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Simulation of an electro-acoustic implant (EAS) with a hybrid vocoder

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Electric-acoustic stimulation (EAS) is indicated for hearing impaired patients with enough residual hearing in low frequencies and severe hearing loss in high frequencies. We aimed at simulating the speech intelligibility provided by EAS with a hybrid vocoder model.

The French Fournier word set was used in this study. We therefore tested several parameters on 24 normal hearing adults. First, the boundary between acoustic and electric stimulation frequency areas (Fc) was taken at 500, 707, 1000 and 1414Hz. Second, we assessed the effect of electrical stimulation channel numbers (1 to 4). Third, we tested the effect of background noise with a cocktail party noise at -6 dB SNR.
It appeared that the 3 electrical channels & 707 Hz Fc condition produced normal-hearing-like results (at least in quiet). In noisy auditory scene, 4 electrical channels & 500 Hz Fc could produce fair speech intelligibility. [Work supported by CNRS, Lyon1 University and Medel].

1 Introduction

1.1 Audition in normal-hearing people

The sound wave when enters, vibrates the eardrum, and then it is transmitted to cochlear fluid of the inner ear via the adaptation of impedance realized by the ossicular chain of the middle ear. The cochlea is made of sensory hair cells which give birth to the nervous message. Then, the nervous message is conveyed along the auditory pathways, it crosses several relays, each composed of specialized neurons, the brainstem and the auditory cortex, where the sound information is integrated and the person becomes aware of it.

Audition is allowed thanks to two main ways of coding the frequential information [1]. The spatial coding is a result of the tonotopic organization of the cochlea and of the cortex (each part allows to encode a specific frequency). The site of maximum displacement of the basilar membrane leads to a certain sensation of pitch [2]. The second coding is the temporal coding. Some neurons can synchronize with the periodic component of the stimulus till a given frequency, which decreases for the most integrated centers, and give additional information about the pitch.

The coding of the intensity is linked to the amplitude of the eardrum's vibration; a high vibration implies a high stimulation of the cochlea, and a high discharge of the fibers on the auditory nerve. On the other hand, the outer hair cells, parallels to the inner hair cells, realize an active mechanism which amplifies the vibration of the basilar membrane and thus the intensity of sound is perceived in a more dynamic way.

1.2 The classical hearing aid

Hearing aid allows curing mild to profound deafness. It can be an "In The Ear" (ITE = the device is placed into the canal ear), or a "Behind The Ear" (BTE) device, which can be more powerful. The sound is captured by one (or two) microphone(s), and it is digitized. This signal goes into a processor which gives more or less importance to certain frequencies and intensities, depending on the hearing loss of the patient. Finally, the signal is amplified and a loudspeaker translates it as a sound which will be conveyed into the canal ear.

1.3 The cochlear implant (CI)

The cochlear implant (figure 1) is a device for hearing-impaired listeners who have a profound to total deafness, and who can't be helped by high-powered hearing aids. This cochlear implant is based on the stimulation of the auditory pathways thanks to an electrode array surgically inserted into the cochlea, which transmit the sound by electrical pulses. The CI is composed of two parts (internal and external). The external part, has the aspect of a BTE, it contains the microphone which captures the sound and digitizes it. The signal is analysed by the speech processor (in the same BTE) and the message is sent to the internal part, placed under the scalp. This implies the selective activation of the different electrodes which send electrical pulses directly on the auditory nerve, each electrode stimulating a particular frequency band.

