conclusions.

There are, however, some obvious recurrent characteristics of these EMG curves regarding the frequency content of (1) the useful signal (recording of action potentials), (2) apparent movement artifacts, (3) microphony, and (4) hum.

(1) The useful EMG signal, in the case of larynx muscles, mostly covers a frequency range from some 100 Hz upwards. There is often energy even at 2000 Hz or higher, but it is normally so that the spectral energy is most prominent below 1000 Hz and

especially in a region from some 200 Hz to some 600 Hz. The signals which seem generally least contaminated by noise and which present the clearest picture of the EMG activity typically exhibit energy also at high frequencies. In such cases, a faithful reproduction of the overall shape of the curves can be obtained even with HP filtering at very high frequencies (in the region 1000 - 2000 Hz), provided that adequate amplification is available (cp. figs. 1 and 2).

This result is clearly at variance with the general experience from large muscles.

(2) Spurious spikes which, according to their location in time etc., must be interpreted as movement artifacts, typically have their spectral center of gravity at low frequencies, i.e. essentially below the useful frequency range of the EMG signal or only slightly overlapping it. As a rule of thumb, these artifacts are situated in the frequency region up to 100 or 150 Hz (see fig. 3a and 3b). However, there are other spurious spikes which have a broader spectrum, or a spectrum shifted towards higher frequencies (see fig. 4). Some of these occur during the test words and typically in connection with features such as the Danish stød (see fig. 5). It should be investigated whether there is a difference in frequency content between <u>different kinds of movement artifacts</u> (e.g. between artifacts caused by external pull in the leads of the electrodes and artifacts caused by violent muscle contraction). This is important in order to know to what extent it is at all possible to discriminate between movement artifacts and suspicious spikes which are in fact part of the EMG signal (note that the interference pattern of contributions from different motor units may give quite a complex curve at times).

(3) Microphony is easily removed by HP filtering. It is mostly dominated by the first harmonic, so that HP filtering in the range 100 - 250 Hz should suffice (depending on the voice), see fig. 6. Contrary to expectation, microphony did not occur only in recordings from the vocalis muscle; we have found no explanation of why it sometimes occurs with one muscle, at other times with another, and why it sometimes occurs only intermittently.

(4) Hum is mains interference, probably picked up if the electric shielding somehow fails to be complete. In our recordings it is only occasionally a problem, and it is generally no problem to remove this interference by HP filtering (cutoff somewhere between 50 and 200 Hz).

Thus, for these EMG data from the internal laryngeal muscles recorded by bipolar hooked-wire electrodes, we conclude that the highpass cutoff frequency normally proposed in the literature - i.e. 100 Hz or lower - is generally not sufficient to eliminate microphony and movement artifacts. Especially in the case of movement artifacts a considerably higher cutoff frequency is fairly often required. The most suitable cutoff frequency seems to depend both on the general characteristics of the individual recording and on the position of the artifact in relation to the articulation involved. The choice of filtering frequency will often be a compromise between the cutoff that is optimal with respect to removal of spurious components and the attenuation of the overall signal caused by filtering. However, it is generally advisable to highpass filter the signal even at the expense of some overall attenuation, and the greatest improvement is often achieved by highpass filtering with cutoff frequencies well above the low range normally proposed.

