Cochlear implants: an introduction

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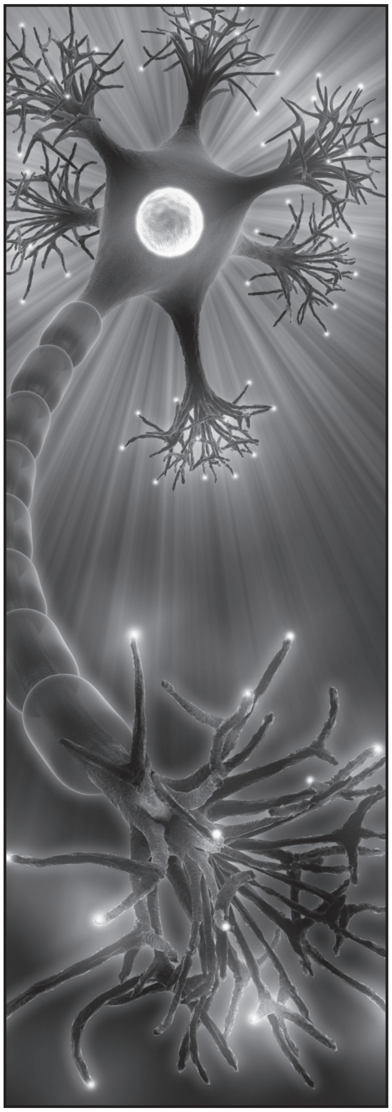

Resumen

El desarrollo de la ingeniería biomédica en las últimas décadas ha permitido una revolución en el desarrollo de prótesis para las personas con discapacidades. El campo de las prótesis para órganos sensoriales, sin embargo, ha probado ser un reto para los científicos, que se encuentran con el problema de descubrir cómo el cuerpo percibe las señales que llegan desde el mundo exterior y las transforma para ser asimiladas por nuestro cerebro. Dentro de este campo se encuentran los implantes cocleares que, aunque aún distan de tener un funcionamiento perfecto, han evolucionado de manera sorprendente gracias a los esfuerzos de los investigadores, y hoy brindan a millones de personas en el mundo la posibilidad de escuchar y comunicarse. Este artículo pretende hacer una breve revisión de los conceptos fundamentales involucrados en la labor del sistema auditivo, y la forma en que los implantes cocleares funcionan.

Keywords: Cochlear implants, auditory prostheses, auditory system, electrodes, speech recognition, sound, ear, cochlea.

Abstract

The development of biomedical engineering in recent decades has led to a revolution in the development of prosthetics for people with disabilities. The field of prosthetics for sensory organs, however, has proven a challenge for scientists, who are faced with the problem of discovering how the body perceives the signals coming from the outside world and transforms them to be assimilated by our brain. Within this field lie cochlear implants which, although still far from having a perfect performance, have evolved surprisingly thanks to the efforts of researchers, and today provide millions of people around the world the possibility to listen and communicate. This article aims to briefly review the basic concepts involved in the function of the auditory system and how cochlear implants work.

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1. Introduction

Over the course of the last centuries, several of aids have been devised for people with hearing impairment. Until the 19th century this devices were usually large cones, trying to focus the energy of acoustic waves, guiding it into the ear. With the advent of electronics, these instruments have incorporated microphones and amplifiers to improve the performance.

Hearing impairments are classified as conductive or neuro-sensory. The first involve defects in the outer or middle ear, which hinder the arrival of sound waves to the cochlea. These can be solved using aids to amplify the signal, or performing reconstructive surgery on the affected part (ossicles, auditory canal, tympanic membrane). In these, the cells responsible for converting the sound wave into an electric signal, are functioning properly, and the problem is, therefore, mechanical [1].

Neuro-sensory disabilities, mean that there is death of the hair cells responsible for the transduction the sound wave into the electric signal that stimulates the neuron. These can occur from exposure to loud noises, hereditary problems or as side effects of treatment with strong drugs. If the patient has extensive damage in these cells and the auditory nerve, it is said to have profound deafness, and can be a candidate for a cochlear implant.

Cochlear implants are devices that take the sound from the environment and convert it into an electric signal which is then processed and passed in the form of electrical pulses to an array of electrodes located inside the cochlea, to stimulate directly the part of the auditory nerve that still works. In this way the brain manages to receive signals from sounds.

