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ACOUSTIC-MECHANICAL FEEDBACK IN VOCAL SOURCE-TRACT INTERACTION

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ABSTRACT

A new method to investigate vocal source-tract interaction is introduced. The method is based on the usage of excised larynges connected to an artificial vocal tract. Measurements of one larynx with a somewhat special behavior are described and analysed in detail. The analysed case gives clear evidence that the resonances of the vocal tract may influence directly or indirectly the vocal fold vibrations.

INTRODUCTION

In recent linear models for vocal fold vibration the vibratory pattern of the folds, i.e. the glottal opening as a function of time, is assumed to be an independent phenomenon in the sense that the vocal tract resonator has no effect on the mechanical vibrations of the folds. Until now the source-tract interaction has mainly been studied on the level of acoustic impedances, where the glottal opening and the subglottal tubes form an acoustic load for the vocal tract. Thus some part of the energy is lost from the vocal tract during every open period of the glottis [1].

It is well known that the sound pressure level (SPL) in the vocal tract just above the glottis is about 120-130 dB during voiced sounds. This study was undertaken to determine if this pressure is able to produce changes in the vibratory pattern of the vocal folds by deforming the mucosa-cover of the folds or by means of some other mechanism. In other words: Is there any acoustic-mechanical feedback in the vocal source-tract interaction?

We used excised larynges in our study. This is a legitimate method, known for instance from the work of van den Berg and Tan (1959) [2]. The novel methodological aspect of this study is that we combined excised larynges with an artificial vocal tract. This method makes it possible to control the resonances of the tract in a known and repeatable way. Since an artificial vocal tract is used, the changes of its profile will affect the vocal folds *only acoustically*. Therefore, we are able to distinguish between the mechanical (i.e. movements of articulators transferred via tissues) and purely acoustical effects. In our method only the acoustic power can affect the vibratory pattern of the vocal folds.

However, the method of van den Berg and Tan has severe limitations. First of all, it is almost impossible to simulate the action of the thyroarytenoid muscle [2], [3], and second, the dead tissue does not permit accurate measurements of the vibratory pattern of the vocal folds over a longer period of time [4]. The first problem is not a serious one, as the body, i.e. the vocal muscle is not of great importance in pitch control of phonation [5]. The vulnerability of the cover (mucosa) of the vocal fold was pointed out already by van den Berg and Tan [2]. The second problem may be solved by limiting the duration of each phase of the experiment and performing an adequate number of repetitions and by stabilizing the arrangement of each phase.

This study was carried out at the Phoniatric Department of the Tampere University Central Hospital in cooperation with the Acoustics Laboratory at the Helsinki University of Technology. In the Phoniatric Department this study is part of a larger long-range project investigating questions in voice physiology. In the Acoustics Laboratory this study is part of a chain of studies dealing with the modelling of speech acoustics.

The experiments we made produced a bulk of material that needs to be studied in more detail. In this preliminary report we concentrate on one of the most interesting phenomena observed.

MATERIAL AND METHOD

The effects of acoustic-mechanical feedback on the vibrations of the vocal folds were examined in three fresh excised larynges taken from autopsies of males. In the dissection the vocal folds were left intact. The epiglottis and the ventricular folds were removed in order to get a better view of the vocal folds [2], [4]. After dissection the specimens were stored in 0.67% NaCl solution at a temperature of +4 °C for 1-2 days.

One of these larynges showed an exceptional high sensitivity to the variations of the supraglottal resonances and therefore it was chosen for closer analysis. It was obvious that acoustic-mechanical feedback in the vocal source-tract interaction should be seen most clearly in this case.

The experimental arrangements are shown in Fig. 1. For the experiment the cricoid cartilage was fixed in an air tight manner on an acrylic plate just above the hole for air intake. The supraglottal acrylic tube (length 17.5 cm, inner-diameter 2.9 cm, volume 115.6 cm^3) was attached to the thyroid cartilage and supported with a holder. An air-tight connection of the tube-thyroid cartilage junction was obtained by using plastic mass (Optosil®) and rubber sealant.

