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A COMPARISON OF CONTACT MICROPHONE AND ELECTROGLOTTOGRAPH FOR THE MEASUREMENT OF VOCAL FUNDAMENTAL FREQUENCY

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Signals from a throat contact microphone or an electroglottograph often are more suited for fundamental frequency measurements with simple analog circuits than the radiated speech signal. This report compares a contact (accelerometer) microphone placed on the neck below the cricoid cartilage and an electroglottograph for measurement of fundamental frequency in connected speech. The advantages and drawbacks of the two methods are discussed.

Two different strategies are generally used to measure fundamental frequency in speech: (a) low-pass filtering with subsequent zero-crossing detection, (b) double-peak-picking. Both strategies assume certain properties of the input signal. For zero-crossing measurement the signal waveform must not have more than one positive or negative zero-crossing in each fundamental period. For the double-peak-picking method there must be only one prominent negative and/or positive peak in each period. These requirements often are not fulfilled when the speech signal is recorded by means of a microphone in front of the speaker's mouth.

An *electroglottograph* offers a signal reflecting the opening and closing of the vocal folds. The signal is obtained by measuring the variations in a high-frequency current flowing between two surface electrodes placed on either side of the neck at the glottis level. The current variation is caused by the difference in the electrical impedance of the tissues when the glottis is opened or closed, and thus corresponds to the fundamental frequency of phonation. The resulting waveform generally meets the requirements of fundamental frequency detectors, and electroglottography is known as an excellent method for measurements of the fundamental frequency in speech (Fant, Ondráčková, Lindqvist, Sonesson, 1966; Fourcin, 1974).

However, in some cases the signal-to-noise ratio obtained from the electroglottograph may be too low to permit reliable fundamental frequency measurements. This problem seems to occur particularly when the carrier

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frequency is comparatively low (below 50 kHz) and the current from the electroglottograph is weak (Lecluse 1977). A thick layer of subcutaneous tissue in the neck reduces the signal-to-noise ratio because of shunting of the current past the vocal folds. In such subjects the electroglottograph works poorly.

An accelerometer microphone, henceforth called *contact microphone*, which is fastened to the neck below the larynx produces a signal related to the vocal fold vibrations and the sound pressure in the trachea. The waveform is reasonably independent of the articulation because of the high glottal impedance (Sundberg 1979). Moreover, the trachea resonances are constant in frequency and more damped than those of the vocal tract. Consequently, the waveform of a contact microphone signal is suitable for fundamental frequency measurements and frequently has been used for this purpose. The aim of the present investigation was to evaluate the reliability of fundamental frequency measurements obtained by the two methods.

METHOD

Equipment

The electroglottograph was constructed by H. Rundqvist and P. Kitzing*. Its design is conventional (Lecluse, 1977), with a rather low carrier frequency of 200 kHz and an electrode voltage of 0.5 V. It contains a bistable circuit which is triggered by the signal from the electrodes. A square-wave signal, which has a constant amplitude and the same periodicity as the electroglottogram is available as one of the outputs of the device.

The contact microphone (Special Instrument type BC-2) is a simple accelerometer containing a piezo-electric ceramic disc as the pick-up unit. The disc is enclosed in a metal container of 15 mm in diameter and 5 mm in thickness and weighs about 20 grams. A small pre-amplifier with high input impedance is placed close to the microphone along the connection wire in order to minimize hum.

The fundamental frequency detector (Fonema type 00063) used for the contact microphone signal is of the dual-peak-sensing type (see Larsson, 1977). The positive and negative peaks in the input signal waveform trigger a bistable circuit, to generate a square-wave output which has the fundamental frequency of the vibrations sensed by the contact microphone.

Experiment

Simultaneous recordings were made with the two devices described.

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The electroglottograph electrodes were attached to a fork held against the speaker's thyroid cartilage and the contact microphone was fastened to the tracheal wall 2 cm below the cricoid cartilage, approximately.

Two different experiments were carried out. In Experiment I the two methods were compared under varied phonatory conditions. Three male speakers served as subjects (PK, GG, JS). Their task was (a) to repeat the syllable [hɑ:] in a continuous sequence, (b) to alternate between breathy and normal phonation, (c) to alternate between modal and falsetto register by varying fundamental frequency, and (d) to start phonation with either closed or open glottis ("hard" and "soft" attack).

In Experiment II the devices were tested on normal reading by different speakers. In this experiment five female and eight male adults served as subjects. Of preference in subject selection were voices which could be expected to cause difficulties for the methods. However, all subjects had normal voices in the sense that none of them reported any voice problems or disorders. All subjects read the same text, which was the Swedish version of "The Northwind And The Sun." It contains five sentences and 156 syllables.

Analysis

In Experiment I, where the phonatory conditions were deliberately varied, the output signals from the electroglottograph and the contact microphone were recorded on separate tracks on a FM-tape recorder. In the subsequent analysis these channels were connected to separate tracks of an oscillograph. In this way simultaneous registrations were obtained of the signals recorded by the two methods.

Because measurements of voice fundamental frequency in the form of fundamental frequency histograms are useful for phoniatric purposes (Kitzing, Lofqvist, 1975, Kitzing 1979, Fritzell, Gauffin, Hammarberg, Sundberg, Wedin, 1977) it is relevant to compare such histograms as derived from electroglottograph and contact microphone recordings. For such comparisons the following procedure was used with respect to the material collected in Experiment II.