2. Sound

The sound is composed of a series of mechanical waves that travel through a medium. According to their frequency, these waves can be audible (in the range from 20Hz to 20kHz, which can be perceived by our auditory system), infrasonic (below 20 Hz) or ultrasonic (above 20 kHz).

Like all waves, sound has properties of amplitude and frequency. Being a mechanical wave, its intensity depends on the pressure that it is able to exert on the medium. The human ear perceives these properties in a sort of subjective values, which are the loudness (dependent on the amplitude of the vibrations), pitch (which is related to the frequency, and is usually a mixture of several pure tones as natural source's frequency varies constantly) and timbre (which allows us to identify what type of source is issued by the harmonics of the fundamental tone).

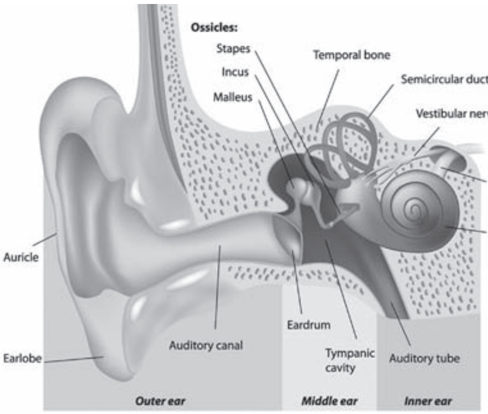
3. Process of hearing

3.1 The Outer Ear

It is basically composed of 2 parts: the pinna and external auditory canal. Its function is to focus the sound waves from the environment to channel them into the middle ear. The ear has a function similar to a satellite dish, because due to its large area (about 15 cm^2) it's able to capture a large amount of energy from sound waves.

The ear canal operates in the same way as a tube closed at one end by the tympanic membrane, thus presenting resonance at certain frequencies. The anatomical characteristics in the ear canal make frequencies between 2000 Hz and 5000 to

Figure 1. Parts of the ear



(http://nyogmd.com/files/how-ear-works.jpg) enter in resonance which is about the range of the human voice.

3.2 The Middle Ear

The middle ear begins at the tympanic membrane, and from it the sound is no longer transmitted through the air but through an elastic solid medium composed of three bones in the ossicle chain and the membrane cited above.

The tympanic membrane has a rounded shape, and being displaced by pressure medium, transmits the vibrations to the ossicle chain. The ossicles are joined together by joints and are suspended to the walls of the tympanic cavity by ligaments (which prevent separation of the interossicle joints during transmission of sounds of high intensity or high frequency). The ossicles are three: hammer, anvil and stirrup, and work as some sort of levers and pistons that transmit and amplify the vibrations of the tympanic membrane into the labyrinth of the inner ear fluid.

3.3 The Inner Ear

The inner ear consists of the cochlea, the auditory nerve and the semicircular canals, although the latter do not participate in the audition process, but as acceleration sensors, for balance. The cochlea and canals are filled with a fluid similar to water.

The cochlea is shaped like a snail, and contains over 20000 hair cells, which, because of its conformation, react diversely depending on the wave frequency that stimulates them. This is facilitated by the action of the basilar membrane, which behaves like a rope physically tied at both ends, therefore, sound travels through as a transverse wave, whose envelope is not laterally symmetrical due to changes in the cross sectional area of the membrane, and consequently each frequency cause a point of maximum amplitude different from the others.

The hair cells are connected with the fibers of the auditory nerve terminals. Thus small shifts in these, initiates the neural activity that transmits information to the brain.

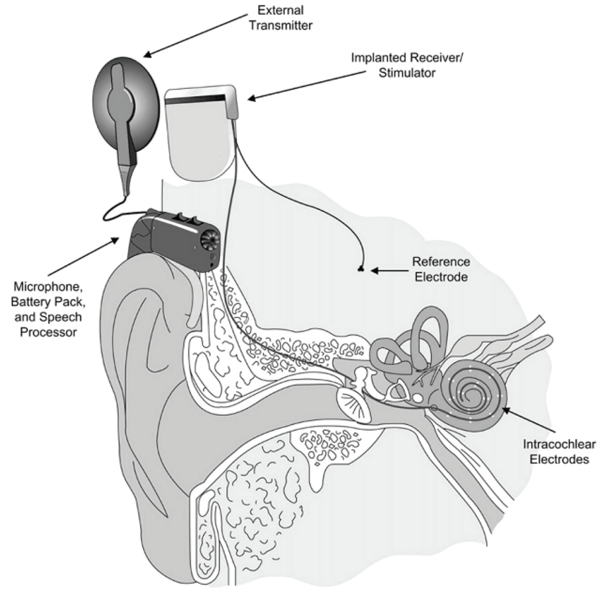
4. Hardware of cochlear implants

All modern cochlear implants are composed of an external and an internal unit. The external unit receives the acoustic signal from the medium and converts it into appropriate electrical impulses depending on the processing and stimulation technique. The internal unit has as main function the transmission of the stimulation signal to the electrodes, and from there to the auditory nerve, but also has telemetry functions. The following section describes the parts of each unit.

