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Date 11/15/97
Sensori-neural Deafness and the Cochlear Implant

by

Margaret Pence

9/30/97
Introduction

The inner ear is part of an intricate network of fluid filled cavities located in the temporal bone of the skull. Within this bony labyrinth is the cochlea which houses the organ of hearing called the organ of Corti. Any number of factors, including disease, trauma and congenital malformations may interrupt the processing of sound through the inner ear. These conditions may lead to partial or complete hearing loss. This type of hearing loss is called sensori-neural deafness.

Since the 1950’s medical researchers have sought to restore some sense of hearing in profoundly deaf individuals by way of stimulating cochlear hair cells, and or direct stimulation of the auditory/cochlear nerve. Their work lead to the development of a device called the cochlear implant. Although not recommended for everyone, this implant has been used with at least partial success in over 13,000 people world wide.

The first portion of this thesis presents general information concerning the anatomy and physiology of the hearing process, pathologies that cause deafness, types of hearing aids available, and specific information concerning the development and use of the cochlear implant. Surgical procedures describing the process of implantation are also covered. The second portion of the thesis report focuses on the illustrations that were developed as part of my investigations of the structure and function of the inner ear, particularly the organ of Corti and its involvement in the hearing process. Their purpose is to visually communicate complex structures and processes.

Over the last few decades concerns have been voiced both in and out of the deaf community over the use of implants, especially in children. My thesis work is not meant to promote or defend the implants but merely to
present information to an interested public.

Anatomy and Physiology of Hearing

The ear itself is a compound organ that serves a dual purpose as a hearing mechanism for the reception of sound and as an organ of balance. Both functions depend on the movement of fluid through a special labyrinth within the skull and the stimulation of special receptor cells within the complex of the inner ear.

The ear is composed of three major areas: outer ear, middle ear and inner ear. The organs of hearing and balance lie within the bony labyrinth of the inner ear.

The outer ear is composed of the auricle and the external auditory canal. In humans, the auricle, the visible external portion of the ear, is considered to be vestigial. It's function, is to direct sound waves into the external auditory canal for better reception within the ear (transmission of sound waves). This function is still important in many mammals but has become inefficient in humans. The external auditory canal is a short narrow chamber (2.5 cm long by 0.6 cm wide) and extends from the auricle to the tympanic membrane or eardrum. The canal is lined with hairs and sebaceous and modified apocrine sweat glands that secrete cerumen, or ear wax. Both the hairs and wax serve to protect the ear from the invasion of foreign bodies. The tympanic membrane, or eardrum, reverberates with sound waves that travel through the external canal and set the ossicles of the middle ear into motion.

The middle ear, or tympanic cavity, is a small air filled cavity that lies within the petrous portion of the temporal bone of the skull. It extends from the tympanic membrane to the auditory (eustachian) tube. The auditory tube

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provides a link to the nasopharynx and is usually closed but opens to allow an equalization in pressure within the middle ear cavity. This is important for the proper conduction of sound through the tympanic membrane. If pressure within the middle ear cavity is not equal to external pressure, the tympanic membrane may bulge in or out and not allow for proper movement against the ossicles. This distortion of the membrane may cause conductive hearing impairment or other problems.

The middle ear contains the three smallest bones in the human body, the ossicles; malleus (hammer), incus (anvil) and stapes (stirrup). They are named for their shape. These tiny bones have the important job of transmitting vibrations of the tympanic membrane to the oval window of the inner ear, which set the fluids of the bony labyrinth in motion and thus excite the receptor cells of hearing. The "handle " of the malleus is connected to the tympanic membrane, or eardrum. The base of the stapes is set against the oval window, the incus serves as the connection between the other two bones.

The smallest skeletal muscles are also found within the middle ear. The tensor tympani originates from the wall of the auditory tube and inserts on the handle of the malleus. The stapedius muscle originates from the posterior wall of the middle ear cavity and inserts on the stapes. Both muscles serve to help control the movement of the bones against their respective membranes thus protecting the inner ear from very loud noises.

The inner ear is a bony maze-like structure that sits deep within the temporal bone and houses the delicate, sensitive receptor cells of hearing and balance (orientation). Within the bony labyrinth sits a membranous labyrinth, a series of fluid filled channels that can be separated into three
distinct areas based on unique structure and function; the vestibule, cochlea and semicircular canals. The membranous labyrinth follows the contours of the hollow bony labyrinth. The bony labyrinth is lined with endosteum and filled with perilymph which is similar in composition to cerebral spinal fluid. Thus the membranous labyrinth is “floating” within it’s chamber. The membranous labyrinth in turn is filled with endolymph which is similar in composition to intracellular fluid. These two fluids are responsible for conducting the sound vibrations that occur in hearing and detecting changes in body position. This paper will concentrate on the movement of sound vibrations through the middle ear to the cochlea that stimulate the firing of the receptor cells of hearing.

The vestibule of the inner ear may be divided into two portions, the saccule and utricle. The utricle is continuous with the semicircular canals while the saccule is continuous with the cochlea. Both these portions contain equilibrium receptors that detect and report changes in head position.

**Anatomy of the Cochlea**

The cochlea is a spiral, snail like chamber (cochlea comes from the Greek for “snail) and is about the size of half a split pea. It extends from the vestibule and coils for two and a half turns around a bony pillar called the modiolus. The axial length of the cochlea is 5 mm, the spiral canal extends to 31-33 mm long. The membranous cochlear duct runs through this chamber ending at the cochlear apex. The cochlear duct and the spiral lamina (a bony extension of the modiolus) divide the hollow cochlea into three chambers: scala vestibuli (superior), scala media (cochlear duct) and scala tympani (inferior). The scala vestibuli and scala tympani are continuous at the apex, a region called the helicotrema and contain perilymph. The scala media or
cochlear duct is filled with endolymph and houses the spiral organ of Corti, the receptor organ of hearing. The membraneous labyrinth is supported by the perilymphatic fluids and a network of tiny blood vessels.

The construction of the cochlear duct is important in the understanding of how sound waves are converted to nerve impulses. There are a series of membranes that surround and contain the duct. The roof of the duct which separates the scala media from the scala vestibuli is called the vestibular membrane. The floor of the duct is formed by the spiral lamina (from the bony modiolus) and the basilar membrane which supports the organ of Corti. The spiral ligament serves as a base of attachment for the basilar membrane and Reissner’s membrane. The flexible nature of the basilar membrane is important in the stimulation of sensory hair cells. The cochlear nerve, a division of the 8th cranial or vestibulocochlear nerve, runs from the organ of Corti through the modiolus to the auditory center of the brain.

**The Organ of Corti**

The organ of Corti sits atop the basilar membrane and is made up of a series of receptor hair cells and their supporting cells. It is named for Corti who first described its architecture in 1851. It consists of the following structure: the pillar cells, Deiter’s cells, Hansens cells, inner and outer hair cells and internal and external sulcus cells. All but the hair cells are supporting structures. The hair cells are the receptor cells that cause stimulation of the afferent nerve fibers. There are approximately 3,500 inner hair cells and 12-20,000 outer hair cells.