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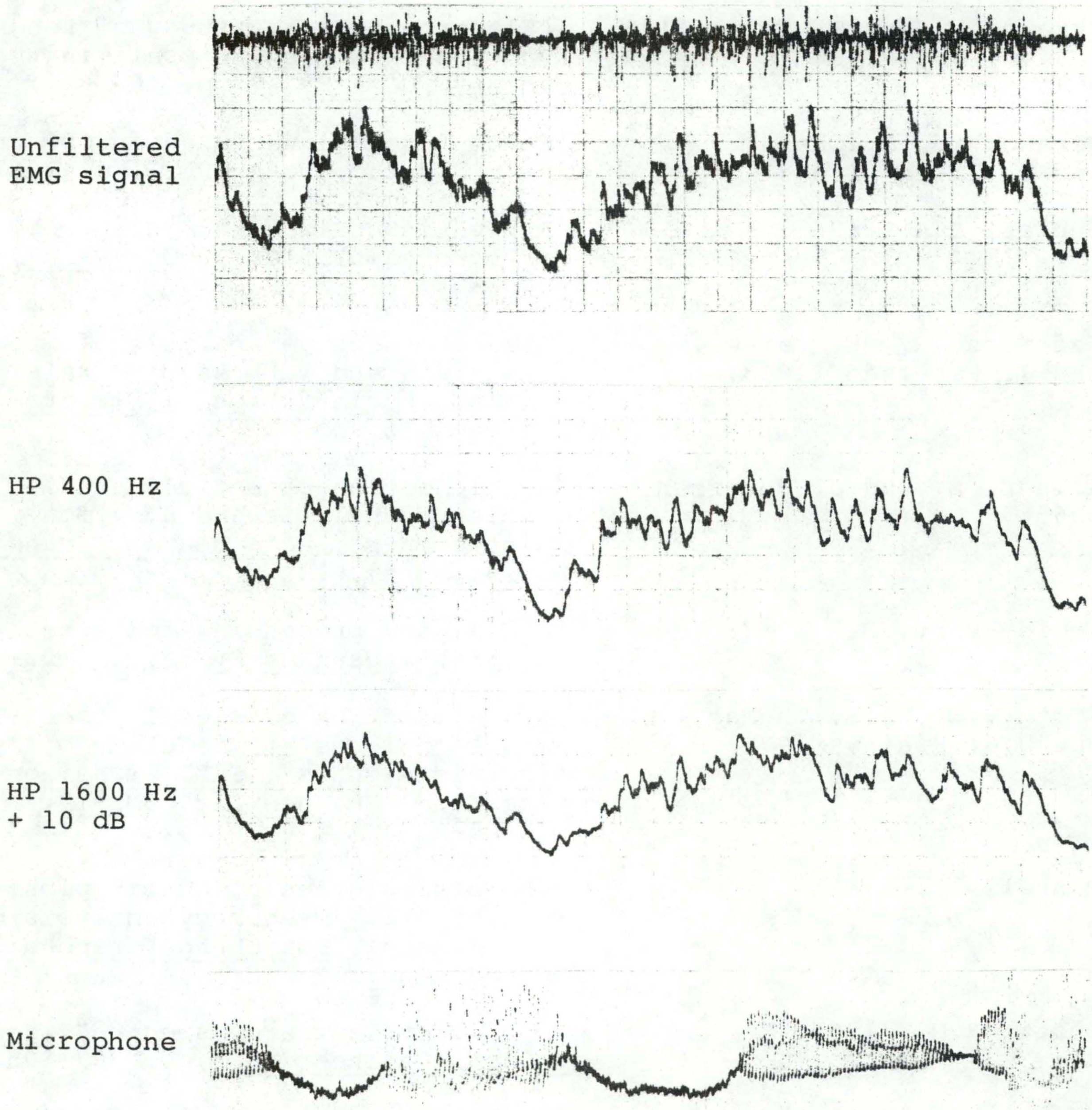

<u>Figure 1</u>

EMG signal of the interarytenoid muscle, highpass filtered at 400 Hz and 1600 Hz. In all figures the uppermost curve shows the unfiltered signal and the lowest one the microphone signal. Subject: MF, text: "(d)e sagde sile" (the text in brackets is not shown in the figure).