4.1 Microphone

Usually placed behind the ear, it converts sound into an electrical signal that will be sent to the processor. Some models allow an additional microphone that can be connected with a cable. Connecting the later usually disables the internal one. A good microphone for a cochlear implant should have a wide frequency response that doesn’t extend to very low frequencies to reduce the uptake of vibrations that may be generated by head movements and walking. The use of a directional microphone can help to improve the relation speech/noise. The sensitivity of a microphone is determined by its casing (i.e. length and

Figure 2. Basic Components of a cochlear implant system. [2]



orientation of the microphone tube affects its frequency response and the directional pattern) and by its location in the body (i.e. placing the microphone in one side of the head reduces the intensity of the high frequency sounds in the contra-lateral side of the head) [3, 4].

4.2 Processor

This is the most important and susceptible of improvements part, as it receives an analog audio signal, decomposed it into different frequency bands, before being processed according to the algorithm using (CIS, CA, SPEAK, etc.) This processed signal is then multiplexed, modulated and sent to the RF circuit, which will transmit the signal wirelessly to the internal unit. The techniques used will be described in detail later.

4.3 Transceiver

It comprises an outer and an inner coil. The external encodes the information and sends an RF signal through the skin to the internal unit. This RF signal also serves as power supply for the receiver-stimulator, which decodes the signal and stimulates the electrode array. The outer coil of transmission is maintained in place by a pair of internal and external magnets in the centers of the coils. The receiver-stimulator is implanted behind and above the ear in a flat or concave zone of the skull. This transcutaneous connection reduces the risk of infection. However, it also limits the update rates and types of waveforms that can be transmitted.

The transmission link is usually bidirectional, allowing data to be transmitted from the internal components, such as electrode's impedances, voltages, failing electrodes and intra-cochlear evoked potentials. These measurements are useful for assessing the status of the auditory nerve and to program the speech processor.

4.4 Electrode Array

The processed signal is transmitted via electrical pulses fired at various positions in a one-dimensional array of electrodes placed near the ganglion cells where the neural impulses that go the brain will be generated. The electrode assembly is composed of a corrosion resistant conductor, and electrodes with good conductive properties, isolated from each other. Ideally, each electrode should be placed in direct contact with a nerve cell to stimulate a sound wave of the appropriate frequency. However, cochlear implants typically have only 4 to 22 electrodes, less than 1% of the number of hair cells present in the cochlea. To solve the problem somehow, the electrodes are arranged according to the distribution of frequencies along the spiral path of the cochlea, as given by Greenwood's function [4].

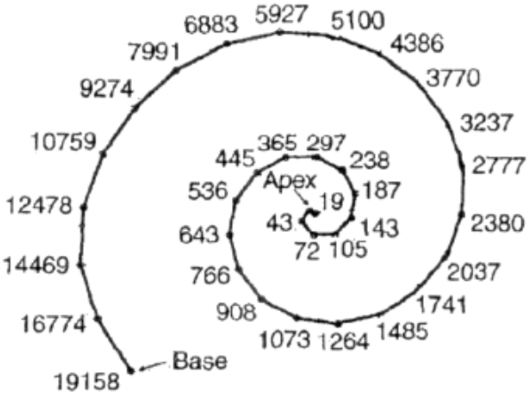


Figure 3. Diagram of the basilar membrane, showing the base and apex. It is shown the position of maximum displacement in response to sinusoids of different frequencies [5].

4.5 Telemetry

The electrodes, apart from stimulating the ganglion cells can also send information to the external drive with respect to the condition of the nerves or the implant itself. There are different methods available, but the passive telemetry, which is performed by means of load modulation (LSK) is the most used technique. The transmission is achieved by changing the load resistance of the implant, for example by changing a second load resistor, in addition to the default load resistor. The replacement of the load resistance changes the current in the implanted device, which in turn changes the current in the external device. This change is perceived in the external device receptor, which is able to retrieve the information originally transmitted by the implant.