The hairs or stereocilia of the receptor cells are enmeshed in a gelatinous structure, the tectorial membrane that extends from the limbus over the organ of Corti and ends in a border net overlying Hansen’s cells.
Fluid movement within the cochlear duct causes movement along the tectorial membrane which pull or tweaks the stereocilia of the hair cells. (Fig. 1) At the base of the cells sit afferent nerve fibers that connect to the cochlear nerve. Stimulation of the hair cells causes a release of neurotransmitters which in turn initiate action potential of the nerve fibers and are eventually transmitted to the auditory center of the brain where they are translated into “sounds”. The location of the hair cells along the cochlear duct correlates to the type of sound that stimulates them. Cells near the oval window are activated by high-pitched sounds, those near the cochlear apex are activated by the lowest frequencies.

Figure 1. Movement of Basilar Membrane
Note the change in direction of stereocilia as the basilar membrane flexes
An examination of the close up view of the cochlea shows the different types of cells and orientation to each other. The inner hair cells, located on the modiolar side of the cochlear duct, are flask shaped and contain synaptic structures at their base. They are surrounded by internal pillar cells and border cells. Outer hair cells are located across the tunnel of Corti and run in 2-3 rows. These cells are cylindrical and contain synaptic structures that connect to both afferent and efferent nerve fibers. The outer hair cells have no internal support and maintain their shape by supporting cells. They sit upon Deiter's cells that form a shallow cup. The apical surface of the cell is held in place by a reticular membrane that also anchors the stereocilia. (These cells may be influenced by the central nervous system.) The stereocilia are located on the apical surface of both hair cells and are arranged in rows with the fibers graded at different heights. The rows on inner hair cells are straight, those on outer hair cells form a V or W shape. The hairs are anchored in a dense cuticular plate (reticular membrane) at the apical surface of the cells. These stereocilia are rigid, composed of actin filaments bonded together in a 'paracrystalline array'. There are also sites along the stereocilia fibers that allow them to bond to their neighbor producing a specific spatial arrangement to the fibers. The different bonds between the hairs also affect their movement. The movement of stereocilia against each other and the direction of movement are thought to play a part in opening ion channels leading to changes in membrane potential and thus firing of the cells along the nerve fibers.\textsuperscript{1} The generally accepted model of hair cell response holds that deflection of the basilar membrane causes deflection of the bundle of stereocilia of each hair cell. The direction of deflection - towards or away from the longest hairs - determines the depolarization or hyperpolarization
of the cell and modulates the activity of afferent fibers that synapse at the base of the cells. The majority of nerve fibers make their synaptic contacts with the inner hair cells. It is therefore assumed that it is the job of the inner hair cells to detect movement of the basilar membrane and to transmit that information to the central nervous system.²

The analysis of outer hair cell activity has been more difficult than inner hair cells. Outer hair cells outnumber inner hair cells roughly 3 to 1. It has also been shown that damage to the outer hair cells affects the mechanical vibrations within the cochlea (efferent nerve fibers run to the cochlea from the Central Nervous System). One hypothesis suggests that the outer hair cells may be able to increase sharpness of mechanical tuning of the basilar membrane. Damaged hair cells maybe unable to control oscillation of the membrane.³

It is the inner hair cells that seem to respond most to sound, 95 percent of afferent nerve fibers (fibers that lead to the brain) innervate the inner hair cells. These nerve fibers respond to sound - specifically to the frequency of sound. The frequency is related to the stimulus threshold of the hair cells and thus the auditory nerve fibers. As sound waves, or mechanical waves pass along the length of the cochlea, different cells are stimulated depending upon the frequency of the waves. This is known as 'place coding of frequency'. Studies that measure the response of different auditory nerve fibers to electrical response have been important in the development of the cochlear implant.

Properties of Sound

Sound depends on a medium through which to travel - namely air. It is a pressure disturbance originating from a vibrating object. Movement
compresses air molecules which in turn bump other air molecules and propagate a wave of movement - a new area of compression. These series of compressions are collectively called sound waves. Over time and distance the outward moving molecules give up kinetic energy and the sound eventually dies. Sound can be depicted graphically by use of S-curves which can also describe two properties of sound - frequency and amplitude. (Fig. 2)

![Image of S-curves showing Wavelength, Crest, Amplitude, and Trough]

Figure 2. Frequency and Amplitude

The crests of the curves represent areas of compression, the troughs represent areas of rarefaction or low pressure. The distance between two crests is referred to as the wavelength and is constant for a particular tone. Frequency
is defined as the number of waves that pass through a given point in a given time. The shorter the wavelength, the higher the frequency, and vice versa. In humans, we perceive different frequencies as differences in pitch. The higher the frequency, the higher the pitch. The human ear can hear from 20 to 20,000 Hz (or cycles) but is most sensitive to those between 1000-4000 Hz. Most sounds are mixtures of several frequencies which lend to their richness, a characteristic called quality. The intensity of sound is dependent on the energy and is related to differences between areas of compression and decompression, or as represented by the sine wave, to the amplitude or height of the sound wave. Sound intensity or loudness is measured in logarithmic units called decibels. The decibel scale as represented on an audiometer begins at zero or barely audible sound. Every 10 dB increase represents a ten fold (logarithmic) increase in sound intensity or energy. This correlates to only a twofold increase in loudness. The normal range of hearing for a healthy adult ear is from 0 to over 120 dB. Severe and profound hearing loss may occur with overexposure to sound intensities over 90 dB.

Sound Transmission and The Hearing Pathway

Hearing occurs when sound waves transmitted to the inner ear, via air, bone and fluid, reach and stimulate the receptor cells within the organ of Corti. This occurs through a process of transference within the middle ear that amplifies the wave energy.

Sound waves are funneled into the ear through the pinna (outer ear) and travel to the middle ear where vibrations against the tympanic membrane set it in motion, vibrating at the same frequency. The motion of the tympanic membrane is transferred, to the oval window of the inner ear, via the ossicles which act much like a hydraulic press. They increase the
pressure on the oval window which then sets the fluids of the inner ear in motion. The tensor tympani muscle can alter the tension of the tympanic membrane and control the level of vibrations. The stapedius muscle can dampen vibrations, if needed, by pulling the stapes away from the oval window. The ossicles provide a very efficient means of translating sound waves from the air to fluid vibrations within the inner ear.

The area of the tympanic membrane is 17-20 times larger than that of the oval window and thus results in pressure on the smaller window 22 times that of pressure on the tympanic membrane. Because the cochlear fluid is highly resistant to motion, this increase in pressure is necessary to overcome any impedance to movement. Normally only 0.1 percent of sound energy is transferred to fluid, the rest is reflected back at the air-fluid interface. It is the job of the middle ear components to reduce that reflection and increase the transference of energy to the fluids of the inner ear.4

Once set in motion, the cochlear fluid or perilymph within the inner ear swings the basilar membrane up and down causing the cochlear duct to oscillate. Sound waves of different frequencies travel along the cochlea from the oval window to the apex or helicotrema back to the round window. Low frequencies travel along the length of the cochlear duct from the oval to the round window, high frequencies (and therefore shorter wavelengths) fail to travel the entire distance.

When pressure waves hit the basilar membrane, they set the entire membrane into motion. Differences in the fibers within the membrane determine how great the effect will be. Fibers near the oval window or base of the cochlea are short and rigid and vibrate in response to high frequencies. As you approach the cochlear apex, the fibers grow long and flexible and
resonate in response to low frequencies. Thus before ever reaching the receptor hair cells, sounds are mechanically processed based on their frequency and wavelength.