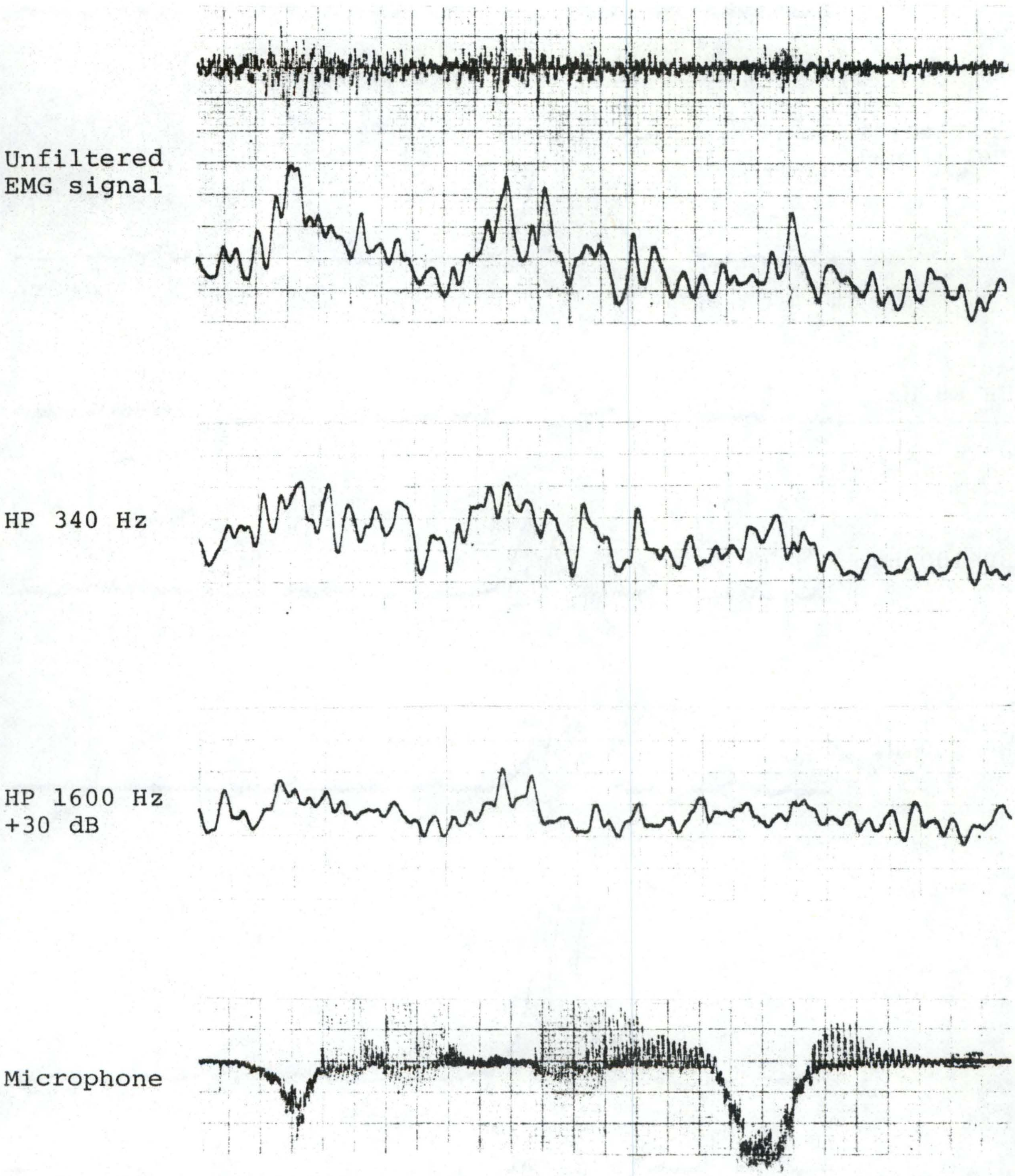

Figure 2

EMG signal of the interarytenoid muscle, highpass filtered at 340 Hz and 1600 Hz.
Subject: JPF, text: "c'est la panne ici".