5. Signal processing techniques

5.1 Single-Channel Implants

They were developed in the early 70's when there was still controversy as to whether such stimulation could produce something more than noise [6]. The most important were the House/3M and Vienna/3M. In the first, the signal received by the microphone was amplified and filtered between 340 and 2700 Hz t then modulated and sent directly to the electrode. The system did not reduce the dynamic range of the input, and for sounds above 70 dB the signal saturated. Vienna/3M device performed a process of pre-amplification, and filtered between 100 and 4000 Hz, to then modulate and demodulate in the transmission. The signal was also compressed in its dynamic range to suit the patient's own range, thus eliminating distortion due to saturation. The results in patients using these devices were quite poor, since the information was preserved well only for low frequencies, giving information of only the fundamental frequency and some of the vowels formants, but very little consonant information.

5.2 CA (Compressed Analog)

This technique showed much better results than the single-electrode implants and was widely used until the arrival of the CIS strategies. It consists basically on compressing the dynamic range of speech signals using automatic gain control, converting it to a smaller range that is covered more easily by electrical stimulation in the ear. Then the compressed signal is filtered and divided into several bands, which simultaneously stimulate electrodes located in different parts of the cochlea. The spectral information is therefore transmitted by the relative energy of each channel [7].

One of the main problems is that by activating simultaneously two or more electrodes, the electric fields of the signals are added, which causes problems especially if the patient has a low number of functional nerves and therefore requires high levels of stimulation. It also requires an optimal placement of the electrodes, to increase the distance between them and reduce their interaction.

5.3 CIS (Continous Interleaved Sampling)

This technique solves the problem of the sum of electric fields generated by the simultaneous stimulation of the electrodes. In this case, biphasic pulse trains are delivered alternately to the electrodes, so that only one is stimulated each time [8]. The signal is first emphasized by a low pass filter and divided into logarithmically spaced bands (usually 6 or 8, covering the approximate range 250 to 5000Hz), then it's rectified (full or half-wave rectification), and the envelope is

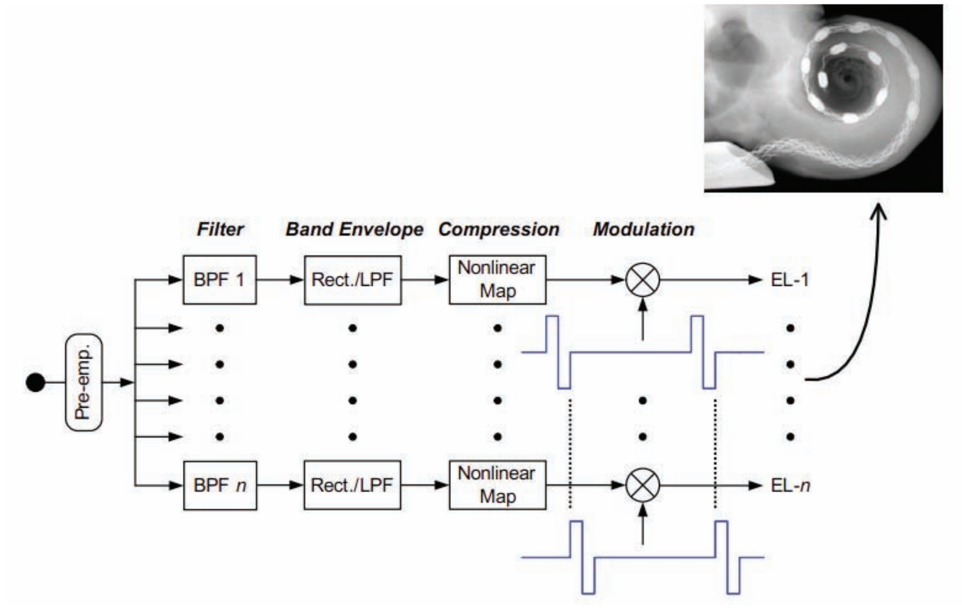


Figure 4. Block diagram of CIS strategy. [2]

extracted This envelope is then compressed and modulated for transmission to the internal unit of the implant.

