Cochlear Implants Overview

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***Abstract*—Cochlear Implants are a prime example of a successful neuroprosthesis, allowing hundreds of thousands of deaf patients to hear. They are the result of a long string of innovations through collaboration of engineers, physicians and other experts, starting from Volta's auditory stimulation experiment in 1800. In this paper, we look at the relevant functioning principles of the inner ear, particularly the cochlea, and how it can be modeled. We describe the current state-of-the-art of cochlear implants and highlight a few technical innovations and implementations in the past century that helped make them a reality, like the use of Gm-C filters, switched capacitors and log-domain filters. We then look at some important considerations in the design of a cochlear implant including stimulation safety and insertion trauma before indicating a few promising leads for tomorrow's cochlear implants.**

I. Introduction

To understand hearing loss and how cochlear implants work it is fundamental to have a basic knowledge of the structural features of the human ear. The ear serves two primary functions; to deliver verbal and spatial information. These primary functions appear and are refined at different structures of the ear. The ear is divided into three parts: the outer, middle and inner ear. The outer ear is composed primarily of the ear lobe, ear canal. They function together to collect, amplify and direct sound waves to the eardrum in middle ear.

The middle ear has three key bone structures, the hammer, anvil, and stirrup. A sound pressure vibrates the eardrum which in turn taps against the anvil, this pushes against the inner ear also known as the cochlea. The cochlea is a hollow tube that is coiled-in together similar to a snail shell. The cochlea is lined with specialized hair cells and filled with fluid called perilymph. The vibrations from the anvil onto the cochlea create a standing wave in the perilymph fluid. These standing waves create frequency dependent bending motions along the tectorial and basilar membrane. This motion causes the hair cells (stereocilia) to bend at the waves maximas and minimas. These flexure motions cause mechanically gated potassium ion channels to open, effectively sending audio signal through the auditory nerves. The outer three sensory rows of the hair cells do not stimulate the auditory nerves however change shape and area of the membrane thus mechanically amplifying low-intensity sound levels.

The vibrations that run through the basilar membrane are filtered by its anatomical structure. The membrane is thick at the base and decreases in thickness but increases in stiffness near the apex (Fig.4). This creates what is called a tonotopical arrangement where low frequencies are stimulated at the apex of the membrane and the higher frequencies at the base.

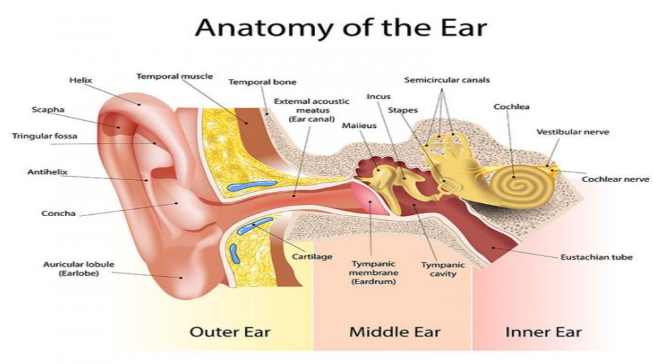

Fig. 1: Structural anatomy of the human ear (from Belton Hearing Aid)