The speech signal from an ordinary microphone in front of the speaker's mouth, the square-wave signal from the electroglottgraph and the signal from the contact microphone were simultaneously recorded on separate tracks of an ordinary AM tape recorder (see Figure 1). In the subsequent analysis a computer program was used to compute the fundamental frequencies and to plot the result either as function of time or as a histogram showing the distribution of fundamental frequency values contained in the speech sample. The computer required two simultaneous input signals. One was the square-wave signal from a fundamental frequency detector, and the other was a signal reflecting the overall amplitude of the speech signal. In all analyses the latter signal was the rectified and

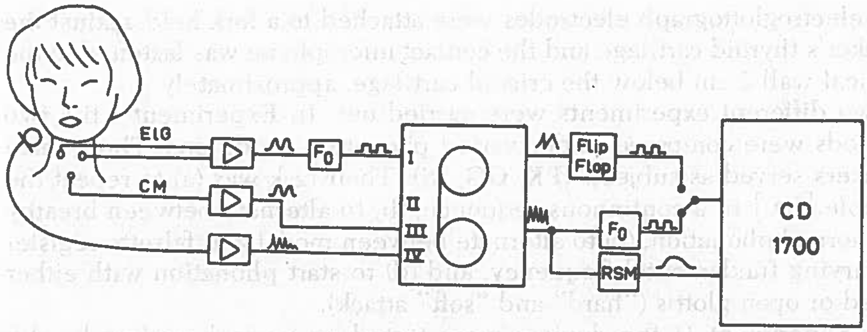

FIGURE 1. Schematic diagram of the data recording procedure and analysis used in experiment II. The electroglottograph signal ELG is fed to a preamplifier followed by a fundamental frequency detector, F0, the squarewave output of which is connected to one track of a tape recorder. A second track of the same tape recorder takes the preamplified contact microphone signal. A third track records the signal from an ordinary microphone. For the analysis either the electroglottograph square-wave restored by a flip-flop circuit, or the contact microphone signal, processed by the fundamental frequency detector F0, was fed to the computer CD 1700. In both cases the rectified and smoothed (R, SM) contact microphone signal was fed to a separate input of the computer, which used this signal as a gating criterion.

smoothed signal from the contact microphone. The square-wave signal was obtained in different ways in the case of the electroglottograph and the contact microphone measurements. In the case of the contact microphone it was obtained from the fundamental frequency detector mentioned above, which processed the tape recorded contact microphone signal. In the case of the electroglottograph the square-wave signal from the fundamental frequency detector built into the electroglottograph equipment was available in the tape recording. The waveform of this signal was distorted by the tape recorder because of the normal phase reproduction characteristics of an AM tape recorder. Therefore this square-wave signal could be fed into the computer only after its waveform had been restored. The restoration was accomplished by means of a flip-flop circuit. A check revealed that no information was lost in waveform restoration except for the first and last glottal cycle in some of the continuous sequences of voiced sounds.

With no input signal the pitch detectors used generated a more or less random output, making it essential to exclude those parts of the signal which corresponded to unvoiced sounds and pauses. Because the amplitude of the contact microphone signal decreased substantially in devoiced sequences, this amplitude was used as a gating criterion. The operator determined an amplitude threshold for the fundamental frequency measurements, so that all parts of the fundamental frequency curve associated with intensities below this threshold were eliminated from subsequent calculations performed by the computer (see Figure 2).

The fundamental frequency curve could be smoothed by means of a non-linear smoothing algorithm (Rabiner, Samber, Schmidt, 1975). The

