

Cochlear Implant Using Neural Prosthetics

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Abstract: *This research is based on neural prosthetic device. The oldest and most widely used of these electrical, and often computerized, devices is the cochlear implant, which has provided hearing to thousands of congenitally deaf people in this country. Recently, the use of the cochlear implant is expanding to the elderly, who frequently suffer major hearing loss. More cutting edge are artificial retinas, which are helping dozens of blind people see, and “smart” artificial arms and legs that amputees can maneuver by thoughts alone, and that feel more like real limbs.*

Research, which curiosity led to explore frog legs dancing during thunderstorms, a snail shaped organ in the inner ear, and how various eye cells react to light, have fostered an understanding of how to “talk” to the nervous system. That understanding combined with the miniaturization of electronics and enhanced computer processing has enabled prosthetic devices that often can bridge the gap in nerve signaling that is caused by disease or injury.

I. Introduction

Today’s neural prosthetics can trace their origin, in part, to a pair of frog legs that caused quite a laboratory sensation in Mozart’s time (c.18th century). The lab belonged to the Italian anatomy professor and physicist Luigi Galvani, who was dissecting a frog at a table. Also on the table was a wheel that generated static electricity for Galvani’s physics experiments. Just as Galvani put a scalpel to the sciatic nerve, which connects to the muscles in the frogs’ legs, his assistant happened to discharge a spark of electricity from the wheel. Galvani noticed that when the spark was released, the legs of his dissected frog jerked. Apparently the static electricity released into the air was picked up by the metal scalpel and passed to the nerve (Figure 1). This led Galvani to conduct other experiments including one in which the static electricity of a thunderstorm prompted frog legs on a rooftop to dance, and another

one in which touching the exposed nerve to a frog leg muscle was enough to cause the muscle to twitch.

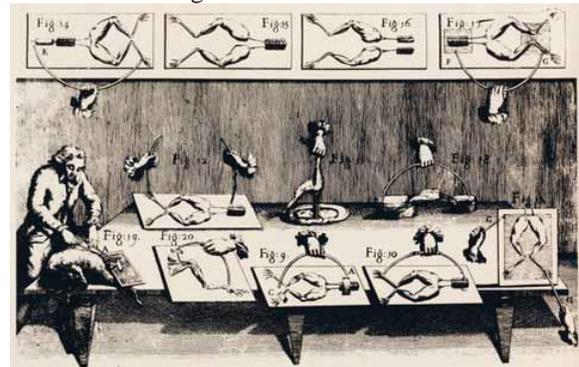


Figure 1 – Galvani’s frog experiment stored in the nerves of all living creatures, and literally sparked the notion that nerves use electrical energy to trigger muscle movement. (Galvani’s experiments also apparently inspired Mary Shelley, who read about them shortly before writing her famous novel Frankenstein, in which electricity is used to bring to life Dr. Frankenstein’s monster.[3])

In the 19th century, the invention of an amplifier of electric current called the galvanometer (named after Galvani), enabled several basic science researchers to eavesdrop on the electrical chatter of muscles and nerves. The experiments these European physicists did on frogs revealed that an electrical current applied to the nerve can briefly reverse the charge emitted by that section of the nerve. This flip-flop in charge from positive to negative quickly spreads down the length of the nerve and to the muscle where it causes the muscle to contract. In other words, by exploring the innate electrical activity of tissues and how that changes in response to electrical stimulation, these researchers had collectively stumbled upon the electrical nerve impulse, which is the basic signaling mechanism that nerves use to communicate with tissues and organs (Figure 3).

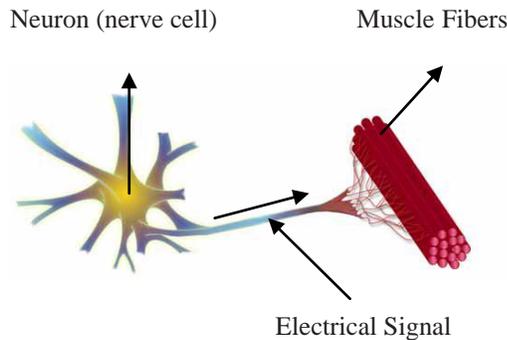


Figure 3 – Nerve Impulse: Electrical impulses travel through motor neurons, or nerve cells, to signal muscle contraction. As described in later figures, electrical signals can also be carried from tissues back through sensory neurons to the brain to communicate the amount of tension in the muscle.

