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Technological Innovations in Cochlear Implants: From Signal Processing to Wireless Connectivity.

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Abstract

Cochlear implants (CIs) are surgically implanted devices that restore hearing in individuals with severe to profound sensorineural hearing loss. By converting sound into electrical signals that stimulate the auditory nerve, CIs have dramatically improved hearing rehabilitation. Over the past two decades, CI implantation rates have surged, driven by advancements in device design, minimally invasive surgical techniques, and refined programming strategies, all contributing to enhanced safety and efficacy. These technological developments have also broadened CI candidacy, now including individuals with greater residual hearing and infants under one year old. This overview examines current CI designs, their historical evolution, and future prospects. It highlights key figures in otology and CI design who have shaped this technology's progress. Recognizing the pivotal role of clinical and surgical anatomy, physiology, and treatment methodologies, this article underscores the significant technological advancements that have benefited CI recipients, paving the way for future innovations.

Keywords: Cochlear implant, Future designs, Deafness, Hearing Rehabilitation.

Introduction:

Hearing, a fundamental sense, intricately weaves us into the fabric of social interaction, communication, and environmental awareness. Its impairment, particularly severe to profound sensorineural hearing loss (SNHL), profoundly impacts an individual's quality of life, hindering language acquisition, social development, and overall well-being. The advent of the cochlear implant (CI) has revolutionized the management of SNHL, offering a pathway to auditory rehabilitation for individuals who derive limited benefit from conventional hearing aids. This sophisticated electronic device, surgically implanted, bypasses damaged hair cells in the cochlea and directly stimulates the auditory nerve, transforming sound into electrical signals that the brain can interpret. The journey of CI technology is a testament to the relentless pursuit of scientific innovation and clinical excellence. From its rudimentary beginnings in the mid-20th century to the sophisticated systems of today, the CI has undergone a remarkable transformation. Early pioneers, driven by a vision to restore hearing, laid the groundwork for a technology that would profoundly impact millions of lives. Initial devices, while groundbreaking, were limited in their ability to provide clear and natural sound perception. However, through decades of dedicated research and development, CI technology has evolved into a sophisticated system capable of delivering increasingly refined auditory experiences. This review paper delves into the technological innovations that have propelled CI technology forward, focusing primarily on two critical domains: signal processing and wireless connectivity. These areas represent the vanguard of CI advancement, driving improvements in speech perception, sound localization, and overall user experience. Signal processing, the heart of CI functionality, has witnessed significant strides in sound coding strategies, electrode design, and personalized algorithms. Wireless connectivity, a more recent but equally impactful development, has transformed CI usage by enabling seamless integration with everyday devices and facilitating remote programming and telehealth. The evolution of signal processing within CIs is a narrative of continuous refinement. Early CI systems relied on simplistic sound coding strategies, often resulting in distorted and unnatural sound perception. However, the development of advanced sound coding algorithms, such as SPEAK, CIS, and HiRes, has dramatically improved speech understanding, particularly in noisy environments. These strategies, by more accurately representing the temporal and spectral features of sound, enable CI recipients to perceive speech with greater clarity and naturalness. Concurrently, advancements in electrode design have played a crucial