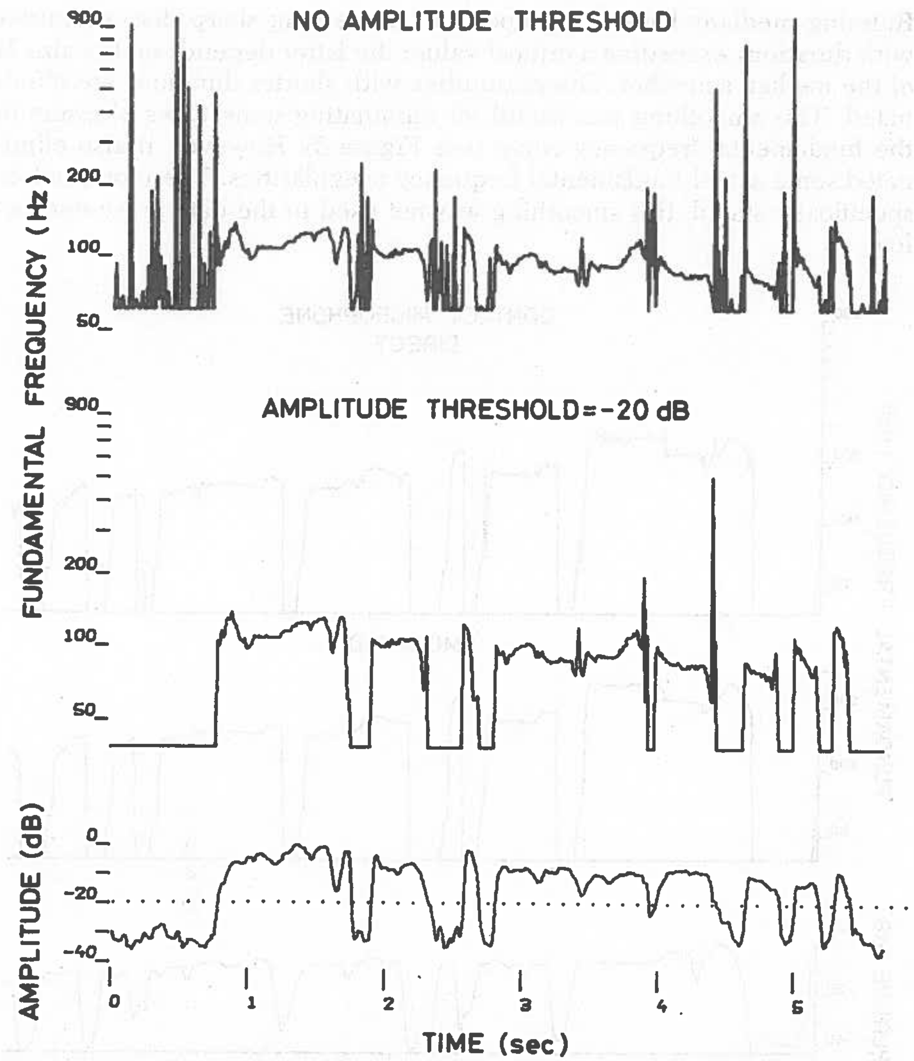

FIGURE 2. Fundamental frequency versus time as plotted by the computer. The top graph was obtained without, and the middle graph with elimination of all parts of the signal which were associated with amplitudes lower than −20 dB according to the bottom (amplitude) graph. Male subject (LA), normal reading.

algorithm used running medians for the smoothing process. The resulting fundamental frequency value, $\bar{f}_n$, of an N-point median smoother, where N is an odd integer number, represents the centermost value of a sequence of the N adjacent samples:

$$f_{n-\frac{N-1}{2}}, \ldots, f_{n-1}, f_n, f_{n+1}, \ldots, f_{n+\frac{N+1}{2}} \quad (1)$$

Running medians have the property of preserving sharp discontinuities with durations exceeding a critical value; the latter depends on the size N of the median smoother. Discontinuities with shorter durations are eliminated. This smoothing was useful for eliminating some types of errors in the fundamental frequency curve (see Figure 3). However, it also eliminated some actual fundamental frequency irregularities. Therefore, unless specifically stated, this smoothing was not used in the data presented below.

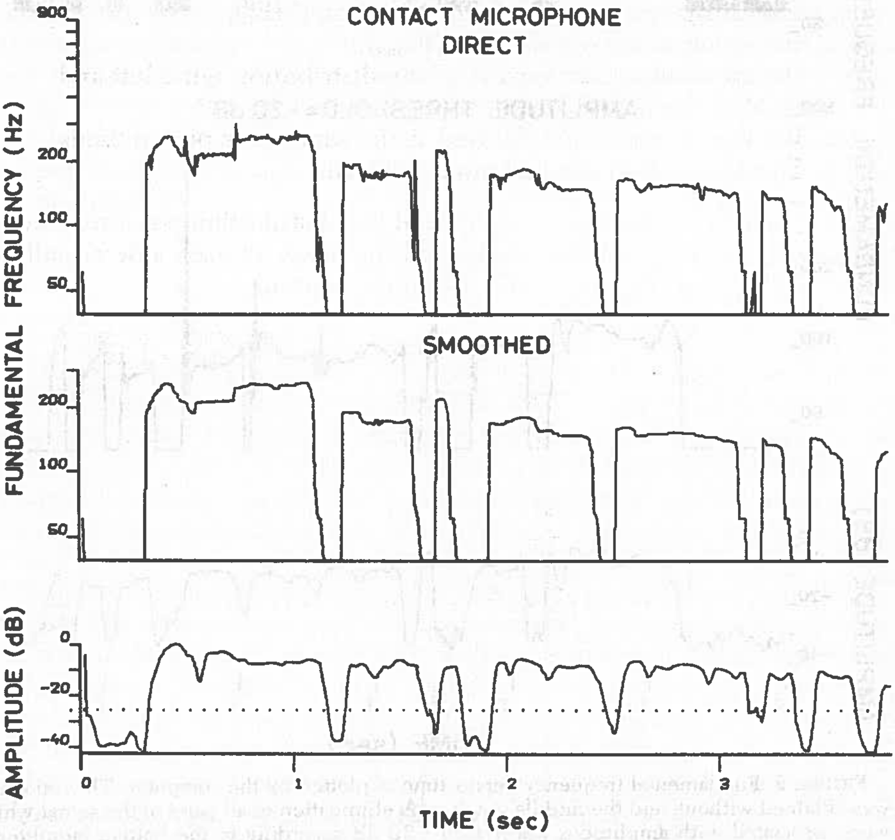

FIGURE 3. Fundamental frequency versus time as plotted by the computer before (top curve) and after (middle curve) smoothing as described in the text. The bottom curve shows the amplitude and the dotted curve represents the amplitude threshold. Female subject (SF), normal reading.

The computer program sorted the fundamental frequency values into frequency classes, 1 Hz wide. The resulting fundamental frequency histogram was plotted on the computer screen. By means of a cursor the operator defined *lim 1* and *lim 2*, in other words the lower and upper limits of the relevant frequency range. The histogram contours could be smoothed by an algorithm which modified each point, F_n, along the histogram contour according to the relation:

$$F'_n = \frac{F_{n-1} + 2F_n + F_{n+1}}{4} \quad (2)$$

This smoothing was repeated twice.