The organ of Corti sits atop the basilar membrane within the cochlear duct. It is made up of rows of cochlear hair cells and their supporting cells. Afferent nerve fibers of the cochlear nerve sit at the base of these hair cells. Up and down vibrations of the basilar membrane cause a "tweaking" of the stereocilia of the hair cells that are enmeshed in the overlying tectorial membrane. This "tweaking" stimulates the opening of ion channels in the hair cell membranes which leads to the generation of receptor potentials. Neurotransmitters released by the hair cells stimulate the cochlear nerve fibers at their base initiating action potentials that are sent along the afferent auditory nerves to the brain. The afferent nerve fibers originating from the cochlea come together to make up the auditory or vestibulocochlear nerve. The cell bodies of these neurons are found in the spiral ganglion at the center of the cochlea.

The auditory nerve travels to the cochlear nuclei located in the pons. Secondary nerve fibers travel to the opposite side of the pons and may project to the superior olivary nucleus or to the inferior colliculus of the midbrain. At the level of the inferior colliculus, impulses from both sides provide information as to the location of sound origination. From the inferior colliculus the nerve fibers travel to the medial geniculate nucleus of the thalamus where all fibers synapse. At this level there is crude discrimination of tone and direction of sound. From the thalamus, impulses travel to the auditory cortex in the superior temporal gyrus and insula where information is further refined and translated (fine tuning occurs). It is at this highest level
where loudness and a precise discrimination of pitch occurs. There are a progressively larger number of neurons involved from the cochlea to the auditory cortex. Efferent stimuli travel along the same route.

Pathologies that cause deafness/Types of Deafness

Any number of factors, including disease, trauma, ototoxic drugs and genetic malformation, may interrupt the processing of sound through the inner ear. These conditions may lead to partial or complete loss of hearing or deafness. Hearing loss may range from the inability to hear a certain pitch to the complete inability to detect any sound. There is no age limit on hearing loss either, it may occur in young or old depending on the cause. The type of deafness is defined by the cause of the hearing loss - either conductive or sensorineural.

Conduction deafness is caused by the interruption of the transmission of sound vibrations to the fluids of the inner ear. Any number of factors may cause this including impacted ear wax, the insertion of foreign objects, and ruptured ear drums. This type of hearing loss generally involves structures of the outer and middle ear. The most common causes of conduction deafness are otitis media (or inflammation of the middle ear) in children, and otosclerosis ("hardening of the ear" or fused ossicles) often a problem related to aging.

Otitis Media can lead to a build-up of fluids within the middle ear which may interfere with the vibrations of the tympanic membrane, often causing it to bulge. Normally the auditory or Eustachian tube allows for the drainage of normal and diseased fluids from the middle ear into the nasopharynx. This can also act as a pathway for infection to enter the middle ear from the nasopharynx, especially in children whose auditory tubes run
more horizontally than in adults. Inflammation of the mucous membrane lining the Eustachian tube may also cause the tube to close preventing drainage and in chronic cases result in a negative pressure within the middle ear. This condition is generally caused by allergies, colds, inflamed tonsils, etc. and can usually be treated with medication or surgery.6

Otosclerosis, or fusion of the ossicles to each other or to the oval window, inhibits vibrations and therefore interferes with the transmission of sound waves. There may be some vibration through the skull, but it is poorly transmitted compared to the usual passage through the ear. Otosclerosis, and other factors inhibiting movement of the ossicles, may be treated surgically. Hearing losses caused by otitis media and otosclerosis are usually treatable and therefore temporary.

Sensorineural deafness occurs when there is damage to neural structures and may occur anywhere along the auditory pathway, from the cochlear hair cells to the auditory cortex. Again this type of hearing loss may be partial or complete and has many causes, both congenital and acquired. Partial hearing loss is often the result of aging, the gradual loss of hearing receptor cells (hair cells) throughout life. This type of hearing loss starts with hair cells at the basal turn and gradually progresses toward the apex. It is characterized by high frequency hearing loss. Extremely loud noises, or prolonged exposure to noise can also cause cell damage. Tumors and disease (such as meningitis) can cause irreversible damage to receptor cells and neurons. Ototoxic drugs may actually destroy hair cells, depending on the patient, dosage and length of treatment. Antibiotics of the category aminoglycosides, especially in conjunction with diuretics, may be ototoxic.
may cause temporary damage. Other factors may include head injuries which lead to reduced blood supply to the inner ear, and illnesses that result in high fever for prolonged periods.

Hair cells are more susceptible to injury than supporting cells or auditory neurons. And a large percentage of hair cells may be lost with little or no degradation of cochlear neurons. The loss of neurons seems to parallel injury to the supporting cells, especially Deiter's and pillar cells. Total loss of these supporting cells almost always leads to severe loss of cochlear neurons. The nerve endings actually attach to the base of hair cells by desmosomes, the nerve fibers lie in invaginations of the cell membranes of the Deiter and pillar cells.

In some cases the auditory pathway to the brain, or the brain itself may be affected. While the outer, middle and inner ear may be intact, those with central hearing disorders may not be able to interpret the sounds they "hear". Complex hearing rehabilitation may bring about some improvement.

Depending upon the cause of hearing loss, cochlear implants may be an option for persons with severe or profound sensorineural deafness. These auditory prosthetics act as tiny transmitters converting sound waves to electrical impulses that stimulate the cochlear neurons directly. Implant surgeries aim to preserve as much of the remaining organ of Corti as possible. This includes trying not to disrupt the basilar membrane or Reissner's membrane and to prevent contamination of the perilymph which can lead to secondary nerve degeneration.7

Types of Hearing Aids

Hearing thresholds are the levels at which the softest sound is heard for each tone. Those with normal to severe hearing loss, range from less then
20 to 90 dB. Individuals with profound hearing loss may not even detect sound above 90 dB. Although some loud noises may be discerned, these individuals cannot rely solely on hearing for communication. Tests conducted by an audiologist will measure the degree of hearing, as well as speech discrimination.

The basic function of a hearing aid is to make sounds louder and thus easier to understand, especially speech. There are several types available and are usually used in conjunction with lip reading to improve communication with the hearing community.

In general hearing aids all work the same way. A microphone picks up sound waves and converts them to electrical signals. These signals are sent to an amplifier that increases their strength, a battery provides the energy to operate. The receiver then converts the amplified signals back into sound waves and directs them into the ear via a specially fitted ear coupler. This amplification and reshaping of sound waves may help compensate for weaknesses along the neural pathway.

**Microphone 🔄 Amplifier 🔄 Receiver 🔄 Ear Coupler**

The types of hearing aids currently available are; In the Ear (ITE), Canal Hearing Aids (ITC), Behind the Ear, Eyeglass aids, Body worn aids, and special function aids that include Cochlear Implants. The latter were developed for those with severe hearing impairment that cannot benefit from traditional amplification devices.