The glottal closure was obtained with two threads attached to each arytenoid cartilage. A constant force was used to pull each thread throughout the experiment. Phonation was elicited by a constant humidified and warmed (37°C) air flow which passed through the acrylic plate. The flow was measured using a flow meter (AGA). Under the acrylic plate was a sampler for condensation water. The sampler acted as the subglottal space [6]. On the side of the sampler there was an outlet for measurement of the subglottal pressure, which was recorded (Frökjaer-Jensen Manophone).

The acoustic load of the artificial vocal tract, i.e. the supraglottal tube, was varied by moving an acrylic cylindrical block in the tube. The position of the cylinder was visually monitored by using a centimeter scale drawn on the tube. The block was 8 cm in length and 2 cm in diameter. This choice was made so as to reserve free space for the cable of the photosensor (see Fig. 1). With this block we were able to vary the frequency of the first formant from 400 to 600 Hz.

The subglottal pressure varied between 10-20 cm H_2O. This is somewhat high for speech but still within physiological limits. The average pitch of this larynx was about 170-180 Hz, higher than in a normal male voice.

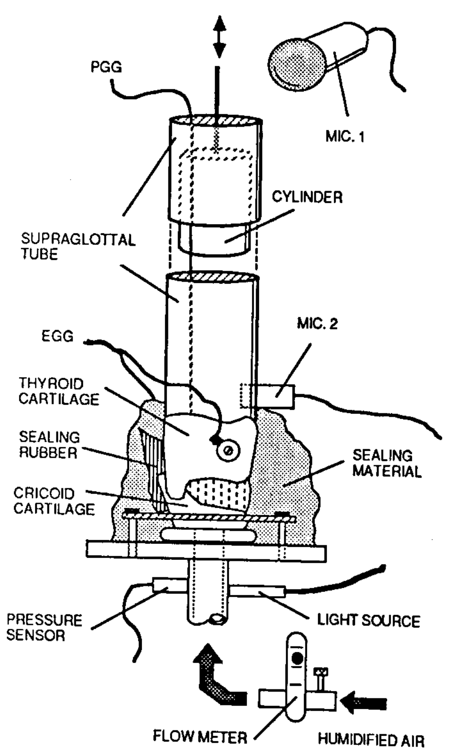

Fig. 1 *The experimental arrangement.*

Electrical signals describing the vocal fold vibrations were recorded by using a high-quality tape recorder (Tascam, acoustical signals only), a FM-type instrumentation recorder (Racal) and a digital PCM coder and recorder (Sony Digital Audio Processor F-1 and Portable Video Casette Recorder SL-F1E). One acoustic microphone (AKG C5657E) was placed close to the opening of the supraglottal tube and the other (B & K 4133) was air-tightly mounted into a hole on the side wall of the tube just above the glottal level. The electroglottographic signal (Frökjaer-Jensen EG 830) was obtained using small coin-shaped brass electrodes attached with a screw symmetrically to each side of the thyroid cartilage on the vocal fold level [4]. The photo-electric glottographic signal was obtained by introducing a light beam into the subglottal space through a window (Frökjaer-Jensen Photo-electric Glottograph). The light which passed through the glottis was detected by a photosensor placed in the supraglottal tube.

The vibratory pattern of the vocal folds was monitored using a laryngostroboscope (B & K Type 4914). The recorded signal samples were analysed at the Acoustics Laboratory of the Helsinki University of Technology using a PC-based (MacIntosh) ISA-system (Intelligent Speech Analyser®, Vocal Systems, Ltd).

RESULTS

One of the larynges showed a special behavior. Its vibrations were typically weak and sounded leaky (noisy) and aperiodic, somewhat creaky. Changing the flow or subglottal pressure did not improve its performance. Only when the block was put in the resonator did the vocal folds start to vibrate strongly with stable amplitudes and periods. When the block was placed in deeper, simulating a back vowel, the vibrations once again became weak and inconsistent. The vibrations were strong only when the block was about in the middle of the tube or in the front.