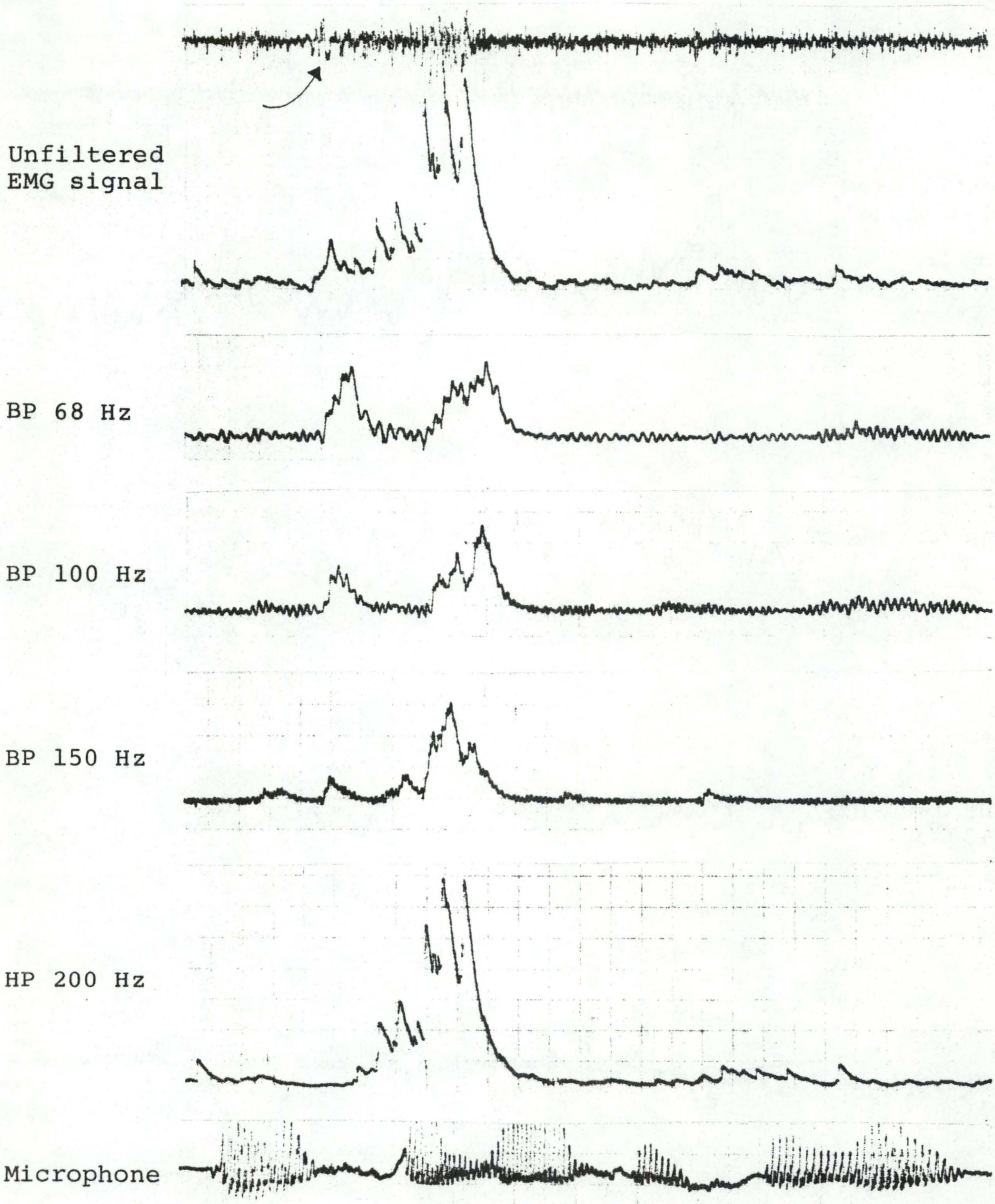

Figure 3a

EMG signal of the vocalis muscle, bandpass filtered at 68 Hz, 100 Hz, and 150 Hz. The lowest EMG curve shows the signal highpass filtered at 200 Hz. The arrow in the unfiltered curve points at the artifact. Subject: JJ, text: "det er hu'en de siger" (' indicates the Danish stød).