role in enhancing CI performance. The evolution from single-channel to multi-channel electrodes, coupled with improvements in current steering and focused stimulation, has significantly improved frequency resolution and reduced channel interaction. This has translated to a more nuanced and detailed representation of sound, allowing CI users to better discriminate between different auditory stimuli. Furthermore, the advent of flexible electrode arrays has minimized cochlear trauma during implantation, leading to improved long-term outcomes. Recognizing the heterogeneity of hearing loss and individual patient needs, researchers have increasingly focused on personalized signal processing. The development of algorithms tailored to individual auditory profiles, based on objective measures such as auditory brainstem response (ABR), has optimized CI settings for each recipient. Moreover, the application of machine learning and artificial intelligence holds immense promise for further refining personalized sound processing, potentially leading to even greater improvements in speech perception and sound localization. Beyond signal processing, the integration of wireless connectivity has ushered in a new era of CI usage. The incorporation of Bluetooth technology has enabled direct audio streaming from smartphones, tablets, and other devices, enhancing user convenience and accessibility. This has transformed the CI from a standalone medical device to a seamlessly integrated component of the user's digital ecosystem. Moreover, wireless connectivity has facilitated the development of remote programming and telehealth solutions. Remote CI adjustments, enabled by secure wireless communication, have significantly reduced the need for frequent clinic visits, particularly for individuals living in remote areas or with mobility limitations. Telehealth platforms have further expanded access to CI care, allowing for remote monitoring, counseling, and troubleshooting. The integration of CIs with assistive listening devices (ALDs), such as FM systems and induction loops, has also enhanced auditory performance in challenging listening environments. These combined systems provide a more robust and versatile hearing solution, allowing CI users to participate fully in various social and professional settings. The development of user-friendly mobile applications has further simplified CI control and monitoring. These apps, often featuring intuitive interfaces and customizable settings, empower CI users to take an active role in their hearing rehabilitation. As we look towards the future, the CI landscape is poised for even greater technological advancements. Artificial intelligence and machine learning hold immense potential for optimizing CI signal processing, predicting individual hearing outcomes, and developing personalized hearing solutions. Gene therapy and biological approaches, while still in their early stages, offer the prospect of regenerating damaged auditory structures, potentially leading to even more natural and effective hearing restoration. The development of advanced biomaterials will enhance biocompatibility and long-term device performance. Optical cochlear implants, utilizing light to stimulate auditory neurons, represent a promising avenue for improving frequency selectivity and reducing channel interaction. Brain-computer interfaces (BCIs) may eventually enable direct communication between the CI and the brain, potentially leading to even more sophisticated and personalized hearing experiences. This review paper aims to provide a comprehensive overview of these technological innovations, tracing the evolution of CI technology from its early days to the cutting-edge systems of today. By examining the advancements in signal processing and wireless connectivity, we seek to illuminate the remarkable progress that has been made in CI technology and to provide a glimpse into the exciting possibilities that lie ahead. The ultimate goal of these technological advancements is to improve the lives of individuals with severe to profound hearing loss, enabling them to fully participate in the rich tapestry of auditory experiences that surround us.