Fig. 2 illustrates how the subglottal pressure varies when the block is moved from a back vowel position out of the tube. Initially the vocal folds are not vibrating properly, the glottis is leaky and the subglottal pressure low. When the block is moved upwards a stronger vibration suddenly starts and the pressure increases indicating a better glottal closure. When the block is out of the tube the vibrations are again weak and the pressure low. This was a systematic and repeatable phenomenon achieved with this larynx. During this experiment the photosensor was removed to make the movements of the block free and to ensure that the possible movements of the sensor were not creating this phenomena.

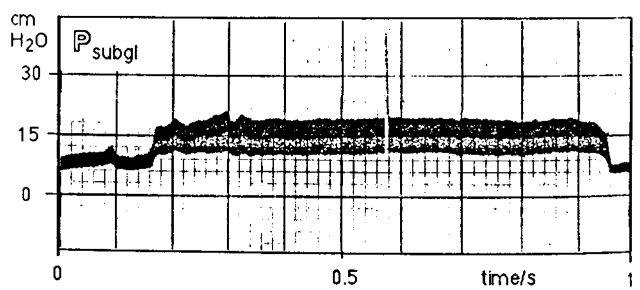

Fig. 2 *Change in the subglottal pressure due to the variation in the supraglottal impedance and in the vocal fold vibration.*

Fig. 3 shows in more detail how the stronger vibration begins and ends. In this figure the DC component has been removed.

Two spectra of the subglottal pressure are seen in Fig. 4. The upper part of the figure shows the signals where the stronger vibrations began and the lower part where they ended. One can note that the increase in the amplitude of this signal is mainly due to the increase of its first harmonic. The amplitude of the fundamental is not changed by much. The amplitudes of the second and third harmonics have also increased. When the block is moved out of the tube and the intensity of the subglottal pressure signal falls off, the changes in the harmonic structure are about the same but in the opposite direction. The intensity of the first three harmonics are affected the most. The strongly increased levels of the first harmonics will also indicate a better closure of the glottis.

The variations in the outcoming acoustic signal are seen in Fig. 5. The general trend is the same as in the earlier figure. The two first resonances of the tube are located at about 600 Hz and 1.3 kHz indicating that the block is in the back vowel position. When comparing the upper parts of Figs. 4 and 5 one can note that during strong vibration, i.e. better glottal closure and higher subglottal pressure (indicated by the white spectrum), the harmonic peaks in the region of the second formant are not seen in the subglottal pressure signal, whereas when the glottal closure is bad these peaks are clearly seen (black spectrum).

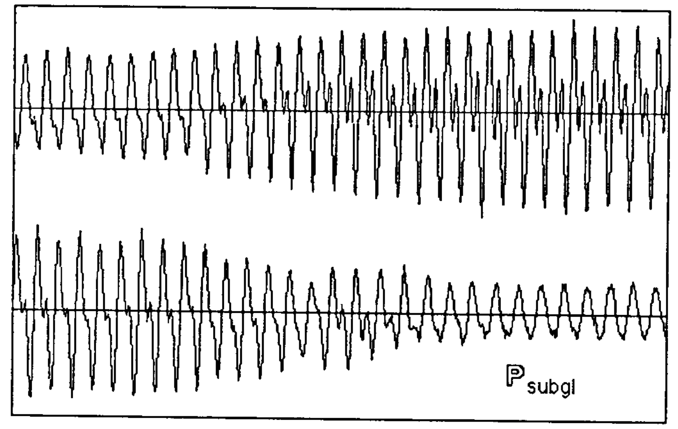

Fig. 3 *Subglottal pressure wave at the beginning and end of the stronger vocal fold vibration.*