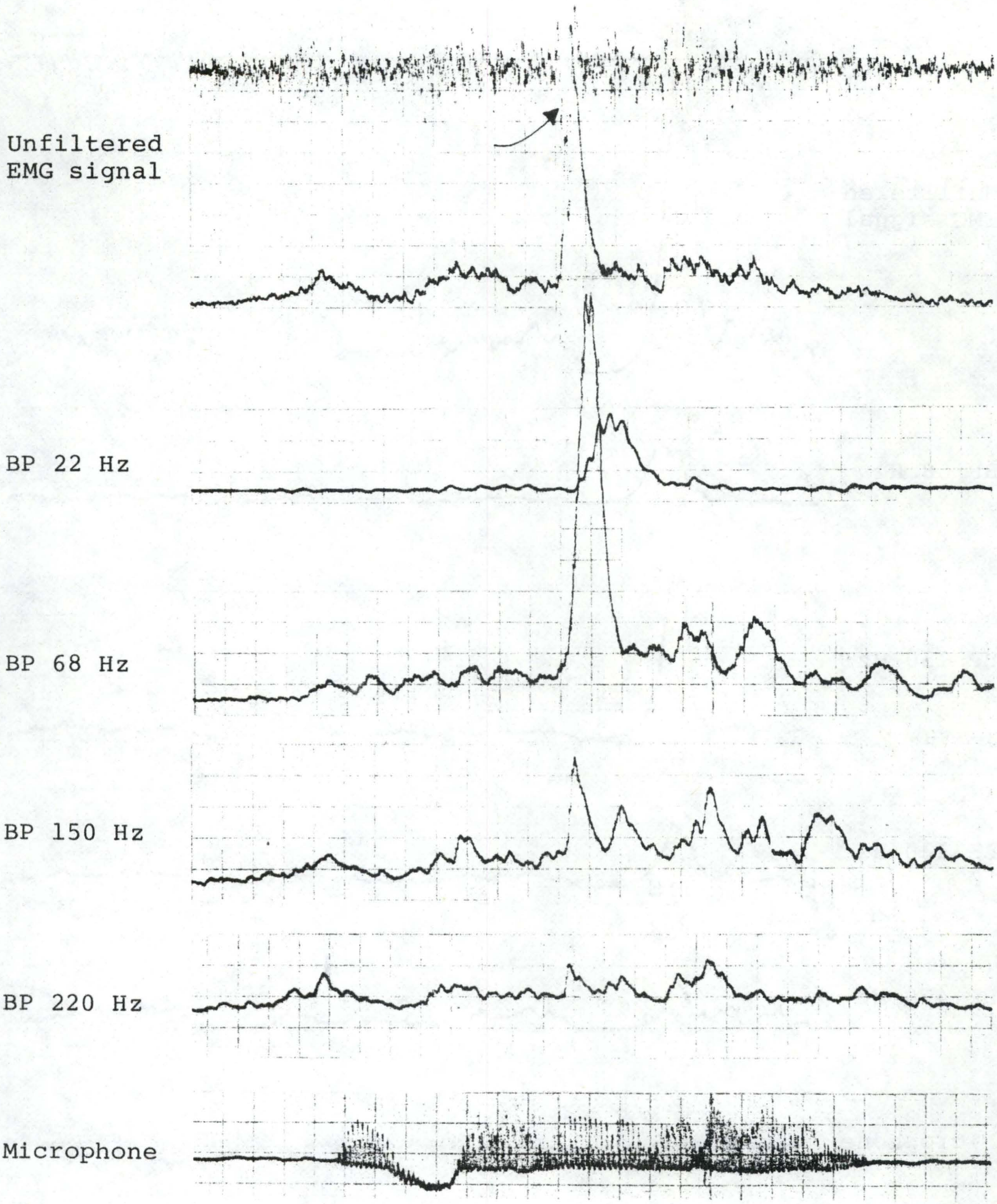

Figure 3b

EMG signal of the interarytenoid muscle, bandpass filtered at 22 Hz, 68 Hz, 150 Hz, and 220 Hz. The arrow in the unfiltered curve points at the artifact.
Subject: LG, text: "de sagde male".

