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Engineering Challenges in the Design of Cochlear Implants

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Abstract- **Hearing aids such as cochlear implants have been used by both adults and children for a long time. In addition, cochlear implants are used by patients who have severe hearing loss either by birth or after an accident. This paper aims to investigate the engineering challenges bounding the design of cochlear implants and present its possible solution to improve the design of implants. First, a detailed introduction of considered implants is given, followed by aspiration and advantages. Numerous engineering challenges in cochlear implants must be addressed, such as selecting and installing electrodes array inside the cochlea, dealing with the problems that occur during speech processing, noise reduction, etc. A detailed process of continuous interleaved sample scheme is also illustrated to understand the working of bionic implants. In the end, future considerations regarding improvements in cochlear implants have been suggested.**

Index Terms-- **Cochlear implants, Design of cochlear implants, cochlea, Bionic implants.**

I. INTRODUCTION

The first-ever cochlear implantation was achieved in 1970 in Los Angeles. Currently, over 200,000 patients have cochlear implants received across the globe. More and more patients now prefer cochlear implants because of their utmost advantages and efficiency [1]. The concept of using electrical stimulations over sensory nerves for acoustic and visual purpose is not new. Such attempts were first made in the early 19th century with the help of medicine and engineering. Volta accidentally documented the first-ever observation after applying an electrical current near his ear canal. After applying current, he was able to hear cracking or bubbling sound [2]. Years after his observation, the first-ever successful impact was achieved in 1937 by Eyries, a physician and Diourno, an engineer. This concept became popular after 1970 when grants were given to researchers by the National Institute of Health in the United States and afterwards in Europe and Australia [3].

Understanding the working of the central auditory pathway got advanced in parallel with the advancement in surgical techniques. The medical industry progressed to dual channels and further to 16 channels from a single channel design initiated in 1970. However, the real advancement was only possible after integrated circuits saw a boom and microelectronics fabrication started. The novel devices, equipped with a sophisticated scheme for signal processing and a quick filtering mechanism, quickly processed numerous active stimulations [4].

Considering the clinical results, the subjective performances were not linearly correlating with the engineering capabilities of the device. A limitation for the number of channels to be used was noticed, beyond which further improvements were not possible to be documented; at least patients could not observe it [5]. The functional performance in lesser ideal environments such as shopping malls and restaurants etc., is considered mediocre. Such limitations are considering both engineering and biophysical factors. Therefore, new cochlear implants must consider addressing the interface among nerve synapses and electrodes, the limited dimension of the cochlea, and how the brain interprets electrical stimuli after processing [6].

II. ASPIRATION OF COCHLEAR IMPLANT

The sound is transmitted through the outer ear in the form of an acoustic wave in the conventional hearing process. The acoustic wave impacts the tympanic membrane, causing motion like a piston of the bones in the middle ear cavity. This cause vibration in the oval window, which is a membranous structure. These vibrations are then passed on to the cochlea having spiral chambers filled with fluid in the inner ear. When the sound wave reaches the inner ear, the wave's amplitude has been reduced through a bandpass filtering process. The bandpass filtering process is for limiting irrelevant stimulation and protecting the ear from louder stimuli. The acoustic waves induce travelling waves upon reaching the cochlea near the basilar membrane, which runs throughout the cochlea. This basilar membrane has dedicated microscopic structures known as hair cells concentrated along with the organ of Corti. The hair cells sense the motion of the basilar membrane with the help of a more petite hair-like structure attached to the basilar membrane known as kinocilium and stereocilia. These motions are causing stereocilia to a constant movement of opening and closing the electrical channels near hair cells controlling efflux and influx of entire ions through fluid [7] [8].

The auditory nerves receiving ends are connected to the hair cells opposite ends. The auditory nerves opposite transmitting ends are projected to various parts of the brain and brain stems, such as the auditory cortex and cochlea nucleus. The opening and closing process of the auditory electrical channel at one of the ends of the hair cell causes a stream of neurotransmitter release through the fiber synapse of the auditory nerve. The processing of the brain starts right from the release of neurotransmitters. Stiffness of basilar membrane varies throughout the cochlea, e.g., near the cochlea base is the basilar membrane, which is much stiffer and flexible near the apex. The varied stiffness of the membrane is acting as a spectrum analyzer throughout the cochlea. The hair cells located near the base are turned to higher frequency spectra, and the hair cells located near the apex are turned to lower frequency spectra. This organization of spectra is throughout brain cortices, brain stem, and auditory nerves [9].