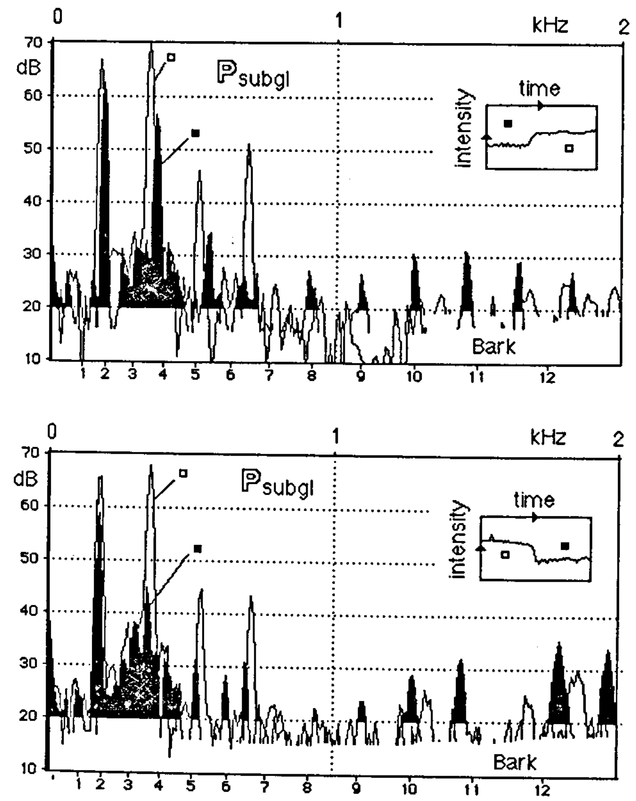

Fig. 4 *Change in the spectra of the subglottal pressure at the beginning and end of the stronger vocal fold vibration.*