The computer program also calculated some statistics and presented the results in a new plot, illustrated in Figure 4. The statistical values were

(1) the arithmetic mean of the distribution (MF_o),
(2) the mode of the distribution (F_{max}),
(3) the ratio between the parts of the distribution lying left and right of the mode (BIAS),
(4) the total sample time defined as the sum of the period times considered in the calculations (TIME).

In addition, a triangular approximation of the distribution was presented. Its top was identical with the mode, and the areas on each side equalled the corresponding areas under the histogram contour.

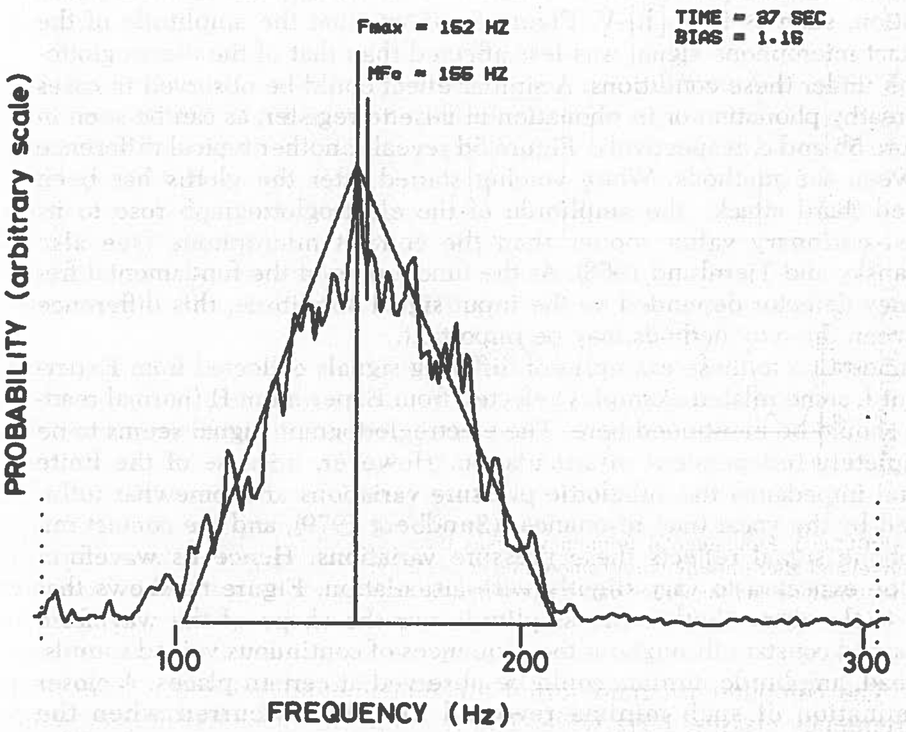

FIGURE 4. Fundamental frequency histogram for female subject (SR), normal reading, as plotted by the computer. The vertical dotted lines correspond to the lim 1 and lim 2 as determined by the operator. F_{max} and MF0 represent the mode and the mean of the distribution respectively.

RESULTS

As was mentioned previously, a contact microphone and an electroglottograph actually record different signals. The contact microphone senses the *vibrations* in the wall of the neck. These vibrations would reflect not only the mechanical shocks resulting from the closing of the glottis, but also the variations of the subglottic pressure, which result from the regularly interrupted transglottal air flow. Such pressure variations can be generated even in cases of incomplete glottal closure, such as in breathy phonation (Kitzing, Löfqvist 1975). Therefore a signal of a reasonable amplitude can be expected from a contact microphone, whether or not the glottis ever closes completely during its vibratory cycle. This is not so in the case of the electroglottograph where the amplitude depends strongly on whether or not the vocal folds make contact. The practical significance of this difference between the two methods was studied in Experiment I. Figure 5 shows a number of examples selected from the recordings in Experiment I with the exclusive aim of illustrating how the recordings made with the two methods occasionally may differ under certain phonatory conditions. Instances of missing or incomplete glottal closure may occur in normal speech when an unvoiced sound appears in intervocalic position, such as in V-[h]-V. Figure 5a shows that the amplitude of the contact microphone signal was less affected than that of the electroglottograph under these conditions. A similar effect could be observed in cases of breathy phonation or in phonation in falsetto register, as can be seen in Figure 5b and c, respectively. Figure 5d reveals another typical difference between the methods. When voicing started after the glottis has been closed (hard attack), the amplitude of the electroglottograph rose to its quasi-stationary value sooner than the contact microphone (see also Dolansky and Tjernlund 1968). As the functioning of the fundamental frequency detector depended on the input signal amplitude, this difference between the two methods may be important.

In addition to these examples of differing signals collected from Experiment I, some related examples selected from Experiment II (normal reading) should be mentioned here. The electroglottograph signal seems to be completely independent of articulation. However, because of the finite glottal impedance the subglottic pressure variations are somewhat influenced by the vocal tract resonances (Sundberg 1979), and the contact microphone signal reflects these pressure variations. Hence its waveform can be expected to vary slightly with articulation. Figure 6a shows that this is the case. Neither the amplitude nor the shape of the waveform remained constant throughout the sequences of continuous voiced sounds. Instead, amplitude minima could be observed at certain places. A closer examination of such minima revealed that they occurred when the waveform changed. Typically, errors appeared when the main peak of the waveform lost in amplitude while an intermediate peak gained in amplitude. Some examples of this are marked by arrows in Figure 6a. In such