1.1. Incidence of hearing impairment in world: Worldwide perspective According to the WHO (2017) reported untreated HL costs nations between $750 and $790 billion a year in direct medical expenses and lost productivity3 According to the World Burden of Disease survey, HL prevalence increased from 1.2 billion people (17.2%) in 2008 to 1.4 billion people (18.7%) in 2017. 6Hearing impairment, which contributed more than 39.5 million years of healthy life lost since 2000, has been ranked by the World Health Organization as the third most common cause of loss of time due to disability, with an increase from 27 million in 2000. WHO projected that Disabled Hearing Loss affected 466 million people worldwide in 2018 (or 6.12% of the world's population). This estimate is projected to rise to 630 million by 2030 and to over 900 million by 2050.

1.2. Incidence of the hearing impairment in Indian context: According to the Census of India (2011), 1.98 million people in the population have various of speech impairments, while 5.07 million people have hearing impairment. 4 In underdeveloped nations, there are more than 10 newborns born alive with bilateral severe to profound hearing loss for every 1000 live births, according to Pasolini and Smith (2009). 11 As per NSSO survey, currently there are 291 persons per one lakh population who are suffering from severe to profound hearing loss (NSSO, 2001). Of these, a large percentage is children between the ages of 0 to 14 years. With such a large number of hearing-impaired young Indians, it amounts to a severe loss of productivity, both physical and economic. An even larger percentage of our population suffers from milder degrees of hearing loss and unilateral (one sided) hearing loss. In a hospital-based survey, Niskar et al. in 1998 discovered 14.9% of kids had either lowfrequency or high-frequency hearing loss. 12 According to Norman et al., (2016) 30.9% of schoolchildren (aged 8 to 14) in the villages of Vadamavanthal, Tamil Nadu, have hearing impairment. According to the Census of India (2011), one out of every 100 children between the ages of 0 and 6 have a disability. There are 2.42 million (20.42 lakh) impaired children in this age group, and 23% of them have hearing impairment13 Moreover, 20% of the 7.87 million disabled people in the 0–19 age range have hearing impairments. The age range 10 to 19 years has the biggest number of impaired people (4.62 million)14 Just 61% of impaired children aged 5 to 19 are observed to be enrolled in educational institutions. Children aged 0 to 14 made up 25.9% of the population in 2018, according to data from India's sample registration survey (Sample Registration Survey of India, 2018). 15 India has the highest school-age child population with hearing impairments given the prevalence rate of hearing impairment in this age group. These kids can be easily located in schools for hearing tests, as well as for the proper rehabilitation, speech therapy, and educational facilities for their best development. The Right to Person with Disabilities Act of 2016 and the Right to Education Act of 2009 both guarantee rehabilitative and educational assistance for children who have hearing impairments. 15 Hence for the treatment and management of the hearing impairment who do not benefit from other medical treatments, various devices like Cochlear Implants were introduced.

1.3. History of cochlear implant development: Allesandro Volta in the year 1800 did an experiment on himself and discovered that electrical stimulation of the auditory system could produce sound. After initiating a w50- V circuit, he felt "une recousse dans la tete" ("a boom within the brain") and heard a sound like boiling thick paste. In the early 1900s, researchers discovered that electrical current directly stimulates the cochlear nerve to create auditory perceptions.16 French otologist Djourno and physicist Eyrie described the consequences of directly stimulating the auditory nerve in a deaf patient in (1957). 18 Radical excision for severe bilateral cholesteatomas sacrificed the right cochlear and facial nerves. The proximal auditory nerve stump was electroded before grafting the facial nerve. After applying a current, the patient was able to distinguish intensity and frequency, appreciate environmental sounds, and recognize many short words. 19 Volta's first report of auditory percepts elicited with electrical stimulation, although it is not certain if the experiment was produced with direct electrical activation of auditory neurons or via electromechanical effects, such as those underlying electrophonic hearing. While his experiment was the first, Volta's observation sparked sporadic attempts to investigate the phenomenon over the next 50 years in Paris, Amsterdam, London, and Berlin. Wilson & Dorman (2008) present that the sensation described by patients was always momentary and lacked tonal quality. Since sound is an alternating disturbance in an elastic medium, it was soon realized that stimulating the auditory system with a direct current could not reproduce a satisfactory hearing sensation. Several US groups implanted prototype CIs in the early 1960s. Blair Simmons from Stanford University implanted 6 stainless-steel electrodes into the auditory nerve through the modiolus in 1964. 19 One of his patients gave William House in Los Angeles an article on Djourno and Eyrie's earlier work. Motivated by this narrative, House implanted numerous gold electrodes in 1961 and worked with engineer Jack Urban to build long-term devices in 1965. House began clinical testing in 1973 with a commercial implant containing a wearable signal processor, platinum electrodes, and an induction coil system. Despite these early successes, other specialists in the area were skeptical, and electrical stimulation for meaningful audiologic rehabilitation in deaf individuals was denounced by the scientific community.20 A National Institutes of Health-commissioned investigatory team reviewed the first thirteen single-channel electrode implantees in 1977, legitimizing cochlear implantation. Robert Bilger reported that CI technology could increase hearing, lipreading, environmental sound detection, and voice modulation with minimal patient risk. 22 In 1978, Graeme Clark in Sydney, Australia implanted his first patient with a multichannel banded electrode for limited open-set speech recognition. The University of Melbourne, the Australian government, and Nucleus Ltd., a medical equipment company, founded Cochlear Ltd. after early success. 21 Computer microcircuit and implanted pacemaker technologies aided early CI commercial device development. The FDA approved the first single-channel CI (House/3 M) for adult profound post lingual deafness patients on November 26, 1984. 3M/Vienna single channel cochlear implant provided sufficient information both in intracochlear and extracochlear stimulation to result in open-set word recognition without lipreading. These results corroborated the previous findings of Hochmair-Desoyer et al. 40 In the last 10 years, speech recognition performance in quiet has plateaued, thus our focus has switched to more demanding listening tasks including background noise, sound localization, and music enjoyment to better simulate normal hearing.