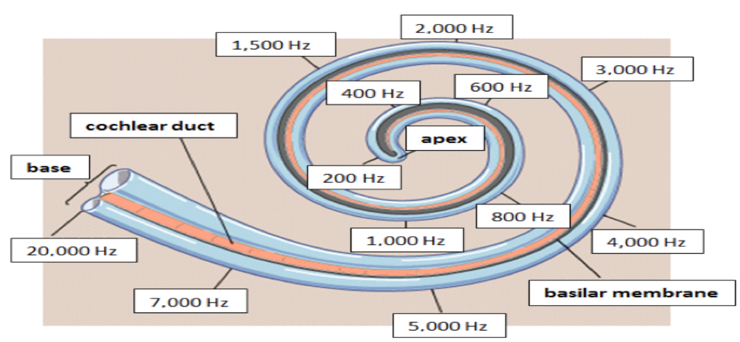

Fig. 2: Tonotopical profiling of the cochlea (from Encyclopaedia Britannica

A. Hearing Loss

Hearing loss can be divided into two groups: conductive and sensorineural. Conductive hearing loss occurs when sounds are unable to travel from the outer ear to the inner ear. This may occur when the eardrum losses elasticity or alternatively the bones at the middle ear lose mobility. Sensorineural hearing loss occurs when the ear sustains damage, either in the sensory hair or at the nerve endings. This hearing loss is most common with age or by congenital malformations. The continual exposure to loud noises deteriorate the hair cells. The inner ear has about 16,000 hair cells, all which are irreplaceable [**?**].

B. Current Cochlear Implants

Cochlear implants allow people with profound hearing loss and even complete deafness to hear speech by bypassing most of the ear all together. It operates using electrical currents which differs from other counterpart hearing aids that rely on sound waves. Cochlear implants consists of three components: a microphone, a processor, and a receiver with an electrode array. The electrodes are surgically implanted into the cochlea. As previously mentioned the cochlea converts sound waves into electrical signals. These signals then travel to the brain through the auditory nerve.

Current devices are unable to appreciate music, and perform poorly in noisy environments. They also offer limited sound localization. Users who speak tonal languages (i.e. mandarin) experience larger difficulty of understanding sound.

When these hair cells are dysfunctional from birth or through cell damage then hearing aids can no longer help the patient and cochlea implants offer the only solution. In this way cochlear implants act as hair cell replacements.

The implant works by receiving sound and passing it to the processor, the processor analyses the sound signals and interprets it. The processor then sends corresponding signals to the cochlea through channels based on the waveform frequencies. Each channel corresponds to an electrode in the array that stimulates a specific spot on the cochlea. What is heard is what your brain interprets from the combination of signals. As mentioned before a fully functional cochlea is composed of thousand of hair cells. With only about 24 channels, cochlear patients have to train their brains to hear and the sound fidelity of these products has not reached that of the human ear.

However, these channels are specifically designed to amplify speech and render it interpretable. These however lack some of the complexity of replicating real world sound. A major limitation is the spatial resolution. Electrode arrays use electrical currents to stimulate the auditory cells. To have a better sound fidelity more stimulation cites are needed. This would add better tonality and sound locality to the brain. This implants are limited by their size (shared electrical interference occurs at small spatial intervals). Also the delicate coiled structure adds another dimension of complexity to insertion.

1) Device Summaries: The market today is filled with various different types of cochlear implants. As mentioned before cochlear implants have three working parts: the microphone, the processor, and the receiver. One brand of cochlear implants is *LIFESTYLE* by Advance Bionics. This cochlear implant contains 16 electrodes, and a pre-bent design that allows it to free float inside the cochlear. This reduces the risk of damage of the delicate structure. This model tries to reduce electric field interactions through raised partitions between electrodes [**?**].

Another device in the market targeted into hearing preservation is the NUCLEUS s 6 SYSTEM, COCHLEAR. This device comes in different models aimed at a different set of needs. The Hybrid L24 is a short electrode intended for low-frequency hearing. This is utilized by making an incision directly to the lower apex section of the cochlea. It also carries an intermediate model called the “slim straight” electrode. This model balances residual hearing and insertion depth. Lastly the *Contour Advance* comes in a preformed spiral shape with two distinct arrays of 11 electrodes each.

Lastly another cochlear implant is the *Maestro Cochlear* by MED-EL. This system comes in three families: FLEX, FORM, and CLASSIC. The FLEX contains electrodes between 20 and 31.5 mm in length. The implant is designed for perfect fit with wave-shape wires and tapered tip for improved mechanical flexibility. The FORM is designed for malformed cochlea in mind. The CLASSIC is designed for deep insertion into the cochlear for a more complete coverage.

