Master ATIAM :

PERCEPTION COURSE

Cochlear Implants of today and tomorrow

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1 Introduction

A current issue. In 2019, the WHO publishes a surprising and alarming statistic : 466 million people suffer from deafness. It predicts a figure of 900 million in 20 years. Many cases of deafness are due to cochlear failure, which can be resolved by cochlear implants. Cochlear implants replace infunctional sensory organs by electrically stimulating the auditory nerve. Unfortunately, these electrical stimuli only allow partial precision in the frequency retransmission of sound. Furthermore, cochlear implants perform well in quiet hearing scenes, but are less robust in noisy environments with a lot of acoustic interference.

Plan of study. Recent research is attempting to provide new solutions to improve the performance of these implants, in particular with ultrasound stimulation of the auditory nerve. After describing the physiology of hearing, we will present the functioning of current cochlear implants and its limitations. Finally, we will present the new solutions and their challenges.

2 Audition physiology

2.1 Cochlea and responsible mechanisms

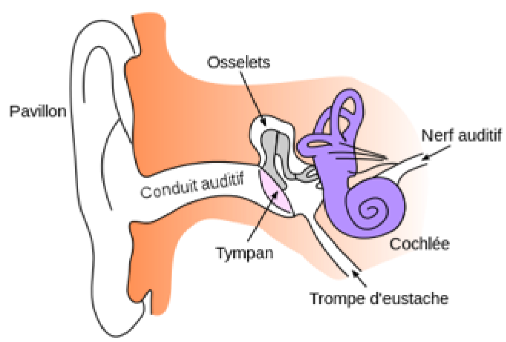

FIGURE 1 – from the outer ear to the inner ear

The acoustic vibration is captured by the eardrum, transmitted to the ossicles and then to the stirrup, which will vibrate and set the cochlea fluid in motion. The hair cells of the cochlea move according to the movement of the fluid and consequently generate electrical impulses in the corresponding nerve fibers. The information in the form of impulses is then transmitted to the brain through the auditory nerve to be interpreted as sound.

The cochlea is a snail-shaped sensory receptor. It is the part of the inner ear that also contains the bone labyrinth : part of the organ of balance. Inside the cochlea is the basilar membrane. At the end of the basilar membrane is the Apex.

We imagine a wave propagating along this basilar membrane. Each point oscillates at the frequency of the incident frequency. The whole membrane is not vibrated in the same way.

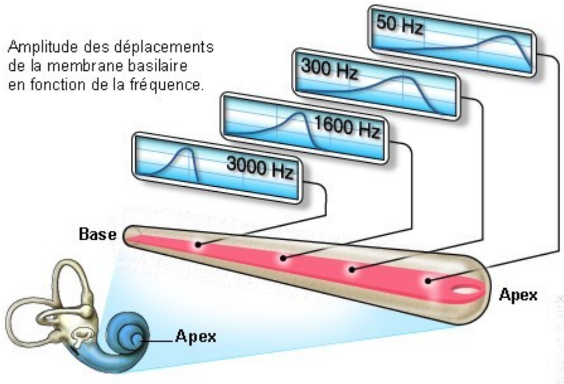

FIGURE 2 – Unfolded basilar membrane. Source : cochlea.eu

There is a maximum of deformation at a certain point. The frequency of the pure sound determines where the maximum deformation is.

For example, a high-pitched sound will have a maximum near the base of the basilar membrane (fast oscillation), while a low-pitched sound will propagate along the entire basilar membrane and will have a maximum near the Apex (slower oscillation). It is a tonotopic coding presented in more detail in the Appendix A.

The hair cells in the cochlea can then excite the nerve fibers of the auditory nerve. For pure sound, the mechanism amplifies the vibration of the basilar membrane over a very narrow portion, allowing for very precise frequency selectivity.

2.2 Hearing loss

Commonly, deafness is linked to the loss of this active mechanism. One is born with approximately 3000 internal and 10,000 external hair cells. But they do not regenerate. The loss of these cells may be related to age, but also to acoustic trauma. The latter were also mentioned at the 2020 IRCAM Amplify on health. Sensorion is a company that develops therapeutic care in the face of sudden neurosensory losses that can sometimes appear in less than seventy-two hours.