**The development of the Cochlear Implant**

The idea of electrically stimulating the auditory system is not new. Interest began in the field with experiments by Volta in 1800. He inserted metal rods into both ears and attached them to a circuit of his newly
developed electrolytic cells. Volta experienced a sensation which he described later as "a blow to the head, followed by a sound like the boiling of a viscous fluid." Despite his unpleasant results, interest continued and by the late 19th century the field was referred to as "electro-otiatrics". Many of the discoveries made have influenced the development of the cochlear implant over the last 30 years.

During the 1960's Drs William and Howard House began studies of electrical stimulation on patients undergoing middle-ear surgery. In 1961 one deaf patient received a multi electrode device which was subsequently removed due to swelling and redness. Premature publicity and inappropriate insulation materials lead to problems and research was stopped for several years. In the late 60's engineer Jack Urban joined the surgical team and three patients were implanted in 1969-70. By then improved materials had been developed in part due to pacemaker research. Several others in California were also conducting research in the field of electrical stimulation with both animal and human subjects. (Robin Michelson at U of C, San Francisco and Blair Simmons at Stanford) Within ten years interest in the implants ranged from enthusiasm to outrage. The 1970's saw much debate over the use and implications of the implants and in general pitted the clinical community against the scientific community. House and Urban reported the first long term implantations and concluded that the device was now ready for widespread testing and development. They cautioned against uncontrolled implantation and use and suggested "careful investigation by teams of surgeons, electronics experts and rehabilitation personnel." In 1973, the American Otological Society held a session on the implants and
many concluded that the implant should not be pursued since it would never be able to restore “normal” hearing. Dr. House and others countered that some sensation of sound was better than none and that studies should continue. “We are entering a new era of otology. For the past thirty years we have been in the conductive hearing loss era... but we are now entering the era of the sensory hearing loss...”¹¹ From that time through the present, researchers have been looking to fully understand the basic principles of hearing that underlie the success of the implants.

Today cochlear implants have become accepted auditory prosthetic devices for both children and adults. It has been established through a variety of studies that the implants are effective options in the rehabilitation of the profoundly deaf. Although results vary depending on the medical, social and psychological situation of the individual patients, almost all receive some benefit from the implants.¹² The best results have occurred with post-lingually deaf adults and according to several studies, pre-lingually deaf children (Miyamoto, et al. 1993, 1997, Clark & Cowen, 1995). Benefits are also shown to improve with continued use. Post-operative rehabilitation and realistic expectations are vital in the success of the implant. Of course continued evaluation of the device is essential. Advancing technology brings about new modifications in their use and therefore new questions in regard to evaluation. Surgical risks and long term evaluations should continue.¹³

**Benefits**

Just what are the benefits provided by the implants and when should they be considered for use? First it should be understood that implants are usually recommended for the profoundly deaf who have already tried other hearing aids and vibratory devices but did not find these helpful. Cochlear
implants may help these individuals hear speech at normal conversational levels, be more aware of safety and warning sounds, lipread (speechread) better, have clearer speech, and monitor the rhythm and loudness of their own speech better. They offer greater awareness of environmental noise and therefore, improved safety.

Those who became deaf as post-lingual adults may be able to understand speech without speech reading and even use the telephone. The overall objective of the implant is to improve the ability of the deaf to communicate with the hearing world. This generally leads to improved psychological and social benefits as well. ¹⁴

Possible Side Effects

It must be understood by the recipient that there is no guarantee the implant will work. Any number of factors may interfere with proper functioning. Careful evaluation, both psychological and physical, before the surgery helps to ensure success. ¹⁵ If there is a mechanical problem with the coil or electrodes, additional surgery may be needed to repair or replace the device. External parts may also be damaged or malfunction but can be corrected without surgery. Another possible side-effect that may occur is infection at the surgical site or around the internal coil. Again, treatment and surgery may be necessary to treat the problem. Muscles in the face may become weak or partially paralyzed due to surgery. The procedures involved are in close proximity to several nerves including the facial nerve which may be damaged or affected in some way. ¹⁶ Usually this problem is temporary and will resolve itself in time. Lastly, the auditory nerve fibers in the cochlea may not respond to the electrical signal impulse, or there may be some other form of unforeseen interference along the auditory pathway to the brain. It is also
possible that calcification and new bony growth may occur around the electrode in the cochlea and block the signals. Once again, secondary surgery may be necessary.\textsuperscript{17}

Follow up treatment with patients may be very important in the successful use of the implant. Negative feelings or disappointing results cause some patients to stop using the implant. They may simply stop wearing the external coil and speech processor.

**How the Implant Works**

The cochlear implant is an electronic device that is composed of two parts: one that is surgically implanted within the cochlea (inner ear) and one that is worn externally. The external microphone picks up sound and changes it to electrical impulses which are fed into a speech processor, also worn externally. The processor translates the electrical signal into an electrical code which is then sent to an external coil held in place just behind the ear by a magnet or headset. The code is transmitted through the skin to the internal coil which in turn is sent along the electrodes located within the cochlea. The electrodes stimulate the auditory nerve fibers directly and the message is sent along the auditory nerve to the hearing processing centers of the brain. As coding systems improve, so do the signals sent to the brain. The number of electrodes necessary for stimulation has been studied and will continue to be developed and improved.

Some of the major differences among commercial cochlear implants include: the location of the external microphone, method of sound processing, the number, type and placement of electrodes, stimulation mode, back telemetry and the programming systems utilized.\textsuperscript{18}

The external components and coding strategy used are designed to
work with a specific internal device. The coding strategy is carried out by the speech processor and refers to the way sounds are processed. "Coding strategies are designed primarily to optimize speech understanding rather than the enjoyment of sounds such as music and environmental sounds," although these other sounds should not be unpleasant.19

A channel is a single line of information about a signal that is transmitted to the inner ear. These lines of communication run parallel to each other. Electrodes refer only to the number of electrical contacts that are inserted into the cochlea (the electrode array). The number of channels and electrodes may or may not be the same. Modern implant devices have 4 or more channels. Studies have determined that four channels are the amount necessary to understand speech, provided optimal conditions.20 Single and two channel users have been able to resolve ambiguities in speech in combination with lip reading. Observations have even been made with 2-channel users who felt they were really "hearing". The illusion was the result of very familiar sound patterns easily recognized in combination with the temporal cues from the lip reading. It was observed that some patterns were so "well learned and robustly stored" they could be understood with only "a minimal amount of spectral detail."21

The number of electrodes needed is still under debate. There may be a point of "diminishing returns" from too many electrodes. Until there is better understanding of speech processing and researchers determine how best to locate the electrodes, it is a matter of quantity over quality. The placement of the array within the scala tympani is also important. Positions close to the medial wall offer closer contact to the ganglion cells within the wall. (Fig.3) The maximum depth of most implant electrode arrays is 24mm
along the length of the cochlea. The distance between electrodes is also important so that there is minimal overlap between neural stimulation.\textsuperscript{22}

Figure 3. Position of electrode array within scala tympani

Another difference among implants are the processing strategies used, either analog or pulsatile. With a CA (compressed analog) processor, electrical stimuli are carried simultaneously on adjacent channels. There is some danger that signals will interfere with each other, however there is continuous information. With the pulsatile CIS (Continuous Interleaved Sampler) there is a staggered arrangement of pulses along parallel channels that helps alleviate this interference. However, this causes large "following distances" between successive pulses that may lead to gaps in information.\textsuperscript{23} Brief changes in in acoustic signals may be missed. Different sound information has its own pattern or formant (predictable digital signal). Recognition and simplification of those patterns occurs in the speech processor. There does not appear to be any clear advantage of one coding strategy over the other at this time.

