Chapter 21
Cochlear Implants

Abstract Cochlear implantation is a multidisciplinary therapy capable of treating acute-to-overwhelming sensorineural hearing loss in children and adults. The cochlear implant system comprises a two-piece equipment. The equipment consists of an internal part that requires surgical placement, and an external part generally worn behind the ear. The internal part of the implant consists of a receiver–stimulator containing the electronic circuitry, the receiving antenna, a magnet, and an electrode array. Direct electrical stimulation is provided to the auditory nerves by inserting the electrode array inside the cochlea. The external part is battery-powered. It consists of a microphone to pick up sound, a speech processor with manual controls, and a transmitting coil to convey information to the internal part of the implant. The two parts work in tandem. Following this implantation, most adults can converse on the telephone, while children can pursue mainstream classrooms.

Keywords Bionic ear • Sensorineural hearing loss • Cochlea • Hearing aid • Electrical hearing • Tonotopy • Microphone • Speech processor • Microelectrode array

21.1 Introduction

"Bionic ear" is another name for the cochlear implant. The word "bionic" originates from "bio- + (electro)nic." "Bionic" indicates the application of electronic engineering and technology to biological systems. It aims at the augmentation or replacement of physiological functions by electronic or mechanical components. As research progresses to link machine and mind, bionic body parts are acquiring many capabilities of natural human ones.

The cochlea is a spiral-shaped cavity in the inner ear. It is usually spiraled like the shell of a snail and accommodates nerve endings, which convert sound vibrations into nerve impulses. The cochlear implant (CI) is an electronic device containing a microelectrode array implanted in the cochlea to support its proper functioning. This implant uses electrical impulses for direct stimulation of the auditory nerve. The stimulation enables a totally deaf person to perceive acoustic signals. CI can provide partial hearing to individuals with varying degrees of sensorineural hearing loss (SNHL). This is a type of hearing loss caused by injury to or deterioration of the inner ear. Its origin lies in the vestibulocochlear nerve (VIIIth cranial nerve).

V.K. Khanna, *Implantable Medical Electronics*,
DOI 10.1007/978-3-319-25448-7_21

This nerve is sometimes called the auditory nerve. Beginning from the ear, it runs to the central processing centers of the brain. In SNHL, the patient may experience difficulty in understanding sound, even when speech is sufficiently loud. Usually, the amount of loss varies with the frequency of the sound. Hence, the audiogram (plotted with sound volume on the ordinate and sound frequency on the abscissa) is not horizontal. It is sloping or dipping at different frequencies.

CI is the only means available presently to break through the ruthless silence disconnecting and estranging the deaf from society [1]. Many individuals with profound deafness have reaped the benefits of this device. Over the past 25 years, and more than ever during the preceding 5 years, it has emerged as a greeted instrument in the quality-of-life enrichment for many persons who were formerly deaf and hard of hearing. The trends indicate that more children are receiving CIs than ever before. The age at which they receive implants is declining from school age to infancy, 12 months, or below [2]. The assistance provided by cochlear implants for development of speaking and communication skills, talking and exchanging ideas in community get-togethers, and scholastic triumphs is proven beyond doubt. It has been found that both speech and lexicon benefit greatly when cochlear implantation is done in children at an age less than 2.5 years [3]. It is expected that soon general education teachers will be instructing a larger number of children with high-tech ears [4].

An extended, acclaimed, fascinating, and captivating history antedates the development of the cochlear implant. This encompasses dynamic reciprocity and teamwork between specialists in engineering and medicine. An intricate balance is struck between tests carried out under designed conditions and moral principles.

21.2 Causes of Hearing Loss

Many dissimilar causes are responsible for partial or total hearing loss [5]. Hearing loss is subdivided into three principal categories. These are known as conductive, sensorineural, and mixed hearing losses.