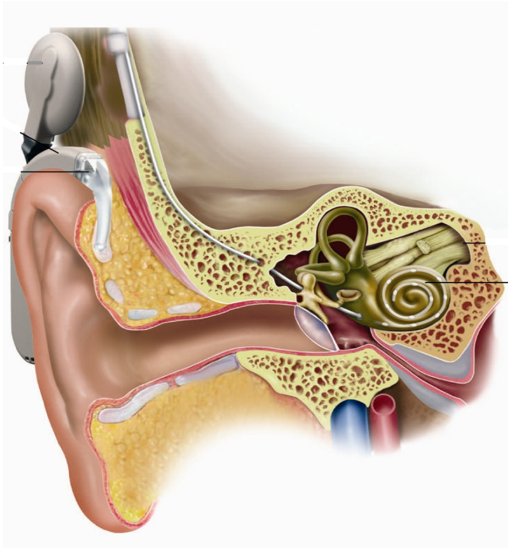

Fig. 1. Principle of the cochlear implant. (source Med-El) The implant is composed of two parts: an external (microphone, processor) and an internal part (implanted electrode array). The two parts are linked at the level of the scalp thanks to a magnetic link in which the information from the external part is transmitted by a radio-frequency coupling. The sound signal captured by the microphone is treated by the implant's processor; the message is transformed as a succession of electrical pulses sent on the different electrodes which will directly stimulate the auditory nerve.

1.4 The electric-acoustic implant

The “conventional” cochlear implantation stay a dilemma for people who are at the limit of the indication ; that is people who have a too important hearing loss to be restored with classical hearing aids but not important enough to consider a cochlear implantation. Recently, cochlear implantation which was only proposed to patients who had a severe to profound hearing loss, has also become accessible to hearing impaired persons who have residual hearing in the low frequencies. New techniques of mini-invasive surgery (soft-surgery) [3,4], coupled to new electrode arrays, allow to minimize the trauma induced by the surgical act and not even destroys the residual hearing, as it could be implied with a conventionnal implantation [5,6]. In parallel, implant manufacturers integrate in one device only (Med-El DUET) the bimodal stimulation, which means that the sound will be still captured by the BTE’s microphone but the part of the mesage contained in the low frequencies is processed by an acoustic unit, as it could be done by a classical BTE hearing aid, while the high frequencies part of the message is processed by another unit which will send an electrical message to the implanted electrodes.

2 Acoustic simulation of the Electric-Acoustic Stimulation (EAS)

2.1 Aim of the study

The EAS combines the functions of the cochlear implant for the electrical stimulation of the high frequencies and a hearing aid unit which amplifies the low-frequencies (250-1500 Hz). In this study, we wish to evaluate the number of electrical channels necessary to restore the lack of speech intelligibility of a hearing impaired patient implanted with EAS, for several cut-off frequencies between acoustic and electrical stimulation. Recent studies [7,8] have shown that using the residual hearing in the low frequencies brings a real benefit for understanding and here we wish to extend these studies in order to show that, for a person who has residual hearing until a certain frequency, N channels are sufficient at the implanted part to restore the lack of understanding. We would like to evaluate N (number of channels) depending on Fc, frequency until which there is usable residual hearing. Our study will be limited to a normal-hearing population for the moment, and we wait for enough patients to be implanted with the EAS system, so that we could confirm the results shown with the EAS simulator.

2.2 Material & Methods

This study has been realized on a population of 24 normal-hearing subjects (hearing loss inferior to 20 dB HL on the 250-8000 Hz frequency range), between 18 and 34 years old, on the right ear only, without practice for the test. To evaluate the speech intelligibility depending on the simulated hearing loss, the subjects listened to lists of words, and they were asked to repeat what they had understood. The phonetic material used was the french Fournier word set (40 lists, each composed of 10 bissyllabic words), pronouced by a single male talker. As we use bissyllabic words, the unit for counting is the number of syllables correctly repeated. Each list contains 10 bissyllabic words, so each right syllable is equal to 5% recognition. In order to simulate the different hearing loss, the speech sounds were modified with the following parameters: the cut-off frequency Fc between acoustic and electrical stimulation (Fc = 500 Hz; 707 Hz; 1000 Hz; 1414 Hz), the type of stimulation, and the number of channels on the simulated implant (1 to 4 channels). The tests were realized in quiet and in a noisy environment at -6 dB SNR.