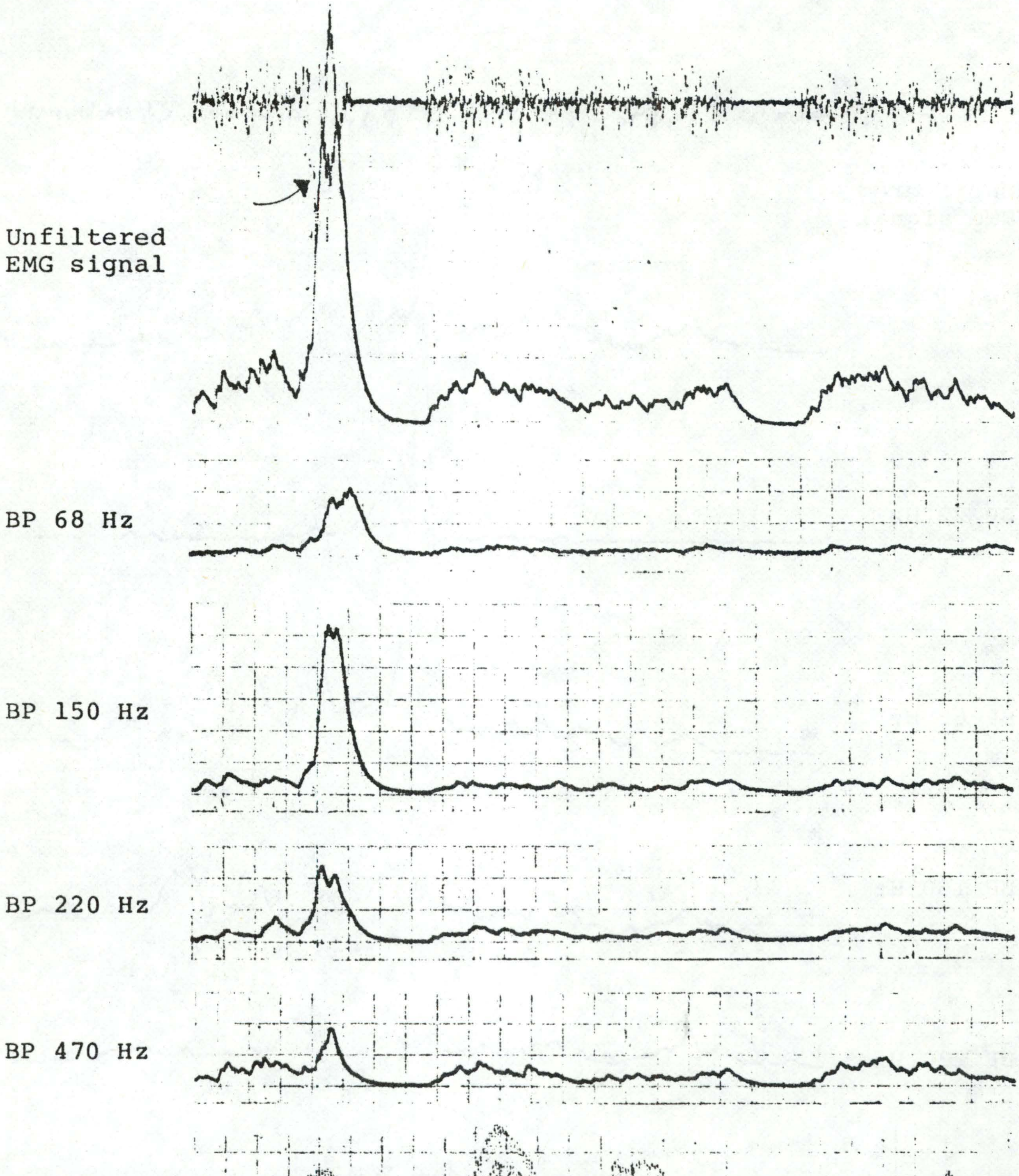

Figure 4

EMG signal of the vocalis muscle, bandpass filtered at 68 Hz, 150 Hz, 220 Hz, and 470 Hz. The arrow in the unfiltered curve points at the artifact. Subject: BH, text: "det er kæ'ler de siger".