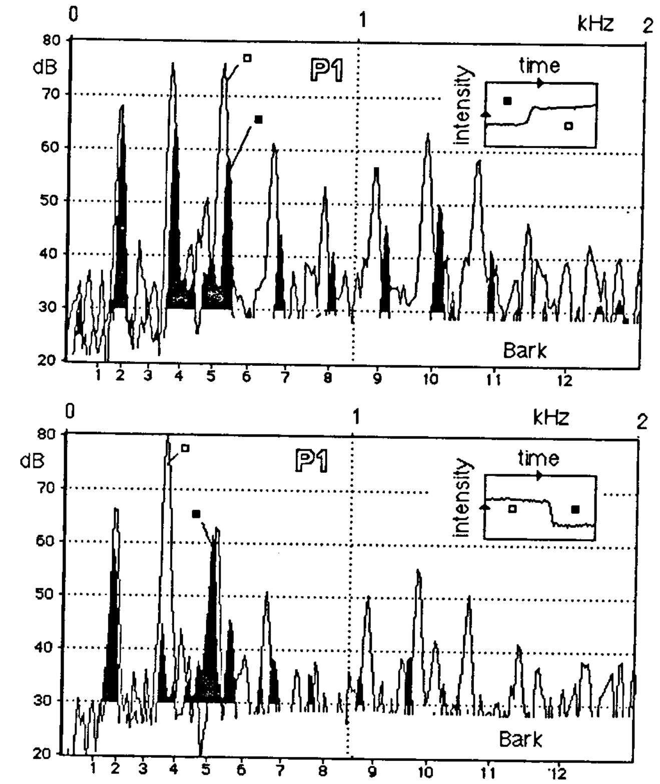

Fig. 5 *Change in the spectra of the outcoming acoustic signal (mic. 1).*

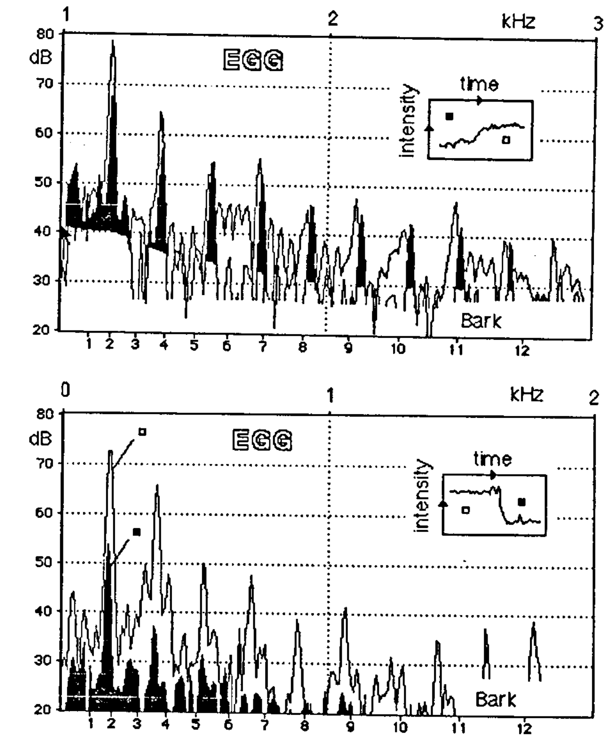

Fig. 6 *Change in the spectra of the EGG.*

Fig. 6 shows the corresponding variations in the spectra of the EGG signal. In the upper part of the figure (increasing intensity) the strongest amplitude change is seen at the peak of the fundamental frequency while the levels of the harmonics are not affected as much. When the intensity is decreasing the change is about the same over the whole spectrum.

Fig. 7 compares two EGG pulseforms normalized in amplitude and frequency taken from the first low intensity region and from the beginning of the high amplitude region. During weak oscillations the decreasing contact (opening) forms only about 20% of the pulse duration (pulseform 1). When the oscillation is strong the corresponding region is about 64% (pulseform 2). In this respect the EGG pulseform is changed radically even if the power spectra (Fig. 6 upper part) remains about the same. This indicates that *the phase relationships are changed.* The weak pulse (1) indicates that there are some types of acoustical forces coming from the tube resonator which are able to make the opening of the glottis faster and the closing slower. This breaks the vibratory pattern of the vocal folds and gives the voice a bad quality. In the opposite case the forces are in phase with the natural glottal oscillations and the voice quality is good.

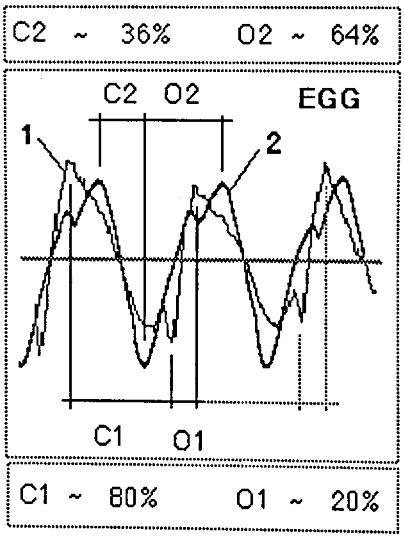

Fig. 7 *Normalized EGG pulseforms:*
1 º at low intensity region — *C º closing periods*
2 º at high intensity region — *O º opening periods*

DISCUSSION

Our new method of combining an excised larynx with an artificial vocal tract has given a clear indication that the vocal tract resonator is able to produce such a high acoustic energy above the vocal folds that their vibratory pattern may be radically affected. The acousto-mechanical phenomena we are investigating seems to be too complicated to be explained with present-day linear models. According to Mozer [7] the phase relation between the fundamental and the first harmonic may affect the vocal fold vibration. The pitch was relatively high in this case and we have estimated that the formant movement in question can make a phase change of about 90 degrees between the fundamental and the first harmonic. Therefore, the strong second harmonic when in optimal phase with the vocal fold vibrations may produce a better closure and otherwise may hinder the complete closure.

Titze [8] has also reported about this kind of interaction: "... it would appear that the vocal tract pressures reflected back to the glottis can assist in sustaining vocal fold vibrations."

Our results have confirmed this: the acoustic power in the vocal tract can assist or hinder the vibrations of the vocal folds. Does this feedback, which seems to be nonlinear, work directly on the mucosa cover of the folds or indirectly via the Bernoulli effect? This question still remains open.

ACKNOWLEDGEMENTS

The authors are grateful to Prof. A. Sonninen for the fruitful discussions during this work. This study is supported in part by the Academy of Finland.

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