3 Current cochlear implants and their limitations

As previously studied, thousands of sensory "hair cells" are attached to this membrane, whose ends ("hairs") bend back and forth according to the vibrations of the basilar membrane.

Cochlear implants try to substitute the sensory organ of hearing. The aim is to directly stimulate these hair cells. The implants were born in 1957 by Djourno and Eyriès. They have developed a lot since, and are used by more than 300 000 people in 2020. Here is a description of the mechanisms present in the cochlear implant, largely inspired from the article [1].

3.1 Principles of operation

The cochlear implant consists of an inner and an outer part.

The inner part of the brain consists of an array of 10 to 22 electrodes surgically implanted along the cochlea.

The electrodes are connected to internal power sources which are activated according to the instructions received from the external part of the device. Cochlear implants take advantage of the representation of the cochlea as a function of frequency : each electrode contact is located near the fibers of the auditory nerve coding for different frequencies and generally evokes a perception corresponding to its location.

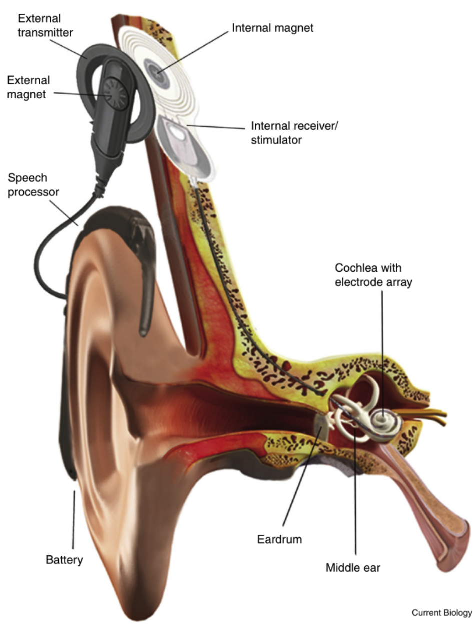

FIGURE 3 – Sketch of a cochlear implant showing the external and internal parts of the device. source : Current Biology

The external part of the device picks up the sound using one or more microphones and converts it into an electrical stimulation code via a battery-powered digital signal processing unit, called a speech processor. This stimulation code, together with the power required to activate the electrodes, is transmitted to the internal part via a radio-frequency link. The receiver decodes the radio frequency signal and sends stimulation currents to the electrodes based on the information present in the original sound. These currents depolarize the targeted nerve fibers, possibly producing action potentials.

The primary goal of treatment with a cochlear implant is to mimic the filtering normally performed by the bypassed parts of the hearing system. The speech processing methods used in today's hearing aids are based on the algorithm called Continuous Interleaved Sampling (CIS). [2] presented in more detail in the Appendix B. After digitizing the sound picked up by the microphone, a pre-emphasis is first applied : this slightly amplifies the high frequencies, which, for speech, has the effect of approximately equalizing the energy between the frequencies. The sound then passes through a bank of filters that breaks it down into several frequency bands, much like the equalizer in a Hi-Fi audio system. There are usually as many filters as there are intracochlear electrodes. This processing step is a rough imitation of the frequency mapping performed by the basilar membrane. (see appendix A). The time-varying envelope of the output of each filter is then extracted, mimicking somewhat the behavior of the hair cells.

3.2 Limits

The 22 or so electrodes do not make it possible to replace the 3000 hair cells. Moreover, we are in a conductive environment, so when we send an impulse we stimulate a whole region. The signal is therefore partially frequency accurate.

As seen in the previous section, the principle of selectivity is very important in auditory perception. However, when hair cells die, this selectivity is also lost. So the amplification of the signal can cause a gain of all frequencies and therefore a very flat, very noisy sound.

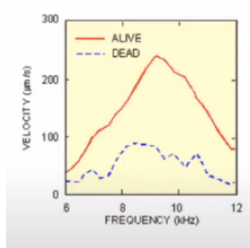

FIGURE 4 – Loss of selectivity. Source : Daniel Pressnitzer course

Finally, the performance of the cochlear implant depends on the individual. The amount of current to be applied to the electrodes may vary. And we are still a long way from perfect precision in the positioning of the electrodes. Therefore, real-time DSP algorithms still need to be improved to better manage complex sound environments, the multiplicity of sources in a mix, or the presence of noise.