21.2.1 Conductive Hearing Loss

This loss is related to defects in either of the two parts of the ear: the outer or middle ear (Fig. 21.1). The main parts involved are tympanic membrane or eardrum vibrating with sound and three small bones called auditory ossicles transmitting sound from the tympanic membrane to the inner ear. Some types of conductive hearing loss are attributed to congenital defects. It may so happen that the ear canal is absent or closed in a child at the time of birth. Also, middle ear structures existing at birth may be altogether absent, malformed, or dysfunctional. Some or all these defects may possibly be corrected by surgery. Defects that are not amenable to surgical correction can generally be corrected by wearing a hearing aid, which is just a sound amplifier.

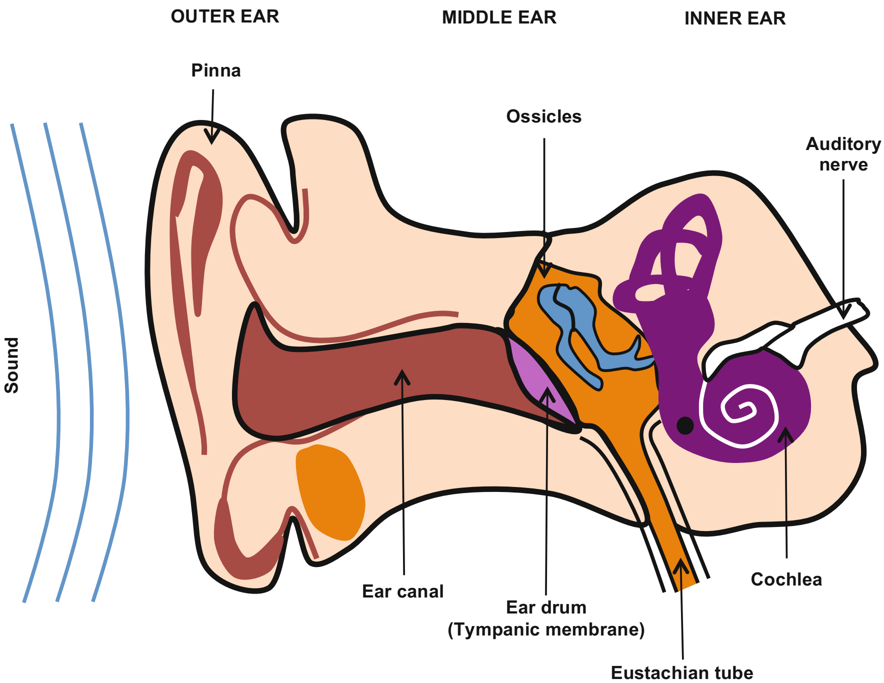

Fig. 21.1 Parts of the ear

21.2.2 Sensorineural Hearing Loss

This is a hearing loss related to nerves. It arises from troubles of the inner ear. The main reason for this type of loss lies in the inner ear or cochlea. The cochlea has the shape of a snail, a mollusk with a hard, coiled outer shell looking like a spiral. It is filled with fluid and contains the sensory hair cells. These cells may be destroyed by injury or in some other way. A natural outcome is profound deafness because it is these hair cells which convert sound waves into electrical impulses. The impulses produced are transmitted to the brain for analysis. For further clarification, the aforesaid electrical impulses move from the hair cells to auditory nerve fibers for interpretation. As the hair cells have been lost, the impulses become ineffective [9]. Therefore, the nerve fibers are not stimulated. Consequently, no hearing response is produced. Individuals suffering from this loss but still possessing an undamaged auditory nerve have profited from the advancements in cochlear implant technology.