1.4. Cochlear implant function and design: Separate external and internal components make up the behind the ear Cochlear Implant system (Figure 1). The transmitter antenna, external magnet, speech processor, battery, and microphone are among the external components. The electrode array, antenna, receiver-stimulator, and internal magnet are among the internal components. An earworn microphone picks up sound, which is then transformed into an electrical signal. The external sound processor receives this signal and converts it into digital electrical code using one of its numerous processing schemes. Via the skin, a transmitting coil that is held externally above the receiverstimulator by a magnet transmits this digital signal through radiofrequency. The receiver-stimulator ultimately decodes this signal into quick electrical impulses that are sent to a number of electrodes specific for particular frequency on an array implanted within the cochlea (specifically, the Scala tympani). The auditory nerve axons and spiral ganglion cells are then electrically stimulated by the electrodes and proceed to the brain for additional processing with digital signal. You may communicate the frequency, and intensity of sound by using these signals to carefully control the firing of intracochlear electrodes not in the continuous time domain. Currently, there are four CI manufacturers: Advanced Bionics Company (Valencia, CA, USA), Cochlear Corporation (Lane Cove, Australia), MED-EL GmbH. (Innsbruck, Austria) & Nurotron (Zhejiang Hangzhou, China). All four implant manufacturers' devices are largely comparable in terms of performance and dependability Electrode arrays have been developed over the past ten years to be thinner, softer, and more flexible in order to reduce trauma during insertion and protect the fragile neuroepithelial structures within the cochlea