Later, studies in the 1920's revealed that the electrical activity runs on a two-way street it can pass not just from the motor nerve to the muscle, but in the reverse direction from the muscle to a sensory nerve. The brain uses motor nerves to tell the muscle to contract or relax. But the muscle can talk back to the brain via sensory nerves that convey the amount of tension in the muscle. One particularly telling experiment was that of the British physiologist (and later Nobel Prize winner) Edgar Douglas Adrian. He had suspended a frog leg from a brass hook and was surprised by the spike of irregular electrical activity coming from nerves in the leg. He first thought that this was due to faulty equipment used to record the electrical activity and frustratingly expected that he would have to spend months rebuilding it. But then he noticed that when the frog leg was placed on a glass plate, the irregular electrical activity stopped only to come back when the leg was suspended again. That's when it dawned on him that the electrical activity was actually an electrical signal being passed from muscle to nerve to tell the nerve (and ultimately the brain in an intact animal) that the muscle in the frog leg was being stretched. (Such stretching didn't occur when the leg was merely lying on the plate.) These "electrifying" findings opened up a whole new way of understanding how the body Works and led investigators to electrically explore how a cacophony of sounds that passes through our ears become music to our minds.[6]

II. Journey into Inner Space

Meanwhile, by the middle of the 19th century, anatomists had mapped out the inner ear. Their dissections revealed that in addition to a thin membrane, called the ear drum, and some of the tiniest bones in the body, the inner ear had a strange snail-shaped structure called the cochlea. The cochlea was filled with fluid and carpeted with thousands of tiny hairs. Because these hair cells connected with the auditory nerve that travelled from the ear to the brain (Figure 4), it was assumed that the cochlea played a crucial role in hearing.

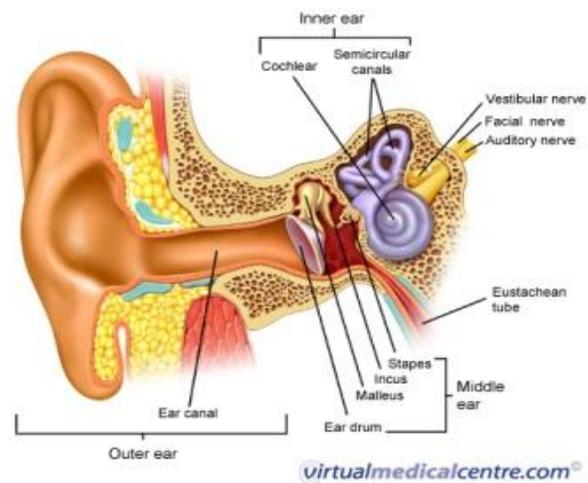


Figure 4 – Anatomy of the ear: The discovery that the cochlea was critical for hearing led scientists to explore the way in which this snail-shaped organ helped translate sound waves to nerve impulses. This, in turn, led to the breakthrough finding that electrical signals could be used to stimulate the auditory nerve, and ultimately resulted in the development of cochlear implants. But there was no experimental evidence to confirm this. Also, ear dissections did not answer a key puzzle—how the cochlea could transform the multitude of sounds that entered the ear into distinct tones (frequencies) that the brain uses to tell the difference between a vowel and a consonant, or between various notes in the musical scale. Fortunately, insight in this regard was provided in 1928 by Georg von Békésy, a physicist who had an ingenious way of *seeing* sound. While working for the Hungarian Post Office on how to improve telephone communications, von Békésy turned to the inner ear for guidance. In order to best transform the human voice into meaningful signals, he first wanted to know how the human ear processes sound. So he dissected the inner ears of animals and human cadavers such that the cochlea remained intact and functioning—not an easy feat given that the cochlea

is encased in the bones of the skull. He then sprinkled light-sensitive silver flakes on the hair cell lining and used strobe photography to mark how the hair cells moved in response to various tones. His basic research revealed that not all hair cells were alike—those close to the base of the cochlea moved more in response to high-pitched tones, whereas hair cells at the tip of the cochlea were more swayed by low-pitched tones. For this research von Bekesy later won the Nobel Prize.

A year after von Bekesy photographically saw the cochlea's response to sound, Princeton psychologists E. Glen Wever and Charles Bray electrically heard speech from this organ. ever was trying to discover if the ear codes the different tones heard by how often electric nerve impulses land on the auditory nerve, much like the clicks and pauses of Morse code are used to represent the various letters in the alphabet. To assess this, the researchers put electrodes on the auditory nerve of an anesthetized cat, and the signals they picked up were amplified and sent via cables to a telephone receiver in another room down the hall. Wever spoke into the cat's ear while Bray listened to the receiver. Bray expected to hear the typical monotone staccato of discharging nerves. But instead he heard exactly what Wever was saying! That was because the researchers overheard the complex electrical chatter of the cochlea. This electrical signaling conveyed minute differences in frequencies across a span of five octaves enabling it to preserve all the frequency variations that comprised Wever's speech. The Princeton finding solidified the importance of the cochlea as an organ of hearing and inspired some scientists to consider restoring hearing in those with damaged cochlea's by electrically stimulating the auditory nerve.[8]