To generate the different types of stimulation, we were inspired by different studies [9,10,11] to make a vocoder, it’s a computing program which recieves as an input the acoustic signal we want to transform, and the output of the program is a sound which reproduces the acoustic signal as it could be heard by a EAS implantee, depending on the situation to be tested. It is this signal that will be heard by the listeners.

About the signal processing, the hearing impaired patient’s residual hearing, amplified by a hearing aid was reproduced by a low-pass filtering of the signal until the frequency Fc. This method is little faithful to the reality because it doesn’t reflect exactly the auditory perception of a deaf person, but it allows us to reproduce the “frequency limitation” which interests us.

The high-frequency part of the signal was encoded in order to reproduce the functioning of a CI. For our study, we considered that the frequential informations above 4 kHz were not absolutely essential for speech intelligibility, that’s the reason why we chose to limit the simulation of the implanted part in the [Fc-4kHz] range.

The cochlear tonotopy is organized depending on a lin-log scale (linear in the low frequencies and logarithmic in the high frequencies) and for our study, the simulated implant only encodes the high frequency. So, the cut-off frequencies between the different channels were chosen in order to respect this logarithmic scale.

All the filterings were realized with the software “Cool Edit Pro” (Adobe Audition), using the function “FFT filter”. The parameters we chose for the filters were coefficients of 100% in the bandwidth and 0% in the attenuated band, with 0% corresponding to an attenuation of 70 dB for all the spectral coefficients of the attenuated band.

To generate the electrical channels, we divided the [Fc-4kHz] part in N bands, N corresponding to the number of channels of the CI (N = 1, 2, 3 or 4). For each channel, the signal is selected by a band-pass filter (we will call Fmin and Fmax the limits of the bandwidth), and its envelope is extracted by full-wave rectification and a low-pass filtering until 50 Hz. Following this step, all the envelopes are filled with a white noise, filtered for the same frequency range, but of which the bandwidth is narrower, which means that each envelope with a bandwith between [Fmin Fmax] is filled with a white noise filtered by a band-pass between [(Fmin + 75Hz) (Fmax – 75Hz)] (this in order to avoid a frequential recovering due to the modulation of the narrow band noise by the envelope).

Once the signal of each channel is made, there is a necessary step of amplification, because of the fact that modulation of the narrow band noise by the envelope reduces the initial energy contained in this signal. So, we need to be sure that the energy contained in the simulated electrical channel is the same as of the energy contained in the initial acoustic signal, filtered by the band-pass corresponding to the channel.

Finally, when all the electrical channels have been amplified, both acoustic and electrical channels are summed, in order to get the acoustic signal for the tests (figure 2).

Among the various types of stimulations tested, we use the "acoustic only" stimulation which allows to reproduce the audition of a deaf person who has residual hearing in the low frequencies, the "electric only" stimulation, to simulate the audition of a cochlear implantee, and finally a situation "acoustic + electrical", to reproduce the sound percieved by a person implanted with an EAS system. All the tracks were randomized and played the same number of time for every subject. We use 40 lists of words and we have 40 situations to test, which prevents any learning of the lists due to repetition by the listeners.

The figure 2 allows us to see how the frequential resolution is damaged in the part which encodes the simualtion of implant.