5.3.1 Feature Extraction Techniques

Unlike CIS and CA techniques, extraction techniques are not characterized by filtering the signal in a few bands, but they extract spectral characteristics of the audio signal as the fundamental frequencies and formant, and then transfer this information to electrodes located in specific parts of the cochlea, according to the feature to be transmitted. The first techniques used the fundamental frequency plus the first and second formant. This gave very good results in vowel identification since these are composed of low frequencies [9]. Later, with the MPEAK technique, identification of the consonants was improved, by adding more bands to represent the high frequencies [10]. This latter technique has proven excellent results for speech recognition without visual aids, but presents a problem in that the extraction of the formants becomes difficult when there is noise in the environment, thus lowering the quality of results in everyday situations.

5.3.2 “N of M” Strategies

In these, the signal is filtered in a number m frequency bands, of which the processor selects the n envelopes (n <m) that have the most energy, and these are transmitted to their correspondent electrodes for stimulation. They can be considered a hybrid between the techniques of feature extraction and CIS.

An example of such technique is the SMSP (Spectral Maxima Sound Processor), which was developed for the Nucleus implant, in the early 90s [11]. This processor analyzes the signal using band-pass filters 16, and a maximum spectrum detector. The signals are processed similarly to the CIS technique, being pre-amplified before passing through the filters that are in a range from 250 to 5400 Hz, then rectified and the envelope is extracted via a low-pass filter. The six outputs with most amplitude are selected to be compressed and transmitted to the electrodes. This process is repeated every 4 ms, and the electrodes are stimulated in an interleaved manner.

6. Advances in design

As mentioned above, the most important part in the cochlear implant is the signal processing, since the way a patient will perceive the signal depends on it. However, it’s not the only field in which research is focused, for optimizing the efficacy of the implant depends on many factors, among which are:

6.1 Electrodes

Nowadays the electrodes come in layers of micro-machined silicon (which gives them greater functionality and provides the ability to attach sensors to gather performance measurements) and connected either by wires or thin strips, usually covered by some type of polymer with good properties of biocompatibility and positioning [12, 13]. Given the large number of electrodes used in certain devices and the small area they will occupy, new techniques that facilitate manufacture and reduce cost are an important field of research. These techniques will also allow to increase the number of electrodes, and improve their spatial distribution, with the intention of providing more information to the nerves that are still active. The coating polymer [14], and insertion methods are also under study, in order to reduce accidents in implantation and subsequent use.

6.2 Modeling

The design of cochlear implants is a complex process, and direct tests on patients are limited, due to the costs and risks of surgical implantation. Direct experimentation is usually performed with guinea pigs, but previously it is very useful to use computational tools to simulate the conditions of the subject.

Recently, implementation of three-dimensional models in the design of cochlear implants has been widespread. Two very important steps in this process are the calculation of the distribution of electric potentials in three dimensions along the cochlea, and applying a neural model to calculate the excitation profiles of the auditory nerves [15, 16].

The first involves computing the potential distribution generated by the current applied to the inner ear by the implant. To solve the first, several types of methods, such as lumped parameter models, the Finite Element Method (FEM) or Boundary Element Method (BEM) can be used. After calculating the potential distribution, a neuronal electric model is used (such as Hodgkin-Huxley, the Colombo-Parkins, or SEF) to describe the behavior of the neuron as a function of the ionic concentrations, conductivities, active nodes, and other variables. Taking into account the distribution of neurons around the cochlea, and the electric potential that will affect them, their response can be estimated.

Researchers are constantly looking to improve the proposed models, including the effects of various factors such as electrode-tissue interfaces [17], or the positioning of the electrodes, and the improvement in the calculations for the mechanical design of the implant.

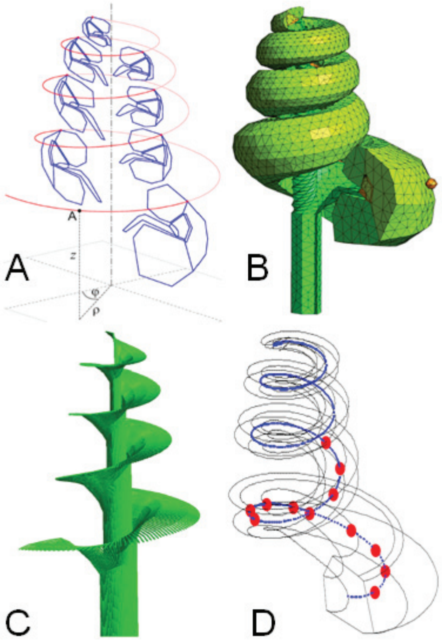


Figure 5. Stages of Finite Element modeling, including positioning of the electrodes. (A) connecting the sections Spiral cross. (B) Mesh of cochlear structure with an electrode in the outside. (C) Illustration of cochlear neurons modeled. (D) Arrangement of electrodes placed in the center of the scala tympani, used for model verification. [15]