Sensorineural damages arise from ageing. Other factors that are responsible for these damages consist of before-birth and accompanying-birth defects arising from the infections transported by a woman to her child in the uterus. Some infectious diseases are toxoplasmosis due to the parasite toxoplasma, rubella or German measles owing to rubella virus (RuV), and herpes from herpes viruses. Infections such as meningitis (inflammation of meninges by viral/bacterial infection), mumps caused by mumps

Table 21.1 Conductive and sensorineural hearing losses

Sl. No.	Conductive hearing loss	Sensorineural hearing loss
1.	It arises from any obstruction that inhibits sound vibrations from reaching the inner ear	It is instigated by mutilation of the infinitesimally small hair cells in the cochlea of the ear
2.	It affects the following parts of the ear: middle ear (three ossicles), eardrum (tympanic membrane), or inner ear	It attacks the ear parts given below: inner ear, vestibulocochlear nerve, or central processing centers
3.	Its root causes are a blockage in the outer or middle ear, such as by buildup of excess earwax, otosclerosis (abnormal bone growth near middle ear), infections in the middle ear, tiny apertures in the tympanic membrane, etc.	Its main causes are ageing, exposure to very loud noises, genetic predisposition or susceptibility, infections of the inner ear due to different viruses, chemotherapy, radiation exposures, and head injury
4.	It can be either temporary or permanent depending on its cause	It is always irreversible and permanent
5.	Its influence is usually trivial or medium in gradation, in the limits between 25 and 65 dB	Its impact can be mild, moderate, severe, or profound
6.	It can often be corrected with medical management or minor surgery	It cannot be remedied medically, but a hearing aid or cochlear implant is virtually always helpful

virus, scarlet fever due to group A *Streptococcus* bacteria, too are damaging agents. Apart from these reasons, mention may be made of the role played by heredity, trauma, exposure to loud noise, and tumors in the auditory system such as acoustic neuroma.

Mild hearing loss conditions can be satisfactorily supplemented by simple hearing aids. These are therefore excluded from the CI list. But if a deaf patient does not have an intact auditory nerve, one has to think of the next generation of auditory prosthesis. This will be the superficial or intrusive auditory brain stem implant. It will circumvent the auditory nerve. It will try straightway stimulation of auditory processing centers residing in the brainstem.

21.2.3 Mixed Hearing Loss

A blend of hearing losses of conductive and sensorineural types constitutes mixed hearing loss.

Table 21.1 presents a comparison of conductive with sensorineural loss.

21.3 CI Versus Hearing Aid

A cochlear implant is strikingly dissimilar from a hearing aid [6].

1. A hearing aid is merely a sound amplifier. A CI is a complex arrangement serving as an electrical stimulator of nerves. A hearing aid only amplifies the sound level to boost its perception. This makes the sound detectable by the inner ear for

a patient who has a damaged middle and/or inner ear. A CI totally bypasses two parts of ear: the outer and middle ones. It electrically stimulates acoustic nerves.

2. A hearing aid is worn externally. It is an external device requiring no surgery. Unlike a typical hearing aid, the cochlear instrument consists of two parts: an externally worn device and an internal implant. Signals produced by the implant are transmitted via the auditory nerve passageway to the brain. The brain distinguishes and identifies these signals as sound.
3. Listening through a hearing aid is like habitual or customary hearing, whereas hearing from CI differs from normal hearing. In CI, less sound information is received and processed by the brain in distinction to normal hearing. This explains why the quality of sound perceived with a CI is different from that of the natural acoustic hearing.
4. Little or no learning process is involved in hearing from the hearing aid. But hearing from CI entails a time-consuming process of learning or relearning and acceptance. Frequently, patient participation in a rigorous preimplantation protocol is necessary. This is required to help the doctor to take decision regarding the suitability of the patient for candidacy. The ensuing step is surgery to insert a part of the device; and then follows an activation process of the external portion of the device that the patient normally wears. In this process, the external portion of the device is programmed. The patient has to go through an intensive auditory training program. Finally, an appropriate educational program is mandated to realize maximum benefit from the device.
5. In comparison to the ancestral hearing aids, a greater cognizance to a wider range of sounds has been brought about by cochlear implants. Experience, exposure, and observation have corroborated this finding. CI allows several patients to distinguish cautionary signals. These patients can comprehend or make out other types of sounds in the ecosystem. Their lip-reading capacity is also enriched. With time and intensive training, the patients can take pleasure and satisfaction from dialogues such as a face-to-face or even a telephonic conversation. Newer devices and processing strategies have enabled CI recipients to receive more benefits. They can hear better in noise or perform conversation over cell phones. They can learn foreign languages too. They can enjoy and appreciate a variety of music. Notwithstanding, these optimistic remarks, downplaying of any undue expectations to regain normal hearing, are essential. This moderation must be done during preoperative counseling and postimplant training of patients.
6. Hearing aids are low-priced. CIs are currently too expensive. As a result, they are virtually unavailable in developing countries.