\textbf{Patient Evaluation}

The implant is not a "cure" for deafness. Recipients must understand that they do not return normal hearing. Wearers describe the "sound"
produced as being electronic and staticy. Careful evaluation of possible recipients is conducted before surgery to ensure that the patient understands this.

CT scans are performed prior to surgery to determine the possible extent of damage and status of the cochlea and surrounding area. The surgeon should know the particular anatomy as well as possible before surgery, for instance, if it will be possible to enter the cochlea through the round window or if it will be necessary to perform a cochleostomy. Co-axial and coronal plane views help to determine the presence of fractures, otosclerosis or malformations. It is especially important to visualize the basal turn of the cochlea and any intracochlear calcification. Mastoid air cells of the surrounding area are prone to infection from otitis media and may lead to mastoiditis which needs to be treated with antibiotics. Fibrous bony growth may develop in this area and cause blockages. Meningitis often leads to ossification of the round window, new bone growth up to 6 mm along the scala tympani is possible. Other tests may determine the extent of nerve damage. Promontory stimulation may determine if the cochlear nerve fibers will be able to be stimulated.

Several factors to be considered in patient selection include; is a hearing aid adequate, has the patient had any ear infections, histology of the cochlea, population and viability of ganglion cells, general medical and psychosocial situation of the person. There is some debate about the use of implants in patients that use hearing aids successfully. Are the implants at all necessary or do they improve hearing? Studies suggest that the implants can offer significant improvements for hearing aid wearers.

In general, success in the use of implants seems to depend on; the
population of cochlear neurons remaining, the level of language and speech
development present, the ability of auditory associated areas to ascribe
meaning to the 8th cranial (vestibulocochlear) nerve stimulation.

As with all hearing aids the level of expectation of the patient is also
critical. It takes time and practice to become accustomed to new sounds.
Depending on the length of deafness, the absence of sound may have become
very familiar - a return to "noise" may be a confusing experience. Success
requires motivation, perseverance and patience. New implant users will
need to work with their audiology team to make any necessary adjustments.
They will need to participate in an aural rehabilitation program.

A history of the patient is important to determine the successful
candidate. The best results have been seen in post-lingually deaf adults. It is
easier for patients to learn to "recode" information if they have heard sounds
before. The sounds heard by the implant wearers are "robotic" in nature and
if associated with memory may have greater meaning. The shorter the period
of deafness, the better, especially under three years.

The outcome of success with the device will also be determined by the
patient’s environment. Those in a positive, well-educated speaking
environment will tend to have better use of the device and will continue to
use it. The best candidates, according to Simmons (1985), are those living in a
hearing world with a strong motivation to continue to do so. The decision to
implant and the success after depends very much on the patients support
system of friends and family. Age also seems to be an important factor.
Those implanted as teenagers constitute the biggest group of "non-users".
Due to the current trend toward earlier implantation, studies that focus on
the benefits to pre-lingually deaf children are becoming more and more
26
The implant is based on electrical stimulation via a transmitter placed in the scala tympani of the cochlea through the round window. Other possible areas that may be affected or will determine the success of the implant; viable neural elements of the acoustic nerve, higher auditory pathway, receptor areas of the auditory cortex.

Implant Research - The Past 30 Years

The original implants used prior to 1978, whether single or multi-channel devices used broad-band analog electrical waveforms that excited broad regions of auditory neurons synchronously. Unlike the normal cochlea in which different resonances specifically effect the firing of hair cells, this broad range stimulation still allowed discrimination of consonants and "temporal cues" provided by the implant. The prosthetic device was helpful as a supplement to lip reading and the identification of "classes" of sounds.

Studies conducted during the 1970's and 80's provided valuable information that enabled vast improvements in the design of the Nucleus cochlear implant speech processor in wide use today. Studies by Tong and colleagues in Australia, provided important information concerning the discrimination of frequency, intensity and patterns of stimulation. Hartman, et al. studied the response of the auditory nerve to electrical stimulation and determined that the spread of neural activity was determined by the location and orientation of electrodes in the cochlea. Important studies by Shannon at the University of California, San Francisco (1983-93) measured hearing thresholds, uncomfortable loudness and the temporal processing of implant patients. It was determined that implant users had a high sensitivity to frequencies below 300 Hz, but that the usable dynamic range with electrical
stimulation was much smaller than that of normal hearing. Users could
discriminate small changes in intensity (less than 1 dB) but with smaller
dynamic ranges, they could only discern 20-30 steps in intensity compared to
200+ steps in normal hearing. Frequency discrimination was similar to
normal hearing for low frequencies (<300Hz) but absent for high frequencies.
The implant has no mechanism to separate different frequencies of electrical
stimulation. Temporal processing appeared normal for implant wearers.
They can detect gaps in stimulation and have normal recovery time from
adaptations from previous stimulus. Overall implant patients had relatively
normal ability to follow temporal fluctuations but no ability to discriminate
frequencies above 300 Hz (on single channel electrodes).

During the 70's and 80's there were continued improvements of
commercial devices thanks to information gathered from research. Actual
performance in patients often exceeded expectations by researchers. Most
recently, developments in cochlear implant signal processing have resulted
in dramatic improvements in performance. New processing strategies, such
as CIS - continuous interleaved sampler, show improved performance with
multichannel speech processors, better than with single channel processes.
(Some multichannel users still receive no spectral place cues and function
only at the level of single channel users. It is not known if this is due to poor
nerve survival or failure to adjust the device properly.)

Implant research has also led to a better understanding of the hearing
process in individuals without impairment as well. Studies have shown that
loudness is actually perceived by two distinct mechanisms in the brain, one
for low frequencies, another process for high frequencies.

During the early years of development of the implant there were a
number of safety concerns that could only be answered over time. Would there be long term negative effects on the auditory nervous system from continuous exposure to electrical fields? Would electrical stimulation precipitate bone growth in the cochlea and the area surrounding the auditory nerve, would it cause the death of any remaining neural elements rendering itself ineffective? Would the devices have to be replaced and would this lead to further trauma? Looking back at twenty years of careful monitoring and research, it would seem that the implants can be used successfully and safely with little or no detrimental effects. Implant devices have proven stable and dependable. Even some devices that have been removed and re-implanted still function well. Hermetic sealing, a process developed for pacemakers was key in early technological developments. It prevents leakage of any kind into the implant, from body fluids, that might cause corrosion or shorting of electrical circuits. Once a device has been implanted for a year, the failure rate is less than 1% (von Wallenburg Brinch 1995).