III. An Electronic Bridge to Hearing

The next step on the way to an electronic bridge to hearing was taken by a physician who spent most of his time dabbling in electrophysiology, the study of the effects of electricity on the body that Galvani accidentally invented. Andre Djourno began his scientific career at Paris University, like most electro physiologists at the time, by studying how electricity stimulates frog nerves. Seeing those powerful effects prompted Djourno to explore the possibility of using electric shocks to revive electrocution victims and regular electrical discharges to prompt nerves to trigger contraction of the breathing muscles in people paralyzed by polio. As part of these investigations,

Djourno did numerous experiments on rabbits (Figure 6).



Figure 6 – Animal models: Animal models, including rabbits, cats, and frogs, were vital to discoveries that led to the development of neural prosthetics such as the cochlear implant. Laboratory animals still play an important role in biomedical research, allowing researchers to study how cells and tissues interact inside the body or how disease affects living systems.

He buried under the skin of these anaesthetized animals an electrical device that was connected to a nerve or muscle he wanted to stimulate with electricity. That electricity was created by a wire coil placed outside the skin of the animal but attached to a source of electricity. When electrical current passed through this external coil it produced a matching current in the implanted device that was passed to the Animal's nerves or muscles. In this way Djourno was able to trigger a rabbit to jump with just the flick of a switch. The electrical frequency Djourno used to stimulate muscle contractions was in the same range as that of speech, so he often checked the effectiveness of his implanted electrical stimulators by using his own voice as the activating trigger. (A microphone was used to translate his speech into electrical signals.) This is probably what led Djourno to note, in 1954, that one possible application of his implantable device would be to stimulate the auditory nerve to restore hearing. Three years later he had a chance to see if this was so. Charles Eyries, a Parisian ears, nose, and throat surgeon, was treating a patient who had gone deaf due to tumors that destroyed both his inner ears (including the cochlea's) and facial nerves, but left his auditory nerve somewhat intact. This patient, who was an engineer, noticed he heard sounds when Eyries used electrically induced heat in his ear to repair his damaged facial nerve. Desperate to have his hearing back, the patient asked Eyries if a similar device might be used to let him hear again. A mutual colleague aware of Djourno's experiments put

the surgeon in touch with the electro physiologist. So when Eyries' deaf patient underwent surgery to try to relieve facial paralysis, he implanted Djourno's electrical stimulator just above the patient's ear and threaded a wire from it to the auditory nerve. The external coil was placed nearby on the patient's head. Much to the patient's delight, he experienced some hearing following his surgery. After years of silence, he could once again hear doors opening and closing, and make out a few words spoken to him. But his hearing couldn't distinguish the different frequencies of vowels and consonants so that he could understand conversations. Encouraged by his initial results, Djourno tried to improve his hearing device, but when he was denied a grant to support this work, he turned to other lines of research. However, his findings inspired researchers around the world to take up the torch, including an Australian group, and three separate groups in California, whose work was mainly funded by the National Institutes of Health. This governmental support enabled them to conduct basic research on how exactly the cochlea transmits speech sounds to the brain, as well as to do animal and clinical studies on the safety and effectiveness of the cochlear implants they devised to restore hearing. By the early 1970's, the first cochlear implant made its debut.[5]

All contemporary cochlear implants work by having microphones that pick up sound, computer chips that code that sound by frequency, and a series of electrodes that electronically convey frequency information to the auditory nerve (Figure 7).

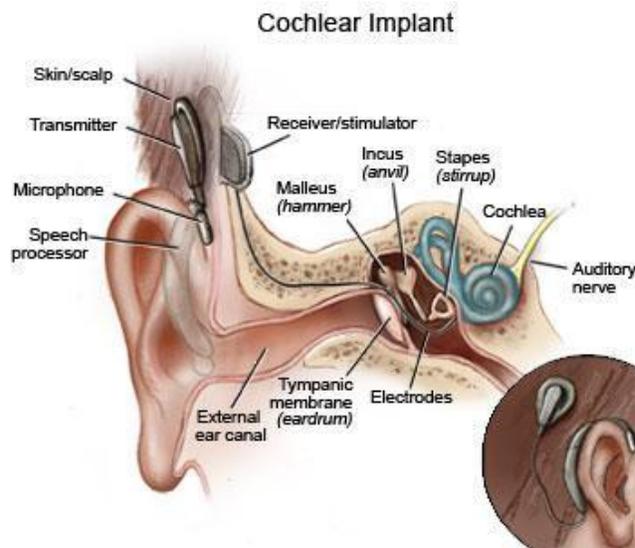


Figure 7– Diagram of cochlear implant: A microphone placed above the ear converts sounds to electrical