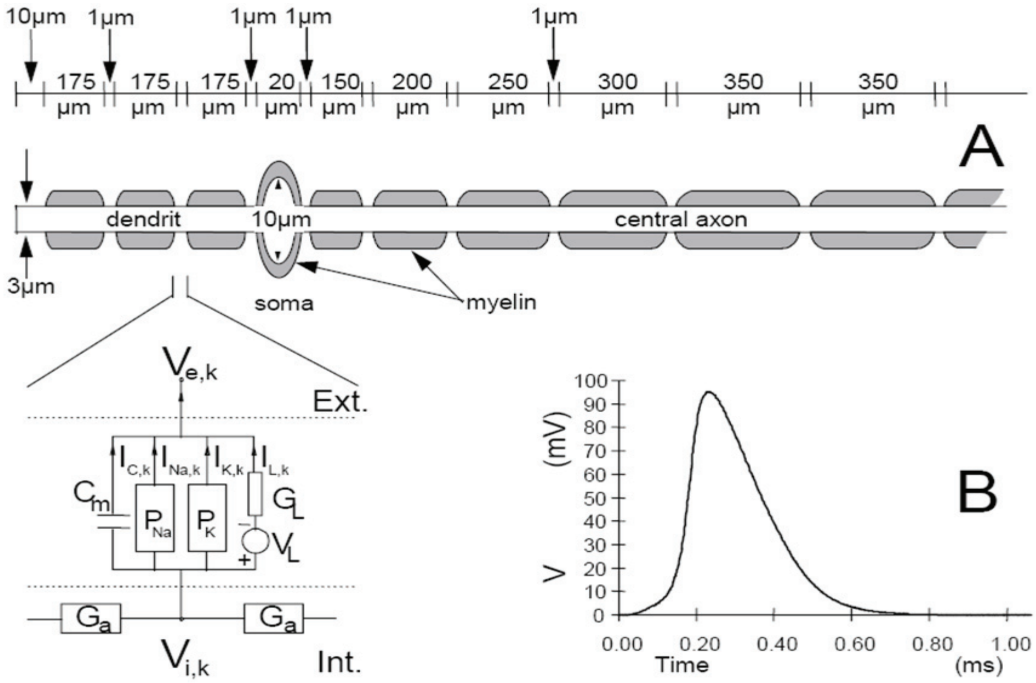


Figure 6. The form and function of auditory nerve fiber model. Stimulation of the fiber produces an action potential (B) which is conducted to the brain through the axon. Below to the left is shown the electrical model of the node of Ranvier, responsible for the generation and spread of potential (A). [15]

6.3 Processors

As the algorithms used become more complex, it has become necessary to use more powerful processing devices. DSPs (Digital Signal Processors) used today in implant's external drives have several features that improve performance. These include the inclusion of specific instructions for normalization and signal compression, the use of multiple processors in parallel and adaptive systems for noise reduction [18]. Another important aspect has to do with energy consumption [19], because more processing power requires also higher energy consumption, so it is necessary to provide more efficient systems.

6.4 Totally Implantable Devices

Finally, the fate of cochlear implants is to be fully installed inside the body without need for external processing units, thus improving the aesthetics and patient comfort. This development requires the miniaturization of their processors, the use of new types of microphones (some use the vibrations of the skull as a means to perceive sound) [20] and more efficient batteries. All this must be accompanied by a high reliability since being completely internal these devices are more difficult to replace or adjust.

5. Conclusion

Cochlear implants are the sensory aid devices that have had major advance in recent years. From the single channel devices to current models of 22 channels with multiple features and processing algorithms, improvements have occurred continuously in both the hardware and software, from virtually zero recognition in the early 70s, to levels exceeding 90% success in the latest devices. Its existence helps to improve the quality of life for millions of people around the world. Materials science, signal processing techniques, and advances in miniaturization and efficient use of energy are involved in its design and creation, making them an excellent field for new developments and multidisciplinary research combining the health sciences and engineering.

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