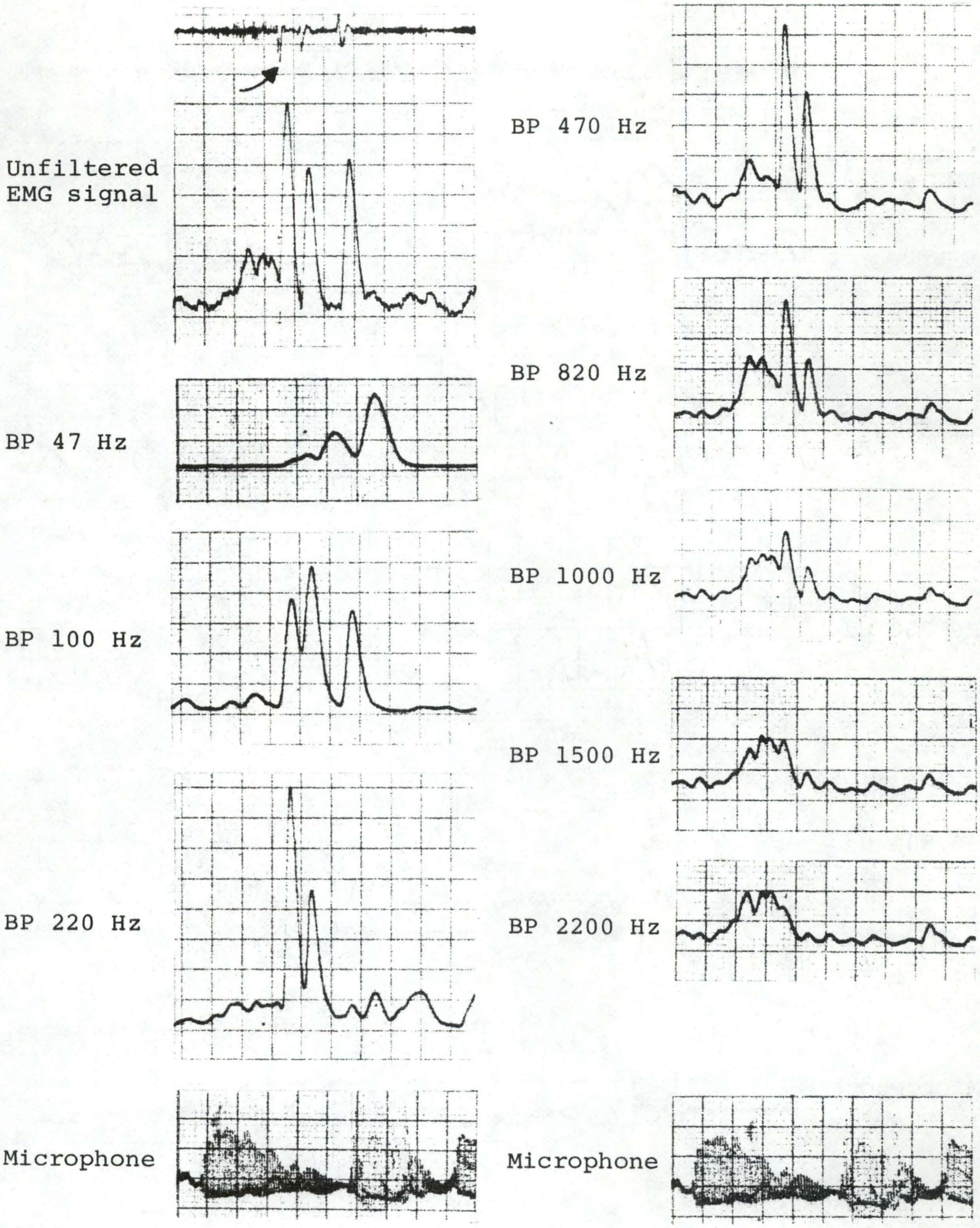

Figure 5

EMG signal of the vocalis muscle, bandpass filtered at different frequencies between 47 and 2200 Hz. The arrow in the unfiltered curve points at the artifact occurring in the stød-phase. Two other artifacts are seen.
Subject: HU, text: "(det er p)i'ber d(e siger)".