Present day cochlear devices work somewhat similarly at the electrode nerve level. The largest difference between most devices today is their speech coding techniques. All of these devices suffer from unintended current flow between electrodes, when the latter are stimulated simultaneously. For this reason different implants use different techniques to minimize this effect. For example just to name a few of the encoding techniques are Continuous Interleaved Sample (CIS), Advanced Combinatorial Encoder (ACE), and Spectral Speak Extraction (SPEAK). These all make a sacrifice on temporal or spectral resolution and perform best under specific conditions [**?**].

C. Historical retrospective on Cochlear Implant technologies

1) First discoveries: The beginning of the road for cochlear implants starts in good part with Alessandro Volta’s daring experiment in which he inserted the two ends of a 50-volt battery in his ears resulting in a ”crackling and boiling sensation” [**?**]. The realization that electrical simulation can lead to auditory perception launched a long lasting quest for a viable cochlear implant. It started with physicians inserting single electrodes with basic wave carriers into the auditory nerves of deaf patients, which provided some useful hearing of environmental sounds but was still extremely limited in its scope.[**?**]

The development of the modern Cochlear Implant is the result of decades of innovations from a variety of research group across the world. In the following paragraphs, we selected a few significant steps in that process in order to illustrate that development.

2) Single electrodes to multi-electrodes systems: In the decades after Volta’s experiment, many scientists and physicians experimented with electrical stimulation of the inner ear. The first prototypes were quite crude, comprised of single electrodes with DC stimulation. A single electrode system was however insufficient to recreate the neural patterns elicited by the basilar membrane and the thousands of hair cells in the normal cochlea, and were certainly inefficient to provide viable speech recognition. Eventually, multi-electrode systems were introduced in the 1960s, providing a great push forward to the field. [**?**]

3) Developing a first filtering model for the Cochlea: One of the great challenges of creating a useful cochlear implant resided in creating a realistic filtering system to simulate its biological function. When first looking at modelling the ear, we can start by separating it into the outer, middle and inner ear. The outer is the simplest, serving mainly to funnel the sound into the middle ear and can be modelled as a simple linear filter. The middle ear in turn serves as an amplifier of the sound, changing the acoustic signal to a mechanical one. The inner ear is however considerably more complex. The first significant challenge was in creating an electrical model for the Basilar Membrane (BM), the component of the inner ear which changes in width and thickness from its basal end to its apex. These changes make different parts of the BM selective to different frequencies, creating the standard human hearing range that we know (20Hz-20KHz) with the highest frequencies selected at the basal end and the lowest at the apex. The first computational model tackling the complexity of the BM was proposed in 1982 by Richard F. Lyon, by implementing a cascade of bi-quad filters [**?**]. Lyon achieved this by considering small BM sections (δx) and assuming them to be uniform, thus allowing them to be modelizable by a simple low-pass notch filter. More small BM sections thus meant a more accurate model. This simple model fell short in one important way: its Automatic Gain Control implementation, which aims to take into account the amplitude of the input to dynamically vary the gain of the filters to guarantee an output within a specific range, did not represent the reality of what happens inside the ear. Indeed, the ear adapts dynamically to the loudness of the sound received from the environment. Lyon implemented it as a post-filtering amplification instead of dynamically changing the gain of the filters, a model closer to reality.

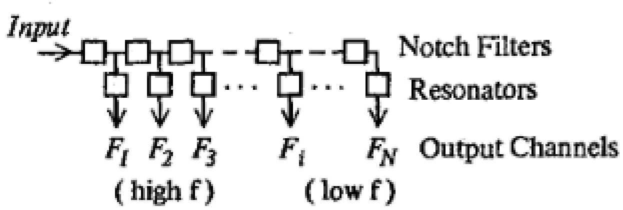

Fig. 3: Filter-bank implementation, from Lyon's 1982 paper

A solution was proposed in 1988 [**?**], again by Lyon, to address this issue. It consisted in adaptively varying the quality factors (Q) of the individual filter stages in response to the input intensity level. This required a half-wave rectifier (modelling the directionality of Inner Hair Cells (IHC) by cutting off the negative portion of the signal) at every stage's output, a strength sensor to detect the intensity of the input as well as a decision circuit selecting a correct Q value for a stage based on the incoming input amplitude. In the same paper, Lyon introduced some practical circuit implementations, although those were limited in scope, not showcasing for example dynamic Q values.