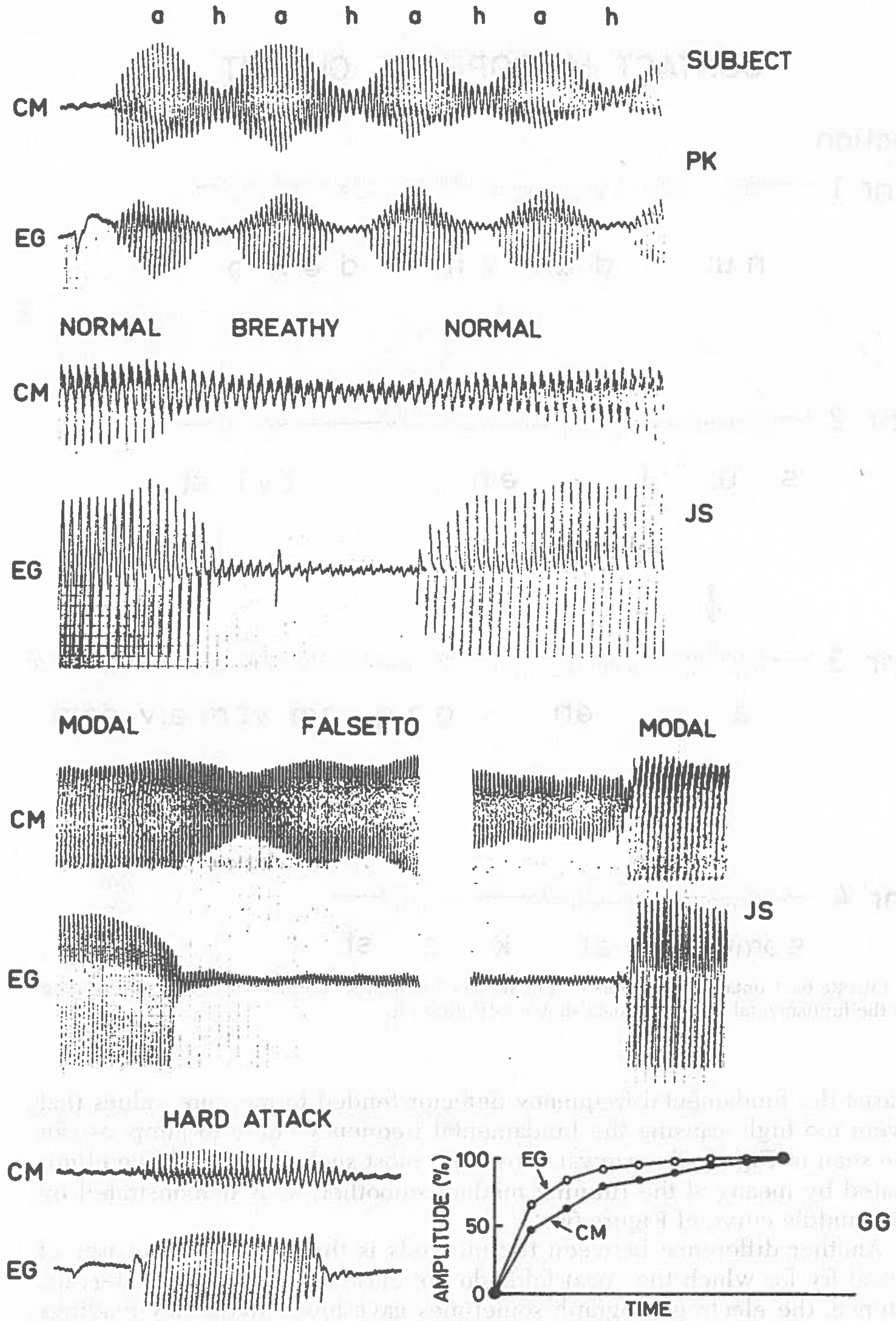

FIGURE 5. Contact microphone (CM) and electroglottograph (EG) output signals for the male subjects indicated by the symbols to the right deliberately phonating in various ways. The graph at the bottom of the figure show the increase in overall amplitude observed during the onset under condition of hard attack.

