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## Chapter 1

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# An Overview of Cochlear Implants

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Many individuals with severe to profound hearing losses derive little or no benefit from conventional hearing aids. For these individuals, the sounds of speech either can't be made loud enough to be heard or are too loud and/or indistinct to be understood. These conditions arise because critical structures in the inner ear, or cochlea, have been damaged in such a way that they no longer respond normally to sound. However, these damaged structures can be bypassed, and the nerve fibers that remain intact in the face of hearing loss, or even complete deafness, can be stimulated directly. The device that accomplishes this direct stimulation of nerve fibers and that, in the best of cases, restores hearing and speech understanding to individuals who have lost all or most of their hearing, is called a *cochlear implant*.

Cochlear implants are not new. The first reports of cochlear implants were published in the late 1950s and early 1960s. However, great strides have been made in the past handful of years in the level of speech understanding that the devices can produce. Now, more than half of the adults who receive an implant can understand sentences with 80–100 percent accuracy. Children who are born deaf and who receive an implant at an early age can acquire speech and language skills appropriate for their age. The aim of this chapter is to introduce, in a relatively painless manner, the anatomy, physiology, and technology behind this revolution in the treatment of severe to profound hearing loss.

An introduction to cochlear implants cannot be completely painless because neither the anatomy and physiology nor the technology behind an

implant is trivial. However, the material is not difficult to follow, especially if you attend carefully to the illustrations that accompany the text (this is the same advice I give my undergraduates—if you can follow the illustrations in the textbook, you will probably pass the exam!). So look at the illustrations, and read on.

## Components of an Implant

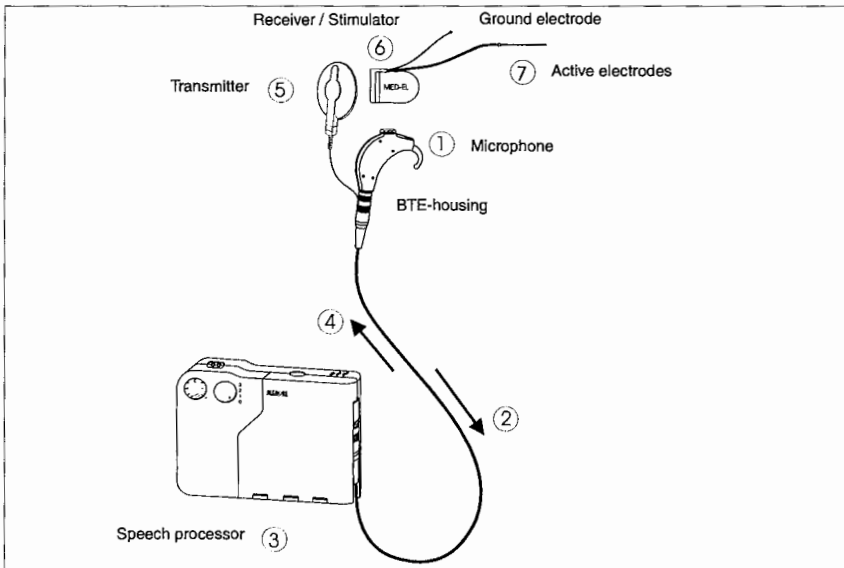
The components of a cochlear implant are shown in Figure 1. A microphone (1), worn at ear level, picks up signals and sends the signals over a small cable (2) to a pager-sized signal processor (3). The battery-powered signal processor performs a series of operations on the signals to make them appropriate for electrical stimulation of the auditory system. The processed signals travel by cable (4) to a radio-frequency transmitter (5), which, in turn, sends the signals across the skin to a receiver (6), which has been surgically implanted under the skin slightly above and in back of the ear. The signals are then sent down a set of very fine wires to electrodes (7), which have been inserted into the inner ear, or cochlea.

To understand the design of a cochlear implant, and the history of cochlear implants, it is useful to understand both the nature of the signal (speech) that the implant must reproduce and the nature of the biological system (the peripheral auditory system) that the implant must replace. We begin, first, with the speech signal.

## Speech Signals

The speech signal contains frequencies from approximately 125 Hz (the pitch of a male voice) to 7,000 or 8,000 Hz (the “s” sound in the word “Sam”). (Hz is an abbreviation for Hertz. Heinrich Hertz was a German physicist who, in the late 1800s, was the first to broadcast and receive radio waves. Hz means the same as “cycles per second.”) Speech can be understood with near perfect accuracy when frequencies of 300 Hz to 3,000 Hz are transmitted (this is the frequency bandwidth of a telephone line). So a cochlear implant should be able to reproduce frequencies at least from 300 to 3,000 Hz. Most devices, in fact, reproduce signals over the range 100 to 5,000–7,000 Hz.

Each of the sounds of speech has a different acoustic signature, that is, each is characterized by a unique set of frequencies. For example, the “s” in “Sam” has frequencies in the range 4,000–7,000 Hz (for a male voice). At the other extreme, the “m” in “Mary” has frequencies around 300–400 Hz. The vowel sounds in a language are characterized by multiple frequencies. For example, the vowel in “beet” is characterized by frequencies at 300 Hz and