It is important to note that most of the circuits cited above used Gm-C filters, which are based on a coupling of OTAs and capacitors. These models largely dominated the cochlear model literature up until 1998, after which several new paradigms including log-domain filters and switch capacitors (introduced in the following paragraphs) came onto the scene. Gm-C filters were however still present in the relevant literature in the following years as well.[**?**]

4) New paradigms: Major innovations came in 1992, when researcher Lloyd Watts proposed the first ever 2-D Cochlea model, which attempted to add a modelling of the cochlea fluid to the BM filtering, resulting in a more realistic model. Notably, this model was bi-directional, as in took into account the fluid (endolymph) reflections. Another important shift in the field came when researcher Jyphong Lin created the first non Gm-C based cochlea [**?**], instead using switched-capacitors (SC) to make the biquad filters. His contributions included fully designed SC Cochlea filters and filter-bank. His scheme presented one major issue however, in that it required a constant Q which, as explained above, made it unpractical for designing a realistic model that takes into account OHC and AGC.

A huge contribution to the performance of the Cochlear Implant came in a publication by Christopher Abel in 1994, who proposed the first current-mode cochlea design: he exploited the fact that the equivalent continuous-time cut-off frequency of a discrete-time filter is proportional to the sampling rate, which allows him to cover lower octave with the same set of filters, by simply reducing the sampling rate by a factor of two. This was useful to save considerable area in the fabrication of the system. Moreover, contrary to Lin's contributions, Abel's system was compatible with a potential Q-decision circuit. [**?**]

Log-domain filters, another current-mode design introduced by Christopher Toumazou [**?**] [**?**] in 1994, were another step forward. Log-domain filters allow us to solve some of the limitations imposed by small-signal linearity assumptions used in classical transistor circuits. By initially compressing the signal to a nonlinear voltage that follows the logarithmic I-to-V relationship of MOS devices in Weak Inversion mode, filtering it and then expanding it at the output we can maintain the input-output linearity while extending our dynamic range since we are not as constrained by the small signal approximations.

With a large number of filters in a cochlea model, it was hard to guarantee the significant values of the filters (and therefore their cut-off frequencies) due to imprecisions in the physical electrical components. EPFL's Van Schaik and Eric Vittoz managed to bring a useful solution to this problem [**?**]. Indeed, MOS devices working in weak inversion mode have an important disadvantage whereas their collector current depends (in an exponential fashion) on the threshold voltage, introducing an important mismatch of the devices. The use of Compatible Lateral Bipolar Transistors (CLBTs) removed that dependency, leaving only the geometrical differences of the devices as a potential cause for mismatch. Since cochlea models were based on fairly long cascades of filters, this was an important improvement to the quality of the models.

Following these researches, the improvements that came in the following years focused on upgrades on the side of the electrical circuits, introducing the use of high-performance log-domain biquads operating in class-AB, using floating-gate transistors to set the time constants for the BP filters, among other innovations. The second focus was on making the cochlear implants fully implantable: Julio Georgiou from ICL demonstrated in 2005 the first fully-implantable log-domain cochlear implant prosthesis system, complete with a speech processor, filters and a rechargeable battery.

D. Important considerations for a cochlear implant system

A modern cochlear implant system includes an external unit composed of a digital signal processing unit, a power amplifier and an RF transmitter. The internal unit receives the transmission and is equipped with a stimulator. Several design constraints need to be taken into account; a few of them are detailed below.