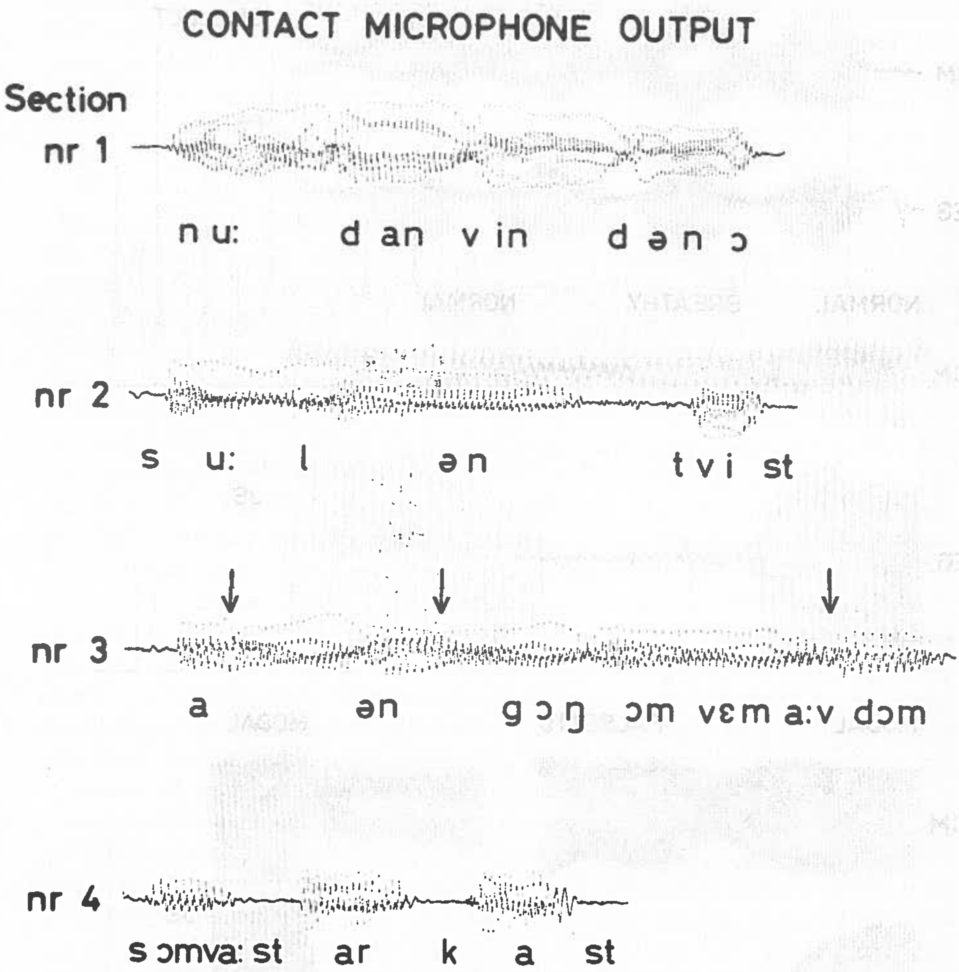

FIGURE 6a. Contact microphone output signal of subject JS, normal reading, corresponding to the fundamental frequency data shown in Figure 6b.

cases the fundamental frequency detector tended to measure values that were too high, causing the fundamental frequency curve to jump, as can be seen in Figure 6b (arrows). However, most such errors could be eliminated by means of the running median smoother, as is demonstrated by the middle curve of Figure 6b.

Another difference between the methods is their behavior in cases of vocal fry for which the vocal folds do not close at regular time intervals. Hence, the electroglottograph sometimes gave lower frequency readings than the contact microphone (see Figure 7).

These several examples have been given to illustrate differences in the output signals obtained by the two methods. The practical significance of