When sound stimuli reach the auricle, it can be stated that they are filtered, modulated, filtered through bandpass and low pass pattern, and afterwards rectified through the transduced form with mechanical to electrical signal conversion. This is an outstanding physiological and engineering feat that is duplicated through cochlear implants. The reason behind human's ability to process and acquire speech and other complex signals like music is because of their capability of processing sounds in both temporal and spectral signals. However, current cochlear implants are not able to process temporal cues. Genetics, infectious processes, trauma, or ototoxicity are the primary reasons for deafness in those patients whose deafness is caused by complete damage or degeneration of hair cells. If hair cells are damaged for a longer time, then the nerve ends start to degenerate. This degeneration is not reversible naturally; however, the spiral ganglion is robust enough to reconstruct the central auditory pathway through a cochlear implant. This is the reason why cochlear implants are recommended at an early stage of life, i.e., 1 to 5 years of age. Cochlear implants bypass damaged hair cells by directly stimulating the auditory nerves in the cochlea with electrical signals after modulation [10].

III. ENGINEERING CHALLENGES IN THE DESIGN OF COCHLEAR IMPLANTS

The contemporary cochlear implants have two parts, i.e., internal and external. The internal part is installed through surgery, whereas the external part has a speech processing unit, batteries, and microphone. The speech processor transmits the auditory input through a radiofrequency transmitter to the stimulator of the internal part of the implant. The signals received at the stimulator are transferred to electrodes through a sealed array inserted into the cochlea surgically. The used electrodes may be monopolar or bipolar configuration, depending on requirements. The surgical procedures are in constant evolution and dedicated to a specific purpose. Figure 1 is a labelled diagram of the cochlea.

A. ISSUES OF ELECTRODES ARRAY

An array of electrodes is utilized to directly stimulate the auditory nerves either in a monopolar or bipolar configuration inserted near the cochlea. The electrodes array is surgically inserted through the drilling of covering of one of the bone chambers near the cochlea base, known as Scala tympani. The electrodes are positioned in a closed vicinity to spiral ganglion to optimize the signal to noise ratio and reduce impedances for reducing the overall power consumption of the cochlear implant [4] [11].

B. ISSUES WITH INSERTION OF ELECTRODES

The surgeons can install an electrode array of approximately 30mm in length whereas, the total length of the cochlea is about 40mm. Therefore, there is a limitation on the total number of placed electrodes inside the cochlea. Furthermore, the limited electrodes array installation compared to hair cells number leads to a physiological conflict because presently, the maximum number of active electrodes is about 22, equal to roughly 13 thousand hair cells. This leads to a challenging point to deliver an adequate frequency resolution to patients with a cochlear implant because every electrode functions for a specific band of frequencies but not for a specific excitation area such as normal hair cells functioning [12].

The basilar membrane's theory of tonotopic arrangement is another problem concerning the design and insertion of electrodes. The hair cells and basilar membrane function together in an arranged manner such that higher frequencies are getting associated along the basal region, and lower frequencies get associated along the membrane's apical region. Therefore, it is a critical engineering and surgical challenge to match frequency regions for the basilar membrane and electrodes array. Furthermore, as electrodes array is approximately 30mm of the cochlea's total size, resulting in non-stimulation of most of the region of the basilar membrane's apical region. Thus, for example, the auditory nerve fibers of lower frequency will not be able to stimulate [13].

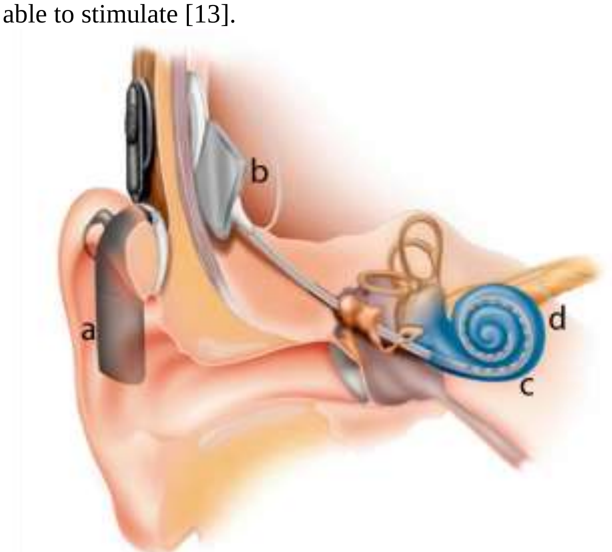

FIGURE 1: Graphical depiction of the cochlear implant system: (a) speech processor, (b) cochlear implant, (c) electrode array, and (d) cochlea. (Photo courtesy of Cochlear Americas, © 2009 Cochlear Americas)

The cochlear implant's central processing unit consists of an integrated signal processing circuit programmed to process sounds. Only three types of cochlear implants are available today, and each type has its own proprietary strategy for processing, but basic principles are the same for all types. The central processing scheme is idealized from the voice synthesizer of bell laboratories for recognition and synthesis of voice, known as continuous interleaved sampling. This scheme consists of non-linear filters, low and bandpass filters, and circuitry for compression to generate a train of pulses ranging from 400 to 18,000pps. Fig. 2 illustrates the block diagram for the continuous interleaved sampling strategy [14].