Table 21.2 presents the main differences between hearing aids and cochlear implants at a glance.

21.4 Acoustic Versus Electrical Hearing

Let us consider a person with a normal functioning cochlea. In such a person, frequencies of sinusoidal vibrations for the different regions of the basilar membrane in the *organ of Corti* do not match [6]. The reason for this frequency mismatching is not

Table 21.2 Hearing aid and cochlear implant

Sl. No.	Hearing aid	Cochlear implant
1.	It makes sound louder by amplification	It helps in sound perception by electrically stimulating the auditory nerve
2.	It does not bypass normal hearing	It bypasses the sensory cells in the cochlea
3.	It does not require surgical operation	It requires surgical operation. For surgery, an inevitable prerequisite is the removal of the hair cells within the cochlea. Perpetual loss of some or all residual natural hearing may occur from such hair shaving. Fortunately, by using flexible electrodes and applying correct surgical methods, preservation of hair cells is achievable
4.	It is externally placed	It consists of one external and one implanted component
5.	It is helpful for people suffering from mild-to-moderate hearing loss. These losses may have arisen from age-related damage to sensory cells, by exposure to loud noise, reactions to drugs, etc.	It is used by people with severe-to-profound hearing loss, mainly, sensorineural hearing loss. A reason for this loss is damage to the hair cells in the inner ear. Nerve pathways of the patient from the inner ear to the brain may also be mutilated
6.	It provides acoustic hearing	It provides electrical hearing
7.	It does not require learning	It needs learning to interpret the sounds produced by the implant
8.	It is available at affordable cost	It is expensive
9.	It provides more flexibility, i.e., it can be manually adjusted, repaired, replaced, and removed	It offers less flexibility, i.e., once a company's device is implanted, the patient has no option unless the device fails or the patient chooses another surgery/device

far to seek. It is the outcome of disparities in thickness and width along the length of the membrane. Therefore, it is said that frequency encoding is performed "tonotopically" by the cell bodies of the cochlear nerve (spiral ganglion). These cell bodies broadcast information from diverse areas of the basilar membrane. The term "tonotopy" needs explanation. It means a structural organization in the auditory pathway. This arrangement facilitates the transmission of diverse tone frequencies unconnectedly. This transmission takes place along individual parts of the structure. Like normal hearing, the principle of tonotopy is also endorsed for electrical hearing.

In a normal hearing person, sound stimuli generate patterns of electrical excitation. These patterns propagate along the nervous system pathways to the auditory nerve. Upon electrical stimulation of the auditory nerve, an action potential or spike is produced. This action potential is transmitted to the auditory cortex of the brain. But it must be emphasized that in a patient with severe-to-profound SNHL, the situation is different. This is because the hair cells are nonfunctional. Consequently, there is no production of spikes along the auditory nerve by the auditory system as observed in a response to sound signal by the normal ear. Noting this failure, the CI electrode is placed in the *scala tympani* neighboring the spiral ganglion of the auditory nerve. This electrode directly stimulates the auditory nerve electrically. It bypasses the middle ear and the part of the inner ear where the o*rgan of Corti* is located. As the brain is unable to discriminate whether the spikes have been generated by hair cells or a cochlear implant, it interprets the CI spikes as sound similar to those from hair cells.