1) Stimulation Safety: Because unbalanced electrical stimulation can be harmful to nerve tissue, a strict biphasic stimulation pulse is usually used in modern cochlear implant systems. To avoid any DC stimulation, capacitors are also usually integrated in series with the electrodes. Moreover, a maximum charge limit is set around 15 to 65 uC/cm2/phase. [?]

2) Low power usage: Because the internal unit is usually not equipped with a battery, the efficiency of the RF power transmission and the low-power design of the internal unit are very important. In today's cochlear implants, Class E power amplifier are commonly used, achieving a 40% transmission efficiency. Moreover, ASK (Amplitude-Shift-Key) modulation is preferred to other methods, for its low power consumption. [?]

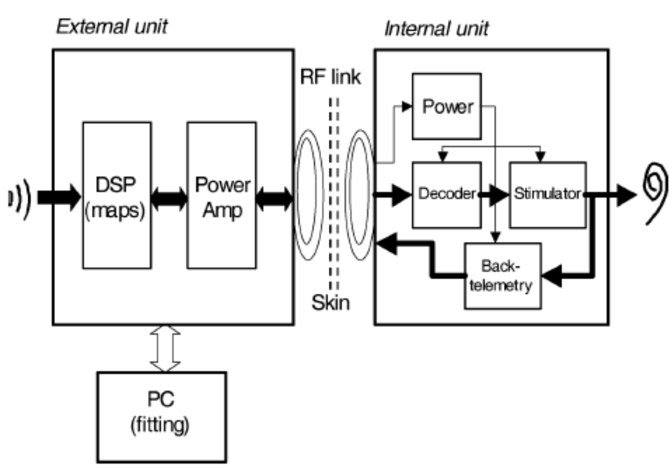

Fig. 4: Architecture and functional block diagram of a modern cochlear implant [?]

3) Insertion depth and trauma: As a general rule, a deeper insertion improves the coupling efficiency between the electrode and the nerve and allows access to lower frequency components. However, deep insertions come with the risk of insertion trauma, which damage the tissue and are ultimately counter-productive as they diminish the coupling efficiency. Several methods have been developed to minimize the damage, including curved electrode tips and changes in the thickness of the latter. [?]

4) Stimulation timing: In multi-electrodes systems, simultaneous stimulation of multiple electrodes leads to an interaction of electric fields of adjacent electrodes, distorting the resolution of the cochlear implant. Adapted speech coding concepts had to be developed to address this issue. One of the more well-known is Continuous Interleaved Sampling (CIS). This method filters the speech into a number of sub-bands and delivers the biphasic pulses, usually at a rate of 1500 pulses per second, to each electrode with a temporal offset, to prevent overlap between the channels. [?]

E. Future Possibilities

Novel research is tending towards optical solutions. As previously mentioned, electrode stimulation suffers from unwanted electric field interactions, created by the wide current around each electrode causing unwanted current flow between nearby electrodes. This can distort or even reduce the temporal spectral resolution of the implant [?].

A 2018 study established a first proof-of-principle, on how optogenetics could activate auditory pathways to achieve spatially restrictive and cell-specific activation of the auditory nerves. The study was conducted on adult Mongolian gerbils and utilized Adeno-associated virus gene to encoded for light-sensitive calcium ion channels [?].

Both normal hearing and deaf gerbils displayed the same avoidance behaviour when one was exposed to acoustic stimulation and when the other was exposed to optical stimulation. This indicated partial restoration of the auditory function by the light stimulation. The results proved that optical cochlear stimulation of up to a few hundred Hertz achieved good temporal fidelity with low light intensities on a rodent subject. Although we are still very far from a commercial product, these early results show promise for optical cochlear implants to one day replace traditional electrode based implants. Optical stimulation eliminates would allow for better spatial resolution and fine tuning of activation of auditory nerve cells.

II. Conclusion

While cochlear implants are already a life-changing medical device for many people, they are still very much in development today as there is still a lot of room to improve the quality of the sound. The latest research indicates that a major shift in the design strategy of cochlear implants could happen, going from electrical stimulation to optical stimulation, along with important improvements in the user experience.

References