C. ISSUES OF SPEECH PROCESSING

Initially, cochlear implants had a compressed analogue scheme for processing. Received signals from the microphone were controlled and fit a dynamic range for auditory nerves instead of hair cells. A bandpass filter was used for filtering the controlled signals and then delivered to electrodes. The temporal and spectral information was incorporated in the final signals. The range of frequency for the bandpass filter is covering the speech spectrum. When the channels number is increased, interference among collocated electrodes also increases. Biphasic current pulses, which are delivered sequentially, is utilized for eliminating this problem. The initial cochlear implants had signal processing techniques modelled based on voice synthesis proposed for telephonic systems. These complex techniques utilize temporal signals by incorporating and detecting information regarding 1st and second formants and fundamental frequency. These implants performed nominally because of the limited capability of separating formants from the noise of the environment [1].

Different processing schemes developed for each block of cochlear implants, which had incremental enhancements in its design parameters. The acoustic signals which were extracted through the microphone were first to be compressed because of bypassing the biological electrical-mechanical mechanism of transduction of cochlea through direct stimulation of the auditory nerves, which had a lesser dynamic range of about 40 dB when compared to 100 dB, i.e., normal auditory range. The compression stage has numerous schemes like power laws and conventional logarithmic compression. Intuitively speaking, when the number of the electrode increases, the faster pulse rate will create electric field interference, nullifying the advantage of having a higher pulse rate. Take an example of the patient who uses MEDEL devices having fewer electrodes and wider spacing among electrodes, and as a result, they enjoy perceivable enhancement and a higher pulse rate than a cochlear implant with a more significant number of electrodes [15] [21].

When designing the bandpass filter, the main design parameter is to distribute central frequencies along with the speech range, i.e., from 0.5 kHz to 8 kHz. Using a simple logarithmic scale may also serve the purpose without any emphasis on first and second harmonics. A few novel schemes comprise the first and second frequency range with log spacing. Such schemes help in the improvement of clinical performance. For example, cochlear implants utilize hamming and FFT windows to generate FFT bins for over 22 channels. Spectral maxima are used for the selection of a subset of these channels for fitting in suitable electrodes. By selecting 8 to 12 electrodes out of 22, the pulse rate could be increased to over 2400pps. The cutoff frequencies are then adjusted through pulse rate. When the pulse rate is high, the cutoff frequencies and a smaller number of samples in each stimulation frame are also high. The signals are once again compressed for modulation of biphasic pulses amplitudes for matching auditory nerves dynamic range. These pulses are then fed to electrodes either in pairs or simultaneously in a non-adjacent mechanism to reduce electrode interaction. This scheme is supporting a higher pulse rate and is also incorporating temporal signals. Whereas in non-simultaneous mode, the pulse rate can be as high as 2500pps, but its averaging scheme has temporal signals. The selection of both modes can be made as per requirements [16] [17].

The cochlear implants containing bandpass filters with logarithmic filter spacing use Hilbert transform to map and detect envelopes of the bandpass signals. Such designs allow deep insertion with wide inter-electrode spacing and enable a pulse rate of more than 50,000pps. A simple way of enhancing temporal signals is accurate modulation of the fundamental frequency. As the processor and microphone of cochlear implants are outside the ear, its clinical performance can be immediately evaluated by engineers and researchers, and relevant changes can be made to achieve high performance [18].

D. ISSUES OF NOISE REDUCTION

Noise reduction is another area where the performance of cochlear implants may be improved. One of the simplest ways is to utilize two microphones; one on the rear and one on the front side. This configuration will result in a similar presentation of noise at either microphone with some delay which would either be cancelled out or subtracted from one another. After compression, the signal and noise will be determined based on amplitudes. The signal which is resulted is then amplified differentially. Few more sophisticated schemes comprise least mean square filtering to minimize noise's spectral contribution [19].