21.5 Components of the Device

As already indicated, the cochlear implant is a two-piece device composed of two basic components. Of these, one component is worn externally. The other component is surgically implanted [7]. The externally worn component of the CI comprises a microphone and a speech processor coupled to a transmitting coil with cables and magnet. The surgically implanted component consists of the receiver/stimulator and electrode (Fig. 21.2).

21.5.1 External Functionality

The tiny microphone is enclosed in a headpiece that is worn at the ear level. It resembles the microphone of a hearing aid. Its role is to detect and pick up the sound vibrations. After picking up the vibrations, it converts them into electrical signals. The electrical signals thus obtained are transmitted to the speech processor.

The patient can wear the speech processor on the body in the style of a pager. A cable connects the speech processor to the headpiece. Sometimes, it is placed behind the ear similar to a hearing aid. It consists of three main parts: a digital signal processing (DSP) section to mathematically manipulate the signal, a power amplifier stage to boost the power level, and a radio-frequency transmitter for telecommunication.

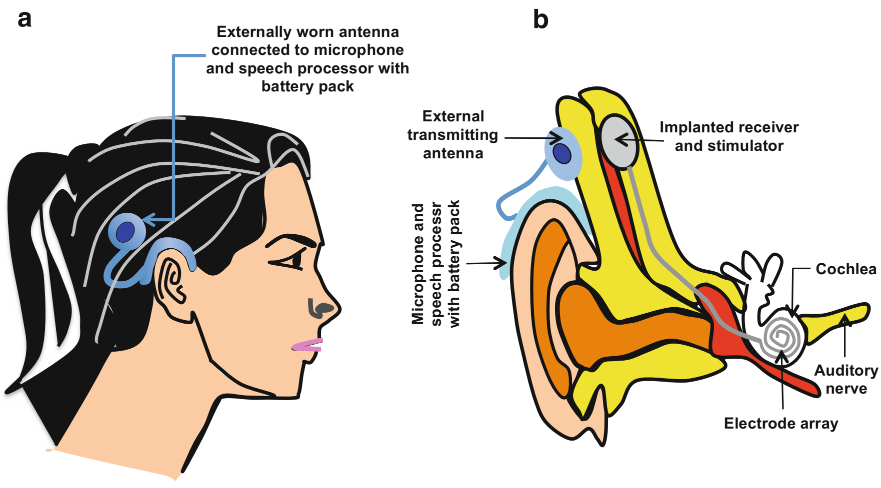

Fig. 21.2 Components of the cochlear implant system: (**a**) externally worn and (**b**) internal

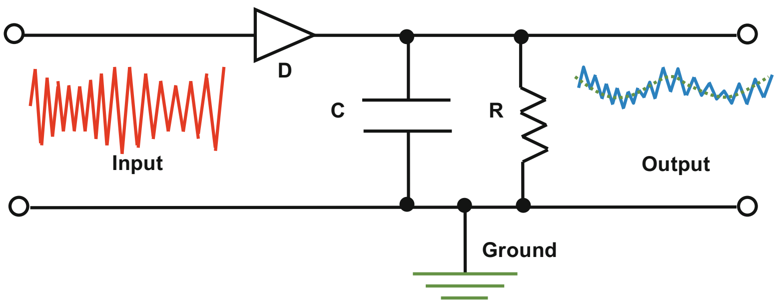

Fig. 21.3 The envelope detector circuit

The DSP is the brain or information-processing center of the cochlear implant system. It receives electrical signals pertaining to sound. It extracts distinctive features in the signal. These features are converted into a rivulet of bits. The bits are transmitted by the radio-frequency link. In other words, the DSP performs signal processing for conversion of the received signal into electrical stimuli. These stimuli are conveyed to the implanted component for electrical stimulation.