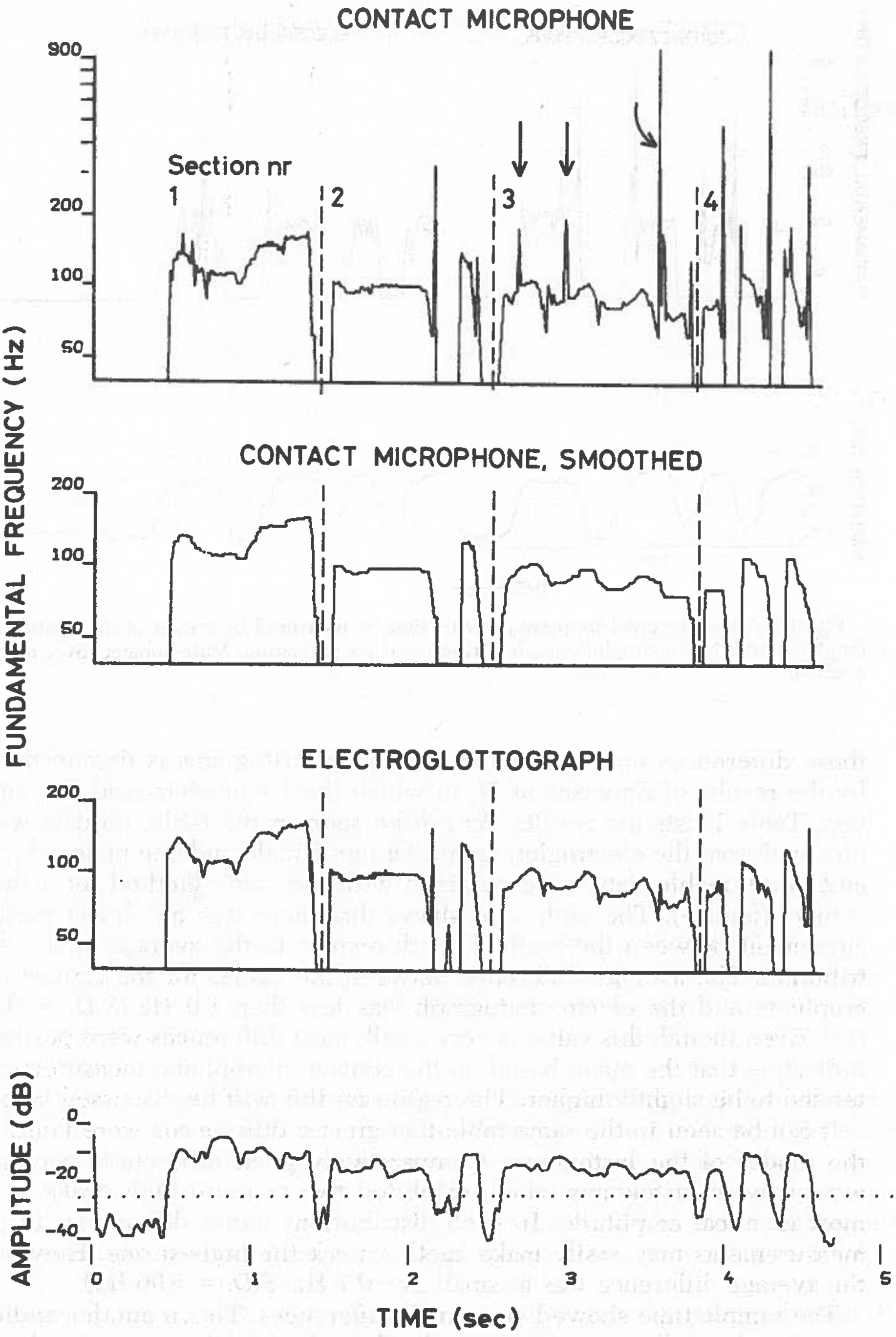

FIGURE 6b. Fundamental frequency versus time as derived from the contact microphone signal shown in Figure 6a. The numbering of the sections is the same as in Figure 6a, and the arrows show the same events.

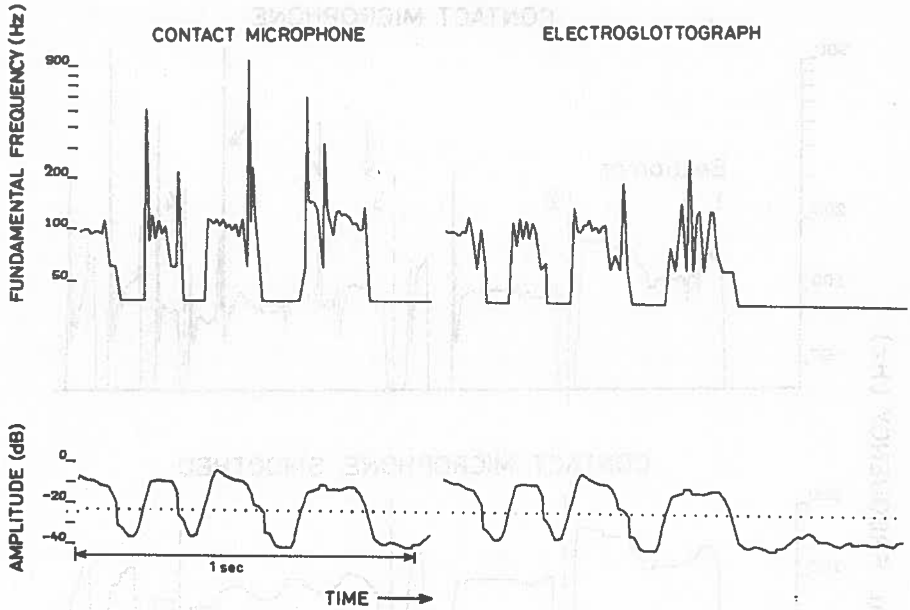

FIGURE 7. Fundamental frequency versus time as measured by means of the contact microphone and the electroglottograph during vocal fry phonation. Male subject (BG), normal reading.

these differences for fundamental frequency histograms is demonstrated by the results of Experiment II, in which the 13 subjects read the same text. Table I lists the results. As can be seen in the table, no data were obtained from the electroglottograph for one female and one male subject, and questionable data were obtained with the same method for a third subject (female). The table also shows that there was an almost perfect agreement between the methods with respect to the average of the distribution. The average difference between the values for the contact microphone and the electroglottograph was less than 1.0 Hz *(S.D. = 0.82 Hz)*. Even though this value is very small, most differences were positive, indicating that the mean based on the contact microphone measurements tended to be slightly higher. The reason for this will be discussed below.

It can be seen in the same table that greater differences were found in the modes of the histograms. Comparatively great differences occurred especially in histograms which exhibited two or more high peaks of almost identical amplitude. In such distributions minor differences in the measurements may easily make another peak the highest one. However, the average difference was as small as −0.7 Hz *(S.D. = 5.96 Hz)*.

The sample time showed very small differences. This is another indication that the differences between the data obtained by the methods are very small. The BIAS measure, on the other hand, suffered from the discrepancies in the mode values because it was strongly influenced by a

TABLE 1. Measures obtained from contact microphone (CM) and electroglottograph (ElG) recordings of the same speech samples. The values within parenthesis were not included in the computation of the average discrepancies (Δ) and standard deviations (SD) shown at the bottom.

		Mean F_0 Hz			Mode F_0 Hz			Time sec			Bias		
Subject	Sex	CM	ElG	Δ	CM	ElG	Δ	CM	ElG	Δ	CM	ElG	Δ
GT	fem.	222	221	1	204	206	−2	22	21	1	2.13	1.95	0.18
IT	fem.	193	193	0	161	160	1	25	24	1	3.92	3.59	0.33
EA	fem.	172	171	1	149	149	0	20	19	1	2.61	2.27	0.34
MR	fem.	164	(160)	(4)	120	(119)	(−1)	17	(17)	0	3.71	(3.16)	–
SF	fem.	166	–	–	146	–	–	20	–	–	1.95	–	–
MK	male	108	106	2	99	100	−1	38	37	1	1.62	1.43	0.19
JS	male	96	94	2	77	84	−7	21	21	0	2.33	1.35	0.98
BG	male	106	105	1	104	104	0	24	23	1	0.86	0.86	0
LA	male	95	93	2	84	85	−1	26	25	1	2.19	1.58	0.61
EJ	male	104	103	1	98	88	10	30	28	2	1.13	2.45	−1.32
ASL	male	106	106	0	100	112	−12	23	21	2	1.49	0.58	0.91
PK	male	96	96	0	90	85	5	22	22	0	1.11	1.78	−0.67
SR	male	155	–	–	152	–	–	37	–	–	1.16	–	–
Average				1.0			−0.7			1.0			0.16
SD				0.82			5.96			0.67			0.70

change of this value. Still, the average discrepancy was only 0.16 HZ (*S.D. = 0.70*). If future research indicates that skewness of the distribution is a relevant measure, a more sophisticated measure of the skewness should be used. Probably a more smoothed histogram would yield a more useful mode value.