Other noise cancellation strategies do not require the use of dual microphones. In such schemes, noise cancellation can either be performed during speech processing or before in the form of spectral subtraction of noise. An S-shaped compression scheme would change the curvature of noise dynamically with respect to the estimated noise floor through every cycle. Patients with cochlear implants can use 3 to 6 channels at any time. With the increase in the number of channels, no improvement has been noticed [22].

Furthermore, the existing coding strategies also depend on understanding how the cochlea's central pathway assesses sound stimuli. It can be said that existing cochlear implants are only grounded on speech processing and recognition. Few researchers proposed the use of fiber optic instead of electrodes array for auditory nerves stimulation. This is supposed to reduce crosstalk and power consumption along with maximization of stimulation rate [20-24].

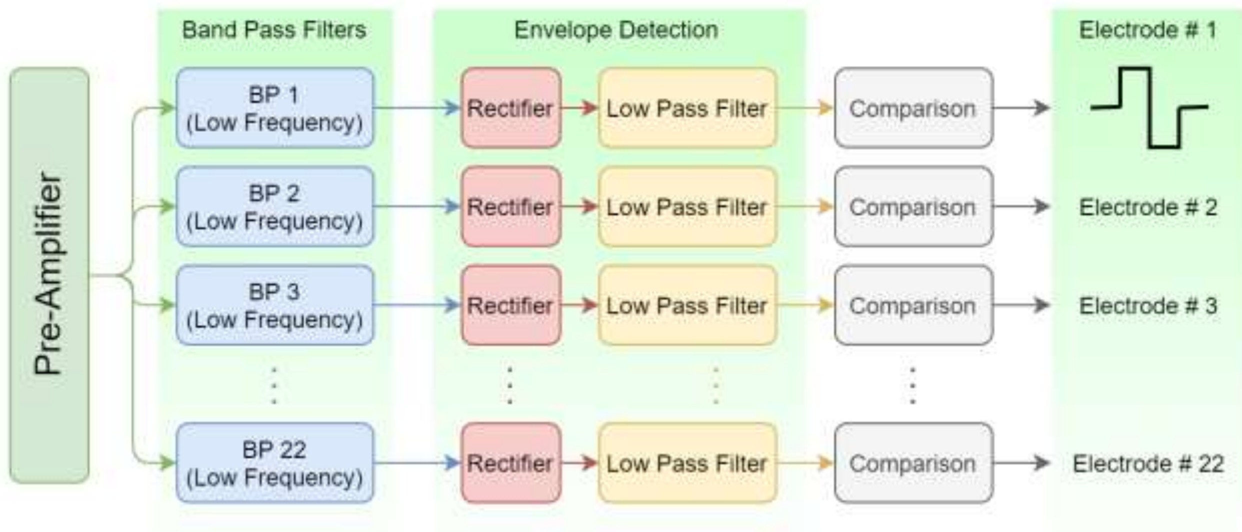

FIGURE 2: An Example of the Continuous Interleaved Sampling Scheme.

The current design of a cochlear implant has RF linked internal and external parts. The data being transmitted is first encoded through different coding schemes, and then error detection schemes are implemented based on its phases and amplitudes. Amplitude shift keying is usually used to modulate RF signals to accommodate low power requirements and higher frequencies. The power amplifier of the external part is with a higher frequency. The receiving and transmission coils must be small in size but must bear the capability of withstanding higher bandwidth. Existing implants have 20mW to 40mW at the internal coil with 40 per cent of transmission efficiency. The design of the internal unit is raising challenges in particular as it must achieve some critical tasks comprising of decoding of data, conversion of received data to analogue signals, and serving as electrodes' current sources as well. The internal unit must also monitor electrode potential and transmit data back to an external unit. High power consumption is required to transmit higher frequencies, which is a fundamental limitation that needs to be compensated. The contemporary implants are utilizing multiple current sources making the design of multi-electrodes possible. However, there is still heat dissipation but in the safe range. Further advancements in integrated circuits and RF engineering would produce efficient results [11].

IV. CONCLUSION

Cochlear implants can be named the most advanced, mature, and beneficial sensory implant developed to date. Millions of patients have benefitted and reclaimed their hearing sensation to living everyday life with cochlear implants. At the same time, other bionic implants like retinal implants have to be developed further in order to yield significant results. The advancements and methodologies of the cochlear implant have been adopted for the development of other bionic implants. These implants have challenged the prosthesis of the natural central nerve system like open-heart surgery and have been a star label to cornerstones for modern medicine. Engineering and medical fields are still seeing a growth in constant improvements in cochlear implants to serve humans in a never served way.

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