For preprocessing, the signal is supplied to an amplifier. Here, it undergoes two operations, viz., filtering and compression. The aim of signal processing unit is to analyze and split the received signal into channels. The signal splitting is done in accordance with its frequency content. This is achieved using a number of band-pass filters. Short-term spectra of the signals are estimated. The signal is subdivided into audio spectral bands. In the next step, the spectral bands are converted into pulsatile signals using envelope detectors.

An envelope detector, also called amplitude demodulator or detector, is a simple and cheap electronic circuit consisting of a diode, a capacitor, and a resistor (Fig. 21.3). It takes a high-frequency signal as the input and delivers an output signal, which represents the envelope of the input signal. This circuit is essentially a half-wave rectifier. When the input signal rises, a capacitor is charged to the peak value of the input waveform. The capacitor voltage is increased through the rectifying diode. As the signal falls, the capacitor is discharged through the bleeder resistor, and the capacitor voltage decreases. Thus the outline of the incoming signal is produced.

Following conversion of spectral bands into digital signals by envelope detectors, shaping of digital impulses is done. The pulses are controlled in parameters such as amplitude, pulse widths, application rates, etc. Calculations of the electrical stimulation parameters are performed for appropriate representation of the spectrum.

The DSP contains memory units or maps. These maps are used to store information specific to the patients. The maps as well as speech processing parameters are amenable to modification or adjustments. A PC-based fitting program is used for this modification. The stimulation parameters depend on an exclusive set of values. This unique set is determined for each implant user separately when the device is programmed. The digitized output of the DSP is a digital code. This digital code is routed via a cable to the primary windings of an electromagnetic transmitter coil.

The transmitting coil is a small disk. This disk is comparable in size to a quarter. It sticks to the skin behind the ear. This sticking is not by any adhesive but by utilizing

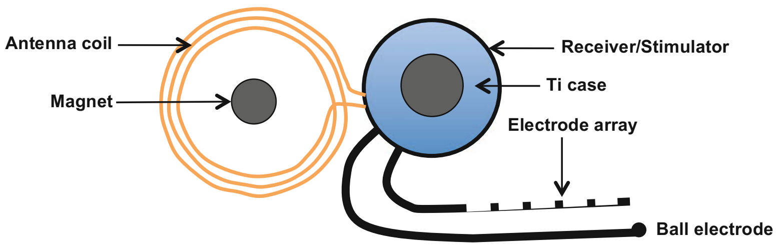

Fig. 21.4 Internal components of the cochlear implant

the attractive force of a magnet. This magnet is also necessary for securing alignment between the internal and external implant components.

A small cable joins the transmitting coil to the microphone. The main role of transmitting coil is transmission of the encoded pulsatile signals to the implant. A secondary but no less important role of this coil is delivery of power. Power is delivered across the skin of the patient to the internal components of the implant via radio-frequency signals. For ensuring high signal quality and power transmission efficiency, the abovementioned sticking magnet aligns the external device to the internal implant.

There are some variations among different CI models. In some models, the microphone and transmitter are included in a single body. In other models, the microphone is located in a segment placed behind the ear appearing as a standard hearing aid.

21.5.2 Internal Functionality

The internal functionality of a CI system (Fig. 21.4) is based on two surgically implanted components: (1) RF receiver-cum-stimulator circuit receives RF signals and supplies stimulating electrical pulses in accordance with the sound signals as provided by the external unit. Besides, responsibility of this circuit also includes supervising all the activities that take place internally because these activities have to be relayed to the external unit. Through a feedback loop, the internal unit of the implant monitors critical electric and neural activities inside. In return, it transfers these happenings to the external unit. For properly executing all the above functions, the receiver-cum-stimulator assembly is housed in a hermetically sealed biocompatible package. This is done to ensure airtight enclosure and absence of any biological rejection possibility. The assembly is implanted subcutaneously by surgery behind the ear. It encloses a magnet. Coupling of this magnet with the one in the transmitter worn externally makes flawless alignment between them possible. (2) Microelectrode array is an electrode array that is introduced inside the cochlea. Its function is provision of direct electrical stimulation to residual nerve fibers of the patient.