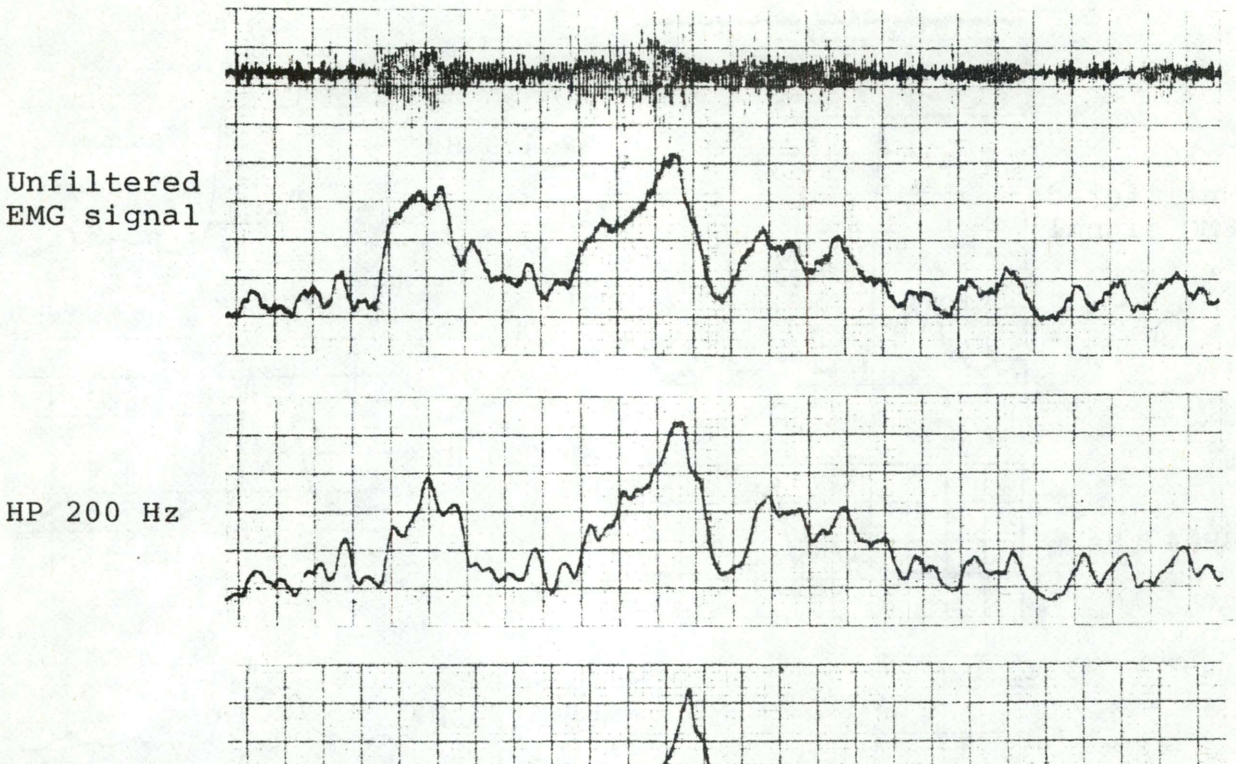

Figure 6

EMG signal of the vocalis muscle, showing microphony in a female voice. The signal is highpass filtered at 200 Hz, 250 Hz, and 500 Hz. Subject: HU, text: "det er ven'nen de siger".