4 Ultrasound stimulation, the cochlear implants of tomorrow ?

4.1 Better focus the stimulation of the auditory nerve

Ultrasound (US) is a mechanical and elastic wave, which propagates through solid, liquid or gaseous media. The frequency range of ultrasound is between 16,000 and 10,000,000 Hertz. This is of course too high to be perceived by the human ear, but a very high intensity, focused flow of ultrasound can be perceived by the human body via other sensory neurons.

As previously observed, the electrodes activate a large population of spiral ganglion neurons (SGNs). It is known that each sub-population of neurons encodes different frequencies. Therefore, the lack of spatial selectivity in the activation of neurons implies a lack of frequency selectivity.

To restore "normal" listening, about 50 frequency channels would be needed. However, current implants have about 20 electrodes that can create only 8 frequency channels. Current research has shown that electrical stimulation will not be able to create more than 8 frequency chains.

Could we change the shape of the impulses to focus the stimulation of the auditory nerve ?

The study conducted in the USCI (UltraSonic Cochlear Implant) project studies ultrasound stimulation as an alternative to electrical stimulation to increase spatial selectivity. Ultrasonic frequencies may be transmitted by bone conduction [3].

4.2 A solution still in the experimentation phase

The mechanisms of ultrasound stimulation remain little known. The question is still to know which phenomena (acoustic radiation force, temperature change) induced by the US are responsible for the activation of neurons in our device in vitro.

What type of neurons in the spinal ganglion responds in the US ?

How are ultrasounds translated into action potentials ? Experiments conducted by the LMA (cochlear implants and ultrasound), IBDM (molecular biology), LNSC (auditory neurophysiology) teams of the Hear-US project are attempting to answer these questions using electrophysiological experiments and analysis from electrodes implanted in animals.

Conclusion

Despite some limitations, current cochlear implants are a very effective solution to the problem of hearing loss.

Research on ultrasound stimulation aims to lay the foundation for the development of a new generation of cochlear implants based on multi-element transducers in a phased array, by analogy with multi-electrode cochlear implants.

Recent progress in audio signal processing using Machine Learning also offers good prospects for improving DSPs. It remains to be seen how to embed these models, which are often very heavy in terms of computation and not yet optimized for real time. As said by the researcher Deliang Wang : "I've yet to see the first hearing aid which really incorporates deep learning for noise removal."

Références

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[3] Martin L Lenhardt, Ruth Skellett, Peter Wang, and Alex M Clarke. Human ultrasonic speech perception. *Science*, 253(5015) :82–85, 1991.

[4] Martin Kompis, Mattheus W Vischer, and Rudolf Häusler. Performance of compressed analogue (ca) and continuous interleaved sampling (cis) coding strategies for cochlear implants in quiet and noise. *Acta oto-laryngologica*, 119(6) :659–664, 1999.

Appendices

A First discovery of tonotopic coding

When we are in the presence of different pure sounds, several areas will vibrate simultaneously ; we will have several deformations along the basilar membrane. The latter is therefore similar to a spectrum analyzer. It changes its mechanical properties according to the sound.

This modeling had been intuited by Helmholtz as early as the end of the 19th century. In his book *Sensation of Tone* written in 1877, he makes an analogy between the basilar membrane and the piano strings, each resonating according to frequency. The cochlea is composed of a set of resonators next to each other that code different frequencies.

In 1961, Georg Von Bekesy received the Nobel Prize by demonstrating that the tonotopic code is verified experimentally.