It must be noted that the internal unit is battery-less. Therefore, it has to derive power from outside. The stimulator obtains power from the RF signal.

During operation of CI, the signals from the external transmitter are electromagnetically captured. The charged-up receiver-cum-stimulator performs the operations of decoding and conversion of the RF bit stream into electric currents for feeding the applicable electrodes. With this intent, the internal receiver first deciphers the data transferred by the external processor. The parameters of the required pattern of stimulation are obtained. The extracted parameter information is then used to control a stimulator circuit. This circuit supplies impulses of electric currents to the assemblage of internal electrodes that have been inserted into the cochlea. The electrodes directly cause stimulation of the cochlear or auditory nerve. They sidestep the transducer cells, which are either nonexistent or nonfunctional. Upon receipt of the signals by the brain as impulses in the form of intelligent wave patterns, the signals are recognized or interpreted as sounds or hearing. The external components are held in their respective positions by the magnet, as repeatedly pointed out. Obviously, the cochlear implant does not magnify sound. So, none of its components is considered as a hearing aid.

21.6 Candidacy for Cochlear Implantation

Primary categories of candidates for CI are the post-lingually deaf and pre-lingually deaf patients. Post-lingual deafness develops after learning to speak and acquiring knowledge of language, usually at >6 years of age. Pre-lingual deafness refers to people who were born with a hearing loss. It also includes those who lost hearing before they began to speak. Main decisive considerations for suitability of a patient for CI are medical history of the patient, health condition, and inner ear structure. Most essentially, the presence of functional auditory nerve fibers to receive electrical stimuli inside the cochlea is necessary for the cochlear implant success. A clear appreciation and strong enticement to accept the long-term commitment and cooperation are demanded from the patient as well as the caregivers.

21.6.1 Presurgery

The surgery is preceded by a series of evaluations and examinations, e.g., computerized tomography (CT) and magnetic resonance imaging (MRI), audiogram scans, and experiments with hearing aids. These investigations are designed to judge the well-being and viability aspects. Both corporal and psychosomatic appraisals are planned to make the candidates ready for cochlear implantation. By the CT or MRI scans, the doctor examines the outer, middle, and inner ear structure for infections with microorganisms, aberrations, or malformations. The audiogram provides the audiologist a quantitative assessment of hearing levels of the patient. A physical evaluation is necessary to prepare the patient for surgical anesthesia. The psychological examination and counseling are done for knowledge acquisition and general attentiveness to provide the patient a realistic expectation from the surgery.

21.6.2 Surgical Procedure

For this surgery, the candidate is usually kept as an outdoor patient. Rarely does this surgery require an overnight hospital stay. Carried out under general anesthesia, the surgery is typically 2–4 h long. A trifling quantity of hair behind the ear is smooth-shaven. A cut is made adjoining the cavity behind the ear. Drilling through the mastoid bone forms a cradle of 3–4 mm size. Having done so, the internal device is installed and secured subcutaneously. Opening up the mastoid bone to gain access to the inner ear, a small orifice is made on the cochlea. Through this hole, the electrodes are threaded into the helices of the cochlea.

21.6.3 Postsurgery

Two to six weeks after the surgery, the implant recipient returns to the doctor for matching the speech processor to the implant. After activating the implant, the processor is instructed for scheduled operations through a computer program, and parameters are adjusted to appease hearing needs of the individual. Non-compulsory rehabilitation program includes therapy for auditory and speech improvement.

21.7 Discussion and Conclusions

Reported designs of cochlear implants include both marketable and investigational systems under development, and all proposed designs share several common features [8]. They detect audio signals with a microphone sealed inside a package worn by the user, much like the hearing aids tied behind the ear. From this microphone, an electric signal is conveyed to an electronic signal processor. This signal corresponds to the pressure variations due to airborne sound waves. The processor converts distinctive features of sound signals into patterns of electric stimuli that excite the nerves to elicit appropriate sensations of hearing from the patient. Considerable manipulability is exercised by the engineers designing the speech processing circuitry and algorithms. This has led to the formulation and realization of many idiosyncratic schemes.