DISCUSSION

The results of Experiments I and II are seemingly contradictory. Experiment I revealed differing output signals from the contact microphone and the electroglottograph in certain phonatory situations. On the other hand these differences did not seem to affect the values characterizing the fundamental frequency histograms to any appreciable extent. The reason for this somewhat unexpected agreement regarding the fundamental frequency histograms must be that the instances of differing fundamental frequency measurements are so rare that they lack statistical relevance regarding the distribution of fundamental frequencies. In other words, in the majority of fundamental frequency data there is a perfect agreement between the methods. It seems justifiable to conclude that either of the methods can be used for fundamental frequency histograms.

On the other hand, the electroglottograph cannot be used on all subjects, for example, when the subject has a thick layer of subcutaneous tissue in the neck, as was mentioned previously. This is not true in the case of the contact microphone. The three subjects for whom measurements could not be made with the electroglottograph in Experiment II produced convincing fundamental frequency data when the contact microphone was used. It should be stressed, however, that 10:3 is probably *not* representative of voices that cannot be measured with an electroglottograph. It will be recalled that in selecting the subjects we attempted to choose voices which could be expected to cause problems for the methods tested.

The mean fundamental frequency tended to be slightly higher in the contact microphone measurements. The reason for this small, but apparently systematic difference is not quite clear. One difference between the methods was that only the contact microphone was able to measure fundamental frequency under conditions of breathy phonation. If breathy phonation is frequently associated with high fundamental frequency, this may explain the higher average fundamental frequency in the contact microphone measurements. Another difference between the methods was that occasionally, excessively high fundamental frequency values were obtained from the contact microphone when the signal amplitude increased and when the waveform changed (see Figure 6a and b). Such errors will contribute to the slightly higher average fundamental frequency. A third difference between the methods which might contribute to the same effect is that observed under conditions of vocal fry, see Figure 7. One of the subjects (BG) offered considerably more frequent examples of vocal fry phonation than the other subjects in Experiment II. Still, the difference in the mean fundamental frequency was not particularly great in his case, as can be seen in Table I. This suggests that the difference between the methods with respect to vocal fry phonation does not contribute appreciably to the mean fundamental frequency.

An important aspect in the choice between the two methods for measuring fundamental frequency is how fundamental frequency shall be defined in the case of the voice. A straight-forward alternative is to equate vocal fundamental frequency with the frequency of vocal fold contact during phonation. If we accept this definition, the electroglottograph is the best possible method to use. On the other hand, vocal fundamental frequency undoubtedly exists even in cases of breathy phonation, which incidentally would occur more often in a phoniatric clinic than in the group of healthy voices considered in the present investigation. For instance, it would be almost impossible to measure fundamental frequency in patients suffering from vocal fold paralysis by means of an electroglottograph, and still it is untenable to deny the existence of vocal fundamental frequency in such voices. Therefore, equating vocal fundamental frequency with the frequency of vocal fold contact is impossible, and no preference can be given to the electroglottograph on this basis.

The main limitation of the contact microphone seems to be its sensitivity to changes in the input signal waveform. Such changes occur particularly towards the endings of continuous sequences of voiced sounds. Here the contact microphone typically fails, while the electroglottograph offers a correct fundamental frequency measure. This suggests that the electroglottograph is better than the contact microphone for detailed studies of fundamental frequency as a function of time, at least as long as non-breathy phonation is concerned. Therefore, for such detailed studies of fundamental frequency in speech an electroglottograph should be given preference in all subjects for whom it works. If it is essential that a number of subjects are measured by means of the same procedure, preference should be given to the contact microphone.

CONCLUSIONS

Both techniques examined in the present investigation have strong and weak points. The electroglottograph rarely fails on those subjects for whom it works at all: those voices that can be measured are generally measured accurately. It records the glottal closures rather than the sound generated by the vocal fold vibrations. It is often difficult to use on subjects having a thick layer of subcutaneous tissues on the neck, and on subjects in which the glottis never closes such as in cases of vocal fold paralysis. The contact microphone, on the other hand, can probably be used in all subjects, even in cases where the electroglottograph fails. Its output signal mirrors the sound generated by the vocal fold vibrations. There is no exact agreement between the fundamental frequency data obtained by the two methods. Mainly, this is a consequence of the fact that variations in the contact microphone output signal waveform cause errors in the fundamental frequency measurements. However, such errors can easily be eliminated by means of a running median smoothing algorithm. For the purpose of obtaining fundamental frequency histograms, the differences in the measurements between the methods are negligible.

For the practical use in the phoniatric clinic, it seems that the electroglottograph should be preferred as long as it works well, and it should be replaced by the contact microphone for remaining patients. If for some reason it is considered important that the same method should be used on a great number of subjects, the contact microphone would represent the best choice.

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