signals, which it sends to a speech processor worn behind the ear or attached to a belt. The speech processor is a computer chip that divides up and encodes the electrical signals by frequency which our brains interpret as pitch. This frequency data and the power needed to activate the cochlea implant are sent often via radio waves, to a receiver stimulator implanted near the ear. This device decodes the sound information back into electrical impulses with each of the frequency groups (channels) sent to eight or more different electrodes placed in the cochlea. These electrodes convey the signals to various portions of the auditory nerve, which then carries them to the brain (the ultimate processor) where they are perceived as speech and environmental sounds. Sound is filtered into different frequency channels in these implants because of the work of Bekey and others that revealed that this is what happens in a normal cochlea via the hair cells. The first cochlear implant only had one electrode and channel. But studies revealed that speech perception greatly improved with the multichannel devices that surfaced shortly thereafter. Today more than 23,000 adults and 15,000 children in the United States have cochlear implants, including a Miss America and a radio talk show host, according to the National Institute on Deafness and Other Communication Disorders (NIDCD, one of the National Institutes of Health).

Success of these implants varies depending on how long patients were deaf prior to the implant, how intact their nerves are in their inner ear, whether they had some hearing before they went deaf, and how successful their post-implant training was. Cochlear implants often enable deaf or severely hearing impaired people to understand speech without the aid of lip reading, and to speak clearly with the right volume. Some people with the implants can also enjoy music, birdsongs, and hear many other environmental sounds besides speech. In deaf children, the devices work best the younger the age at implant. About 2 or 3 out of every 1,000 children in the United States are born deaf or hard-of-hearing, and more lose their hearing later during childhood, according to NIDCD.

When such congenital hearing loss is not effectively treated early, it can lead to permanent problems with language development and linked learning and social difficulties. The Institute recommends screening newborns within the first month of life for hearing loss because children begin learning speech and language in the first 6 months of life. Most children who receive the cochlear implant and training before age 5 or 6 are able to speak and understand speech as well as their normal hearing peers, and those who receive the implant as infants or toddlers tend to

develop language at the same pace as those with normal hearing.

Some experts in hearing were surprised by the success of the cochlear implants. How could a small number of electrodes mimic the sensitivity to sounds of the 15,000 hair cells seen in the ears of those who can hear adequately? That challenging question sent basic researchers scurrying back to the lab to try to find answers. What they discovered not only furthered understanding of how we hear, but made the prospects of giving sight to the blind an attainable goal. [11]

IV. From Redundancy to Artificial Cochlear Devices

It turns out that when it comes to hearing, only a fraction of the information on the frequency of a sound sent to the brain is needed to understand speech. Recent studies indicate that the normal cochlea divides frequencies into the equivalent of 28 channels before sending them to the auditory nerve, but we can hear with far fewer channels. Researchers at Arizona State University used processors to divide and compress the frequency bands in speech listened to by people with normal hearing. (The processing of the speech mimicked what is done by a cochlear implant.) Their studies reveal that as few as 8 channels are needed to discern speech adequately. Presumably, a lot of the complex sound information sent to the brain is redundant, experts now think, so one doesn't have to capture it completely to provide adequate hearing.

V. Conclusion

Part of the success of cochlear implants is also due to the amazing ability of the brain to see the big picture from sketchy information. For example, consider those personalized license plates that, due to the limited number of characters they can have, omit vowels yet are still understandable to the person reading them during a traffic jam. We see "LVMYDG" yet realize it stands for "Love my dog." Our brain is able to fill in the missing letters so we can read the license plate. Similarly, our brain can fill in missing frequencies so we can hear what people are saying to us. Those of us with years of experience listening to people talk are better able to fill in the missing sounds. This may explain why people who have been deaf for a short time do better with cochlear implants than those with long-term deafness. But with proper training, many people who have been deaf for most of their lives can learn how to make

sense of what they are hearing with their cochlear implants. Studies show that people with the implants do better at discerning speech over time as they gain more experience with them. This shows the remarkable plasticity of the brain that refutes the notion that the brain is permanently hard-wired.

However, studies in cats reveal that there does appear to be a critical window of time during which the part of the brain that processes sounds and fosters language skills develops most readily. These studies have mapped the sensitivity of various regions of the brain to various sound frequencies and found that when it comes to hearing, it's all about location—high frequency pitches activate different minute sections of the brain than low tones. When kittens are deafened shortly after birth, their brains never develop this sound specialization unless their hearing is restored within a short period of time. Yet when these deafened kittens are given cochlear implants, the sound-processing regions of their brains appear to develop normally. This probably explains why cochlear implants are often so successful in young children, and has important clinical implications now that universal screening of newborns makes it possible to detect deafness by one month of age.[24]

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