The deliberations and criticism over the resolution to use cochlear implants in children who were deaf before learning to speak have brought forward several legal and ethical issues. These are notified permission, agreement, and parental decision-making, the cost–benefit analysis of surgery and therapy, danger valuation, etc. But the most remarkable amelioration in hearing, speech, and language has been noticed in children. Please remember, the lower the age of a child when the surgery for implantation was carried out, the more is the benefit obtained from CI [9, 10].

Review Exercises

21.1 Explain the meaning of the term, “bionic.” Hence, justify why is the cochlear implant referred to as a “bionic ear.”

21.2 What is meant by sensorineural hearing loss? What are its main causes?

21.3 Describe six important features that differentiate a cochlear implant from a hearing aid.

21.4 In what ways hearing from a cochlear implant is dissimilar to that from a hearing aid?

21.5 What is tonotopy? Does the principle of tonotopy apply to electrical hearing? Explain.

21.6 What are the roles of externally worn and surgically implanted components of a cochlear implant? How do these two components work together to provide the perception of sound to the patient?

21.7 What are the functions of the following parts in generating the output signal of the external component of a cochlear implant: (1) the microphone, (2) the speech processor, and (3) RF transmitter?

21.8 Does the internal unit of a cochlear plant have a battery? How is it powered? How does it deliver electrical stimulation to the cochlear or auditory nerve?

21.9 What are the main candidates of cochlear implantation? What characteristics qualify a patient to receive this implant?

21.10 Before planning CI surgery, what tests and examinations are typically performed? How is the implantation surgery done? What are the follow-up steps to surgery?

References

1. Zeng FG, Rebscher S, Harrison W et al (2008) Cochlear implants: system design, integration, and evaluation. IEEE Rev Biomed Eng 1:115–141
2. Fagan MK, Pisoni DB, Horn DL et al (2007) Neuropsychological correlates of vocabulary, reading, and working memory in deaf children with cochlear implants. J Deaf Stud Deaf Educ 12(4):461–471
3. Connor CM, Craig HK, Raudenbush SW (2006) The age at which young deaf children receive cochlear implants and their vocabulary and speech-production growth: Is there an added value for early implantation? Ear Hearing 27(6):628–644
4. Stith JL, Drasgow E (2005) Including children with cochlear implants in general education elementary classrooms. Teaching Except Child Plus 2(1):13 p. http://escholarship.bc.edu/education/tecplus/vol2/iss1/2. Accessed 10 Feb 2015
5. Tierney J, Zissman MA, Eddington DK (1994) Digital signal processing applications in cochlear implant research. Lincoln Lab J 7(1):31–62
6. Roux TL, Laurent C (2015) Cochlear implants in developing countries. In: Swanepoel DW, Fagan J (eds) Open access guide to audiology and hearing aids for otolaryngologists, ©University of Cape Town. https://vula.uct.ac.za/access/content/group/27b5cb1b-1b65-4280-9437-a9898ddd4c40/Cochlear%20Implants%20in%20Developing%20Countries.pdf. Accessed 10 Feb 2015

7. Shpizner BA, Holliday RA, Roland JT et al (1995) Postoperative imaging of the multichannel cochlear implant. Am J Neuroradiol 16:1517–1524
8. McDermott HJ (2004) Music perception with cochlear implants: a review. Trends Amplif 8(2):49–82
9. Weinberg A (2005) Pediatric cochlear implants: the great debate. Penn Bioethics J 1(1):1–4
10. Ali W, O'Connell R (2007) The effectiveness of early cochlear implantation for infants and young children with hearing loss. Nzhta Tech Brief 6(5):1–63