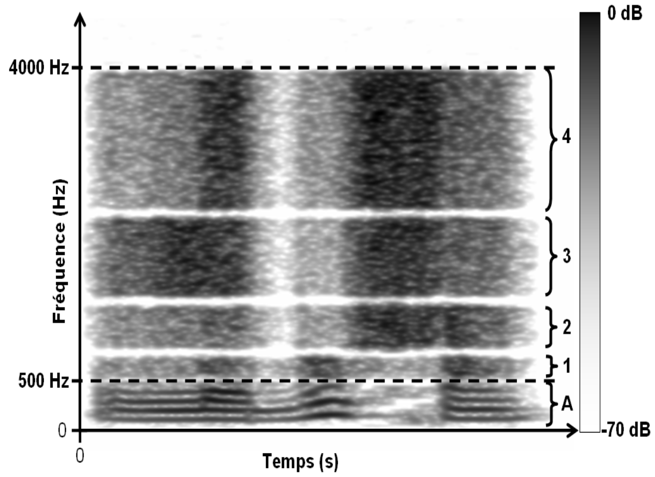

Fig. 2. Spectrogram of the french word « le bouchon » encoded for the situation Fc=500 Hz with 4 electrical channels. The brackets show the different bands : A = acoustic stimulation ; 1, 2, 3 and 4 = n° of the simulated electrical channels.

2.3 Preliminary results

For the interpretation of the results, we considered that the lack in speech intelligibility was restored when the subject's score in syllables recognition was superior to 90%. The first results (figure 3 and 4) seem to show that, in quiet, one channel (■) in the part coded by the CI is sufficient to restore the loss of a deaf person who has residual hearing until 1400 Hz. Also, 2 channels (▲) are sufficient to restore the loss of a deaf person who has residual hearing until 1000 Hz, 3 channels (●) with rests until 700 Hz and finally 4 channels (×) with residual hearing until 500 Hz. The studies [12], [13], [14], realized with patients implanted EAS (figure 5), present recognition scores for monosyllabic words between 0% and 13% with the acoustic part only, between 45% and 61% with electrical part only, and between 50% and 75% for the EAS situation.

For the situations "EAS" and "cochlear implant only", the results with the implantee are quite consistent with the results obtained with our simulation. On the other hand, about the results for "using only the acoustic part", we can't quantify exactly the cut-off frequency of the residual hearing in patients and we can't say there is a perfect similarity between the results obtained for our model and the results obtained with the implantees.

We can see on figure 6, that in very noisy environment (using a cocktail party noise), with residual hearing until 1400 Hz and 4 added electrical channels, we can reach very good scores of about 50%.

3 Conclusion

After new analysis of the results, we expect to show that, for the same given information, the electrical channels of the implant have a more important contribution for an implantee who has residual hearing, than for an implantee who hasn't some. We also wish to compare the results of this simulation, with the performances of the EAS implanted patients, in real situation, once we will have enough EAS implantees, for the same conditions (hearing aid only, CI only and EAS).

For figures 3 and 6, every point is the mean result for the 24 normal-hearing subjects. The vertical bar represents the standard error. The curves represent respectively, from the bottom to the top, acoustic stimulation only (♦), acoustic stimulation + 1 electrical channel (■), acoustic stimulation + 2 electrical channels (▲), acoustic stimulation + 3 electrical channel (●), and acoustic stimulation + 4 electrical channel (×).

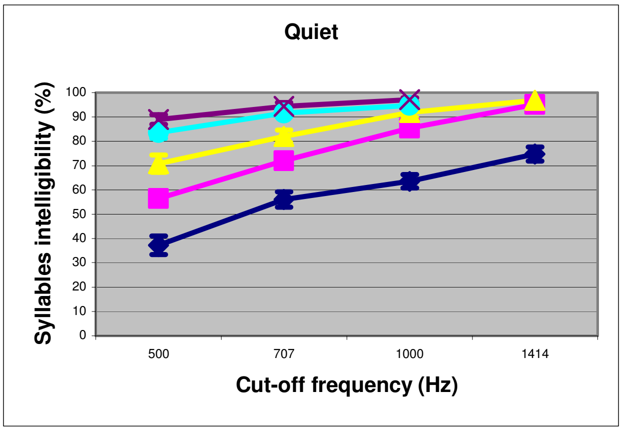

Fig. 3. Syllables intelligibility (%) depending on the cut-off frequency between acoustic and electrical stimulation, in quiet.