Another safety concern, and a debate still in progress is the implantation of pre-lingually deaf children. If a child is congenitally deaf, can they still benefit from use of the implant, or is some auditory experience required? Also will there be detrimental effects to the still developing auditory system? Studies would indicate that there is benefit. The patterns of stimulation provided by the speech processors are rich enough for the developing nervous system to form connections that will allow them to process information in much the same way as a normal hearing child. Some results question the appropriateness of the stimulus - "wrong information" such as that presented in situations with alot of background noise, could cause the brain to adapt in a way that is detrimental to continued successful
development in later years.\textsuperscript{31}

\textbf{Surgical Procedures}

Since the 1970's there have been a number of implant devices on the market. The major types include the single-channel intracochlear implant and the multichannel device, most often used. The type of device used may depend upon economic and clinical considerations. The single channel implant most widely used has been a model introduced by House and Urban in 1972. A number of factors, including safe surgical technique and ease in manufacturing, enabled this implant to be developed early. Most single-channel devices work in the same manner and are similar in design. The surgical procedure involved in placement of the device is virtually the same.\textsuperscript{32} One possible advantage of the single channel is that it may be placed outside the cochlea, against the round window, although studies have shown that better results occur when the electrode is passed a short distance (6 mm) into the scala tympani. In children and patients that are being implanted for tinnitus suppression, it is still preferable to leave the electrode outside the cochlea.

The objective of the multichannel implant is to take advantage of the "spatial representation of frequency in the cochlea" so that speech may be interpreted in the profoundly and totally deaf to improve communication. The best way to take advantage of this spatial stimulation is to place an electrode array along the basilar membrane within the scala tympani, beginning at the basal turn of the cochlea. (Fig. 4) The array is also flexible and tapered to follow the turn of the cochlea and allow for easy placement, and if necessary, replacement.\textsuperscript{33}

Presurgical testing will determine if certain types of pathology and
anatomical variations exist. Fibrosis or bony growth present in the basal turn can be removed up to 6 mm to allow for insertion of the electrode. Or if completely filled, the electrode may need to be placed around the turn. Alternatively, an extracochlear multichannel device may be necessary.

Fig. 4  Electrode inserted into cochlea

The surgical procedures discussed here are well established and general for a variety of implants, based on the techniques for implanting the Melbourne/Cochlear multichannel receiver. The surgeon’s understanding of the relevant anatomy is vital in the success of the implantation. It is necessary to be completely familiar with the anatomy of the round window and basal turn of the cochlea, since it is possible that a bony overhang may obscure the surgeon’s view of the window. More extensive drilling may be required to expose the round window. Experience may be gained in the temporal bone laboratory.
There are several incisions that may be used to expose the implant area. They include the postauricular inverted-U, extended endaural, C-shaped and inverted-L. A generous margin around the site of the proposed implant provides flexibility for the surgeon in case of unforeseen problems. A dummy package is placed in the approximate position of the implant site and marked. Depending on the experience and preference of the surgeon, the skin and subcutaneous fascia may be raised separately from the deep fascia and periosteum. Tension sutures may be used to hold the flap/s out of the way. Extra precautions, such as bi-polar coag, are taken to prevent damage to soft tissue.

Once the skull is exposed, a limited mastoidectomy is performed to expose the mastoid antrum, the lateral semicircular canal and the short process of the incus. Knowledge of local anatomy is important in avoiding damage to the facial nerve. The short process of the incus provides a guide to the vertical course of the nerve. Removal of bone is carried out with a cutting burr and fine drill. Irrigation is used during drilling to prevent over heating. Landmarks that the surgeon looks for in determining the drilling site are the mastoid air cells and tegmen of the dura (to prevent drilling into the brain cavity).

Once the antrum is exposed and the facial nerve located, a posterior tympanotomy is performed to expose the round window via the facial recess. The facial recess is bounded by the short process of the incus, the facial nerve covered by a thin layer of bone and the chorda tympani. The operation proceeds through the facial recess to get to the round window. The stapes and malleus will be visible through the opening made into the middle ear. The ligaments that hold the incus in place may be seen on either side and help in
locating the course of the facial nerve. The stapes provides a guide to the scala tympani if the round window has been obliterated. (The inferior margin of the scala tympani at the basal turn is 3 mm below the lower margin of the stapes foot plate.) Extended drilling is often necessary to provide adequate exposure of the round window which may increase risk of injury to the facial nerve. The chorda tympani should also be identified and if possible preserved. It is often difficult to locate the round window. This portion, as well as most of the surgery, will be performed under magnification.

Once the middle ear and the round window have been located and exposed, the package bed is prepared. A template is used to mark the position at least 1 cm behind the postauricular groove. It is drilled down to a depth that keeps the implant from protruding significantly from the skull. In some cases it may be drilled down to the dura. Upon completion of the package bed a groove is drilled between the bed and the mastoid cavity. This provides a pathway for the lead wire.

In order to facilitate placement of the electrode in the cochlea, the membrane of the round window must be exposed. The bony overhang, crista fenestra, may need to be burred down, drilled anterioinferiorly. The membrane of the round window is incised to provide entry to the scala tympani at the basal turn. Or if necessary, due to obstruction of the window, a cochleotomy anterolateral to the round window may be performed. If the window is obliterated due to meningitis, a hole may be drilled higher along the turn to find lumen, or an extracochlear device may be needed. The bone is thinned with a diamond paste burr until a dark blue line (underlying endosteum) is observed. Bone is then picked away to provide an opening adequate for the unimpeded insertion of the electrode. The hole should be
approximately 1 mm wide (it may be necessary to extend it up to 2 mm wide to provide adequate visibility). Bone growth and fibrous tissue may require further removal to expose the scala tympani.\(^37\)

An insertion claw is used to direct the electrode tip into the opening of the cochlea. Holding the package in the other hand, the electrode is gently advanced into the cochlea at the basal turn. The "stiffening rings" around the electrode are used to feed it into place. Insertion is halted if any significant resistance is felt to avoid damage to the electrode and the basilar membrane within the cochlear duct. Damage to the spiral lamina and basal membrane leads to loss of ganglion cells (auditory nerves). Since the electrode is thought to stimulate the peripheral process of the auditory nerve and spiral ganglion cells, any damage is undesirable. Withdrawal and rotation of the electrode guides the tip away from the membrane and around the basal turn.

Once the electrode insertion is complete, the package is secured in place by suturing it to the skull. If the overlying flap of skin and fascia are too thick (over 6 mm), it may be necessary to excise the deep fascia. If the flap is too thick, the external magnet may not be held in place properly. The skin flap is sutured over the device once everything is in place. Sutures may be removed after 10 days. An x-ray should be taken at the time of surgery or before the patient goes home to ensure that the device is in the proper place.

After the surgical wound has healed, the external portion of the device is fitted. Recovery periods vary depending on the type of device and surgical procedures involved, usually 10 days to 6 weeks. The device used also determines the tolerance for distance between the internal receiver and external coil. For instance, the Nucleus device allows for no more than 6 mm between the parts, therefore it is important that postoperative swelling is at a
minimum before the headset and speech processor can be fitted.

**Future Improvements**

At the present time, the perfect device that would enable complete speech discrimination does not exist. The various single and multichannel devices on the market offer the profoundly deaf improved awareness of environmental sounds, improved speech reading and possibly some speech discrimination. In the opinion of one researcher, advances in implant performance have resulted from a combination of basic knowledge, research and just plain luck. We are currently approaching the best performance possible from this random search process and the next wave of improvements will need to be based on more systematic studies of basic principles involved in implant function and studies of speech recognition in the brain. With the continued support and interest of speech and auditory specialists, hopefully there will be improvement in the coding schemes necessary to stimulate the impaired auditory system to the point of producing intelligible speech. The basic system will probably not change much, it is the coding schemes that offer the greatest hope of improvement. Techniques for mapping the surviving auditory neurons within the cochlea may also improve the way these neurons are stimulated and therefore offer improved discrimination.