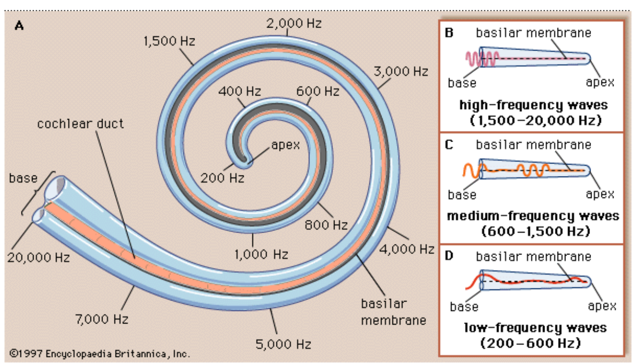

FIGURE 5 – The basilar membrane. Source : Encyclopædia Britannica

B Comparison between two speech recognition DSPs

In the Continuous interleaved sampling (CIS), the pulse amplitude is derived from the envelopes of the bandpass filter outputs. In contrast to four-channel AC, five or six bandpass filters are typically used in CIS to take advantage of the additional electrodes implanted. This also reduces the interaction between channels. The experiments performed in the article [4] show that CIS performs best in quiet environments, while AC is ultimately effective in high noise environments.

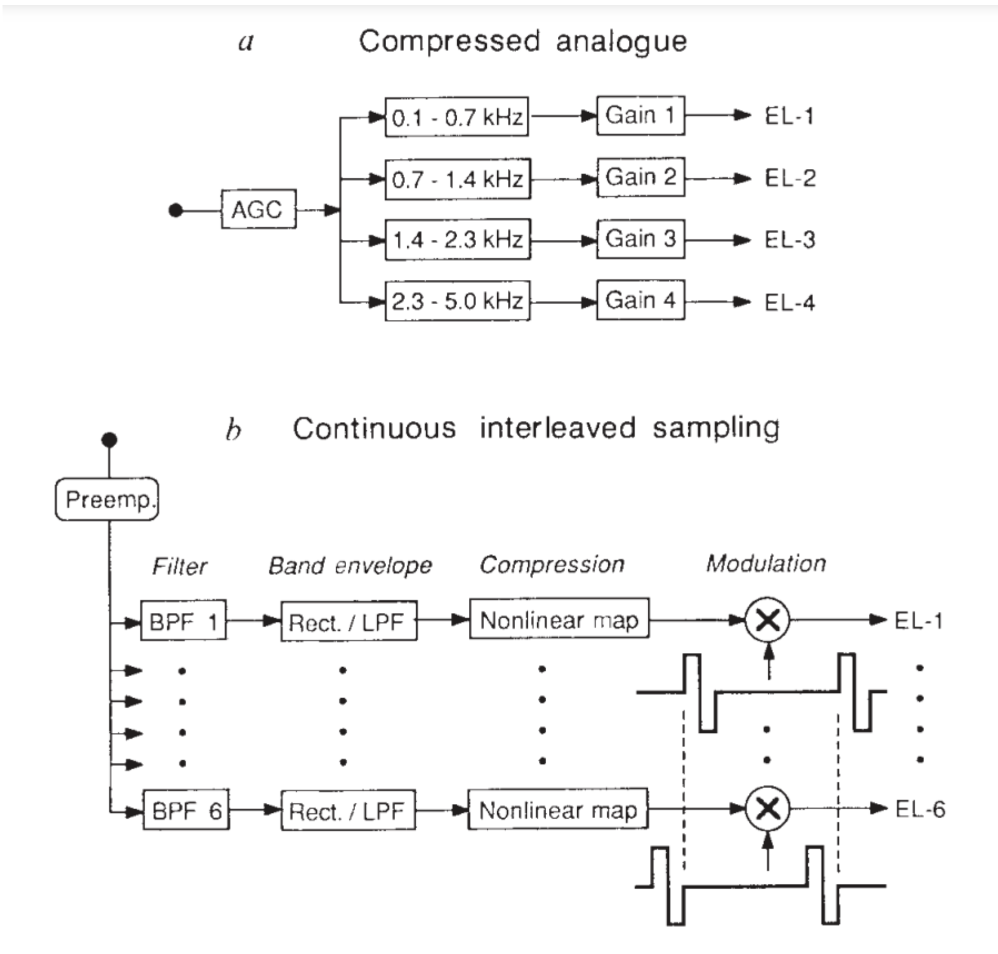

FIGURE 6 – Two classic DSPs. Source [2]