1.5. Minimizing trauma: Early Cochlear Implant systems were thought to cause considerable intracochlear trauma during electrode insertion, which would then irreversibly lose any remaining hearing. The adoption of altered surgical methods and electrode design, however, has resulted in increased rates of hearing preservation following implantation during the past 20 years. In the past ten years, there has been a paradigm change toward the creation of soft surgical procedures and less invasive electrode designs in order to enhance performance. When electrodes are inserted, there are at least three primary processes that might cause an acute mechanical inner ear injury. The electrode can also be implanted through the membrane of the round window or by a cochleostomy established anterior to the round window. It is possible to fracture the osseous spiral lamina or spiral ligament during electrode insertion since the round window membrane is situated close to the vertically oriented osseous spiral lamina. Traumatic abutment of the lateral scalar structures at the first basal turn of the cochlea and beyond is a second frequent cause of harm. The majority of electrodes show a very straight mid-scalar route along the cochlea's basal turn. The majority of electrodes, on the other hand, are compelled to go toward the basilar membrane once they reach their first turn. If enough force is exerted, the electrode may fracture the interscalar partition or dislodge the basilar membrane, which would allow the electrode to extend into the Scala media or perhaps the Scala vestibuli. Finally, there seems to be a limit to how deep an electrode can go without causing significant harm with today's designs. During implantation, reducing electrode-related trauma has a number of positive effects, including: Limiting damage can preserve natural hearing in patients with residual low-frequency hearing, enabling concurrent electric-acoustic stimulation (EAS) strategies. 2. Revision surgery may be less difficult if intracochlear damage is reduced as this may reduce the amount of intracochlear fibrosis and ossification. A smaller cochleostomy can be achieved with a thinner, shorter electrode since it is less likely to harm the sensitive scalar structures. On the other hand, a deeper insertion in case of bipolar stimulation would potentially allow for better frequency coverage as the electric field is created in a smaller region limits the stimulation of frequencies. Therefore, it is necessary to stimulate more populations of surviving nerve fibres or spiral ganglion cells to activate in that case. Length of insertion depends on the type and size of electric field generated by ground and active electrode. The subject of the appropriate depth of insertion is therefore brought up by this factor, which is one of the most significant in terms of current CI electrode design when stimulation is bipolar electric field. Canfarotta et.al, reported in his article, cochlear implant recipients implanted with a 31.5-mm array experienced better speech recognition than those with a 28- mm array at 12 months post activation. Deeper insertion of a lateral wall array appears to confer speech recognition. What is too deep, considering the other end of the spectrum? Contrastively Van de Marel et al. found no correlation between angular insertion depth and postoperative CVC word scores, while correcting for age at implantation, duration of deafness, preoperative phoneme score, and preoperative word score ($p=0.89$). In their analysis, Van de Marel et al. did not correct for electrode scalar location and electrode-to-modiolus proximity. All participants were implanted with the same type of electrode (HiFocus I/IJ) and with the same surgical technique (extended round window approach). This homogeneity in implantation characteristics prevented bias of results caused by differences in CI systems and by differences in electrode designs which is a strength of this study. Spiral ganglion frequency mapping indicates that an electrode must be placed deeper to stimulate low tone frequencies (1000 Hz); according to place theory. The place theory for normal hearing suggests that neurons closer to the base of the basilar membrane are optimized for encoding high frequency signals (up to 20khz), while neurons near the apex encode low frequency signals (down to 20hz). Nevertheless, it appears that with the current electrode models, such as depth of insertion would result in unacceptable harm. The place theory fails to account for human frequency discrimination below 1000hz (Mannell, Robert Theories of Hearing Macquarie University, 2008). This relatively low electrode count compared to the estimated 32,000 sensory hairs. The sound processing unit typically groups, compresses, and delivers frequencies to localized electrodes in trains of pulses limiting the frequency range and sample rate which is less than ideal for tonal languages. (Plack, Chris earing Pitch Right Place, Wrong time He Psychologist, Vol. 25, NO, 12, PG. 892, December 2012). Longer implant stems are needed to accommodate more electrodes increasing risk of surgical trauma. (MD et al., 2016 in his article importance of electrode location in cochlear Implantation Laryngoscope Investigation Otolaryngology.

Summary:

Today's CIs use 9 to 22 electrodes to stimulate fewer spiral ganglion cell populations than the healthy cochlea's 3000 inner hair cells and 30,000 auditory neurons. We cannot recover normal hearing after sensorineural deafness. Difficulty understanding speech in noise, perception of music and most delicate the perception of tonal languages is still a major issue in cochlear implants. This is because the coding strategies are speech focused. There is an interleaved 'radio' silence' in between to avoid current flow on other electrodes leading to channel interactions in digital signals. Therefore, the speed at which digital signal stimulate each electrode should be very fast. However, it doesn't correspond the input sound signal speed which leads to robotic perception, raises all the major problems related to music perception, speech in noise & tonal languages. We must be heartened that even with gross stimulation tactics, a majority of patients are experiencing remarkable hearing recovery, and we continue to witness consistent development with each implant design and processing strategy. Implant users had improved speech recognition in noise, musical appreciation, and sound localization thanks to bilateral cochlear implantation. Spatial and temporal resolution and user performance variations will likely be addressed in future versions. Innovation is accelerating, and cochlear implantation's future looks bright. 5.

Conclusion:

In order to advance medical science, it is crucial to have a deep understanding of the developments in clinical and surgical anatomy, physiology, treatment techniques, and the influential individuals involved. The history of Cochlear Implants is marked by pioneering figures and collaborative efforts in their design. In recent years, Cochlear Implants have seen notable progress, integrating technological advancements to improve patient outcomes.

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