A number of studies have been conducted to determine the performance differences between different brands and types of implants. Although results vary, all types of implants enhance lip reading abilities. New speech coding strategies offer improvements such as discrimination in noisy situations. In some cases implants may not be sufficiently customized to the individual patient. Fitting now is oriented toward the capabilities of
the device. Improvements may result in looking at the capabilities of the patient. Pre-operative estimation of surviving nerve fibers, with electrical stimulation during auditory brainstem response recording, becomes more essential as multichannel devices are improved. Many questions still need to be answered to determine why there is such variability among patients implanted with the same device.41

Current surgical procedures try to minimize any further damage to the cochlea and the surviving hair cells. However studies have shown that implants may lead to loss of ganglion cells and degeneration of distal processes. Electrode penetration of the scala media may also lead to new bone formation around the electrodes. Flexibility of the electrode and the geometry of the basal turn play a role in the amount of damage done during implantation.42 Again, improvements in presurgical testing may eliminate some of these problems. Radiography and MRI’s help to determine the extent of congenital malformations and aplasias of the labyrinth. Damage of the cochlea has also been attributed directly to the length and design of implants.43

**Summary**

During the 1960’s when the idea of replacing part of the auditory sensory system with a mechanical device was first proposed, many felt that it was too complex a proposition and would never work. At the time, researchers were only just beginning to fully understand the complex processing of sound through the human ear. Yet, even these early models met with success in restoring some degree of functional hearing to profoundly deaf individuals. Today, many implant users worldwide can understand running speech (even without lip reading) and many can even
converse on the phone.

According to various researchers, advances in implant performance have resulted from a combination of basic knowledge, research and just plain luck. The research to explain why implants work lags behind the actual improvements. In the opinion of Shannon, we are currently approaching the best performance possible from this random search process and the next wave of improvements will need to be based on more systematic studies of basic principles involved in implant function and studies of speech recognition in the brain.
Artwork

My objective for the artwork produced for this thesis was to visually present information pertaining to the overall subject of hearing and the auditory nervous pathway involved. All of the work is appropriate for use in any number of ways, but especially for poster size presentation. The first three major pieces include information of interest to the general public and are meant to educate anyone interested in the hearing pathway. The second set illustrate information specific to the use of cochlear implants including the surgery itself and the position of the implant when in use.

To begin with, I reviewed information concerning the auditory system, sensorineural deafness and the use of cochlear implants in the profoundly deaf. My goal was not to promote or condemn the implants but to present necessary and useful information to an interested audience. The illustrations I chose to create help present the data in a visually interesting, yet easily understandable manner. The process of hearing is obviously not a visible one, but the anatomical features are. Understanding the pertinent anatomy hopefully lends itself to a better understanding of the highly complex mechanisms involved. Labels and text that accompany the illustrations help to clarify the information presented.

The subject of each informational poster is as follows;

- **The hearing pathway** - orientation to the middle and inner ear
- **The organ of Corti** - a cellular level view of the organ of hearing
- **The auditory pathway** - the route of auditory neurons to the brain
- **Surgical procedures** - placement of the cochlear implant
- **Cochlear implants** - orientation of the device in place
The artwork for each piece was created individually using traditional illustration techniques. The middle and inner ear, organ of Corti, auditory pathway and orientation of implant device were all painted in watercolor (Winsor & Newton Cottman brand), first with wet wash technique, then refined with dry brush. In order to even out tones in certain areas a layer of pastel dust was applied using a carbon dust technique with sable brushes. Final details were added using pastel and prismacolor pencils.

After producing the initial artwork, the pieces were copied and reduced to appropriate sizes using a Cannon color copier. These copies were then scanned into the computer at 300 ppi and brought into Photoshop for color adjustment. The original pastel palettes were adjusted to slightly darker hues with greater contrast. The various illustrations were copied and pasted into layers of the final presentation size of 11x17 in a new document. A color background was added and additional elements such as arrows were created in Photoshop and placed appropriately. When the final background art was complete, the layers were “flattened” and saved as EPS files for importation into Quark Xpress. I chose to add the text and labels in Quark for ease of manipulation and clarity of text. The final computer generated pieces were printed on several color printers to obtain the best results possible.

The artwork for the surgical procedures were done using traditional carbon dust techniques on Color-aid brand paper (clay coated). Initial sketches were made from watching a surgical video on cochlear implants. (Discovery channel surgical program - House Corp., Dec. 1994) Further research was conducted from surgical atlases and illustrations compared to other published works. I was also able to spend some time in the temporal bone lab at the University of Rochester Medical Center which helped in obtaining a better
perspective of the orientation of the cochlea within the skull and the
structures involved in the surgical procedures. The completed illustrations
again were scanned into the computer at 300 ppi and brought into Quark for
the addition of the accompanying text.

I also chose to create two editorial illustrations as an outgrowth of the
more traditional pieces. The first is an oil painting of an adolescent girl,
profile view. Sound waves float through the background of the figure
bombarding the auditory senses. In a semi-transparent view, the location of
the internal structures of hearing - namely the cochlea is revealed. The skull
and mandible are shown to orient the viewer to the location of this structure.

The second illustration was created for a fictional magazine cover for a
real journal - *Annals of Otology, Rhinology and Laryngology*. It was created
with an article in mind, "Cochlear Implants: Future Research Directions,"
confronting the controversy over the implant. The bony and membranous
labyrinth are represented. Both are transparent to reveal the pathway taken
by the electrode portion of the cochlear implant. The magnified view of these
tiny structures sit atop a blue-print type plan for the circuitry involved in
creating the implant - a mechanical device being implanted into a
morphological form.

Supplemental illustrations were created using pen and ink as an
outgrowth of writing this thesis paper. They are intended to clarify specific
processes referred to in the text.

The information presented in all these illustrations serve to create a
better understanding of the anatomy and physiology involved in the hearing
process, or in some cases, the inability to hear as well. The intended audience
is the general public, sixth grade reading level and higher. The information
might be that presented to a deaf individual considering implantation, or their family, as well as anyone else interested in the subject.

Illustration Text

The Hearing Pathway

This illustration depicts the gross anatomy of the middle and inner ear in relationship to each other within the skull.

*Hearing is a specialized sense that allows us to perceive and interpret sound.*

*During the process of hearing, sound waves from the environment are received by the ear, converted to nerve impulses and transmitted to the auditory centers of the brain where we interpret them as “sound”.*

*The Outer Ear - or pinna, helps funnel sound waves into the external auditory canal. The canal is 25-35 mm long and ends at the tympanic membrane.*

*The Middle Ear - is a small, irregularly shaped cavity within the petrous portion of the temporal bone of the skull. It extends from the tympanic membrane to the oval window and houses the small bones of the ears - the ossicles. The middle ear is approximately 15 mm high and 2-4 mm wide.*

*The Inner Ear - is made up of three cavity systems - the semi-circular canals, the vestibule and the cochlea. These systems are encased in a fluid filled membranous canal within the “bony labyrinth”. The entire structure of the inner ear is no larger than the diameter of a dime. The semicircular canals function in maintaining balance. The “snail shell” like cochlea is key in the processing of sound. The auditory nerve arises from within this structure.*

The Organ of Corti

*The interior space of the cochlea is divided into 3 separate fluid filled*
chambers - the scala tympani, scala media and scala vestibuli. The organ of Corti is located within the scala media, or cochlear duct.

Fluid movement within the chambers of the cochlea cause the basilar membrane to rise and fall in waves depending upon the frequency of the sounds being received. This movement causes the cilia of the hair cells to pull against the tectorial membrane and stimulates them to release neurotransmitters. The neurotransmitters in turn excite the cochlear nerve fibers. This is where the transmission of signals along the auditory pathway begins.

The auditory pathway

The afferent nerve fibers originating from the cochlea come together to make up the auditory or vestibulocochlear nerve. The cell bodies of these neurons are found in the spiral ganglion at the center of the cochlea.

The auditory nerve travels to the cochlear nuclei located in the pons. Secondary nerve fibers travel to the opposite side of the pons and may project to the superior olivary nucleus or to the inferior colliculus of the midbrain. At the level of the inferior colliculus, impulses from both sides provide information as to the location of sound origination. From the inferior colliculus the nerve fibers travel to the medial geniculate nucleus of the thalamus where all fibers synapse. At this level there is crude discrimination of tone and direction of sound. From the thalamus, impulses travel to the auditory cortex in the superior temporal gyrus and insula where information is further refined and translated (fine tuning occurs). It is at this highest level where loudness and a precise discrimination of pitch occurs.
The steps shown here are a partial representation of the surgical procedure for placing the internal coil and electrode array of the cochlear implant device. Rather than show each step individually, several steps have been combined for efficiency. The orientation illustration shows the location of the surgery behind the ear.

**Making the initial incision** The first step is to mark the location of the incision. Several flap incisions are currently in use. The one shown here is a modified version of the inverted-U incision. The marking of the incision may be expedited by placing a dummy package in the approximate position. The marking device shown here may be used to mark the location of the internal coil on the skull beneath the skin as well.

**Limited mastoidectomy** The next step shows the drilling into the mastoid bone after the flap of skin, fascia and muscle have been pulled back. A limited mastoidectomy will expose the mastoid antrum, the lateral semicircular canal and the short process of the incus. A burring tool is used to chip away the bone.

**Preparation of the package bed** The third step illustrates the preparation of the package bed. It is drilled out after the surgeon has determined and marked the position using a template. It must be placed at least 1 cm behind the postauricular groove. The bed is drilled down to a depth to prevent the package from protruding significantly above the surface of the bone. Note the position of the exposed antrum.

**Feeding the electrode into the cochlea** After the drilling is complete, the electrode is inserted. Exposure of the round window is desirable and may require drilling away of a bony overhang anteroinferiorly. The electrode may
be inserted through the round window into the scala tympani, or if necessary, at the basal turn of the cochlea. This second option requires a cochleotomy just anterior to the round window. The presence of extensive fibrous tissue or bone may require further drilling into the scala tympani to facilitate placement of the electrode. A special fork like instrument is used to feed the electrode in to the desired depth. The insertion should be stopped if any significant resistance is encountered to prevent injury to the basilar membrane.

Securing the inner coil package in place Following placement of the electrode, the package containing the internal coil is secured with dacron ties to the skull. It is further anchored in place by suturing the skin flap over it. Normally the surgery takes 2-3 hours to complete. If there are no further complications the patient may leave the hospital in 1-4 days.

Cochlear implant in place
Frontal Section showing device in place. (After Ed Zilberts)
Following a healing period of 3-6 weeks, the patient will try the implant device for the first time. They are fitted with the external parts: the microphone, speech processor and external coil. The external coil is usually held in place by a magnet or headset just over the location of the internal coil. Electrical codes are sent across the skin from the external to the internal coil and are carried along the electrode to the cochlea. Signals are picked up by sensory neurons leading from the cochlea to the cochlear nerve. Awareness of sound occurs in the auditory cortex of the brain.
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Hearing is a specialized sense that allows us to perceive and interpret sound. During the process of hearing, sound waves from the environment are received by the ear, converted to nerve impulses and transmitted to the auditory centers of the brain, where we interpret them as 'sound'.

The Outer Ear - or pinna, helps funnel sound waves into the external auditory canal. The canal is 25-35 mm long and ends at the tympanic membrane.

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The Inner Ear - is made up of three cavity systems - the semi-circular canals, the vestibule, and the cochlea. These systems are encased in a fluid-filled membranous canal within a bony labyrinth. The semi-circular canals function in maintaining balance. The auditory nerve arises from within this structure.
THE ORGAN OF CORTI

Identification Key
1. Cochlear nerve
2. Scala vestibuli
3. Scala media/cochlear duct
4. Scala tympani
5. Organ of Corti
6. Tectorial membrane
7. Inner hair cells
8. Other hair cells
9. Cells of Hensen
10. Dettmer's cells
11. Basilar membrane
12. Pillar cells
13. Inner sulcus cells
14. Cochlear nerve fibers
15. Limbus

The interior space of the cochlea is divided into the scala vestibuli, scala media, and scala tympani. The organ of Corti is located within the scala media, or cochlear duct. Fluid movement within the chambers of the cochlea causes the basilar membrane to rise and fall in waves, depending upon the frequency of the sounds being received. This movement causes the cilia of the hair cells to pull against the tectorial membrane and to release neurotransmitters. The neurotransmitters in turn excite the cochlear nerve fibers. This is where the transmission of signals along the auditory pathway begins.
The Auditory Pathway

Sensorineural deafness may occur anywhere along the neural pathway to the brain. Damage may be caused by genetic abnormalities, disease, drug use, trauma, etc.

Thalamus - all fibers synapse at the medial geniculate nucleus. Crude discrimination of tone and location of sound.

Auditory Cortex - loudness and precise discrimination of pitch.

Midbrain - fibers extend to the olivary nucleus or the inferior colliculus.

Pons - auditory nerve reaches location of cochlear nuclei.

Nerve fibers from the cochlea join to form the auditory nerve.

High Pitch

Low Pitch
Cochlear implant in place
Following a healing period of 3-6 weeks, the patient will try the implant device for the first time. They are fitted with the external parts: the microphone, speech processor and external coil. The external coil is usually held in place by a magnet or headset just over the location of the internal coil. Electrical codes are sent across the skin from the external to the internal coil and are carried along the electrode to the cochlea. Signals are picked up by sensory neurons leading from the cochlea to the cochlear nerve. Awareness of sound occurs in the auditory cortex of the brain.
Surgical Procedures - Multichannel Implant Surgery

Step 1 - Making the Initial Incision
Step 2 - Limited mastoidectomy
Step 3 - Preparation of the package bed
Step 4 - Feeding the electrode into the cochlea
Step 5 - Securing the inner coil package in place
Sinus within a sinus: a Mammoth Extramural Ethmoid Air Cell

Management of Posterior Cranial Fossa Meningiomas

Mycobacterial Disease of the Head and Neck: Current Perspective

Cochlear Implants: Future Research Directions