The understanding is restored (> 90%) thanks to 1 channel if the hearing-impaired person has residual hearing until 1400 Hz, thanks to 2 channels with rests until 1000 Hz, 3 channels with rests until 700 Hz and 4 channels with residual hearing until 500 Hz.

Finally, we have to precise that our model has some limits. On one hand, the envelope of our "electrical" signals is low-pass filtered till 50 Hz, while the CI stimulation allows encoding until 300 Hz, thus the results we get are under-evaluated when compared to the reality. On the other hand, for our simulation, we did suppress the interactions between the electrical channels, and the consequence is an over-evaluation of the results.

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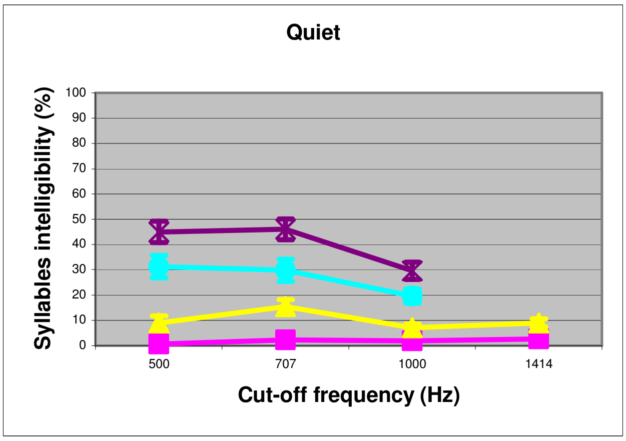

Fig. 4. Syllables intelligibility (%) depending on the cut-off frequency between acoustic and electrical stimulation, in quiet (mean results on 24 normal-hearing people), for the situation electrical part only. The curves represent respectively, from the bottom to the top, 1 electrical channel (■),2 electrical channels (▲),3 electrical channel (●), and 4 electrical channel (×).

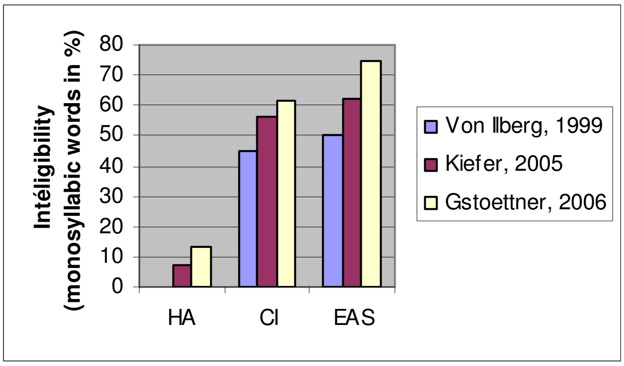

Fig. 5. Intelligibility of monosyllabic words (%), results obtained in the studies [12], [13], [14] for the situation hearing aid only (HA), cochlear implant only (CI), and cochlear implant combined with the hearing aid (EAS).

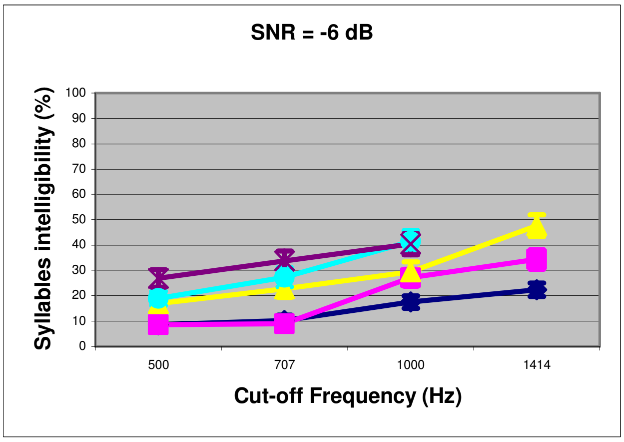

Fig. 6. Syllables intelligibility (%) depending on the cut-off frequency between acoustic and electrical stimulation, in a noisy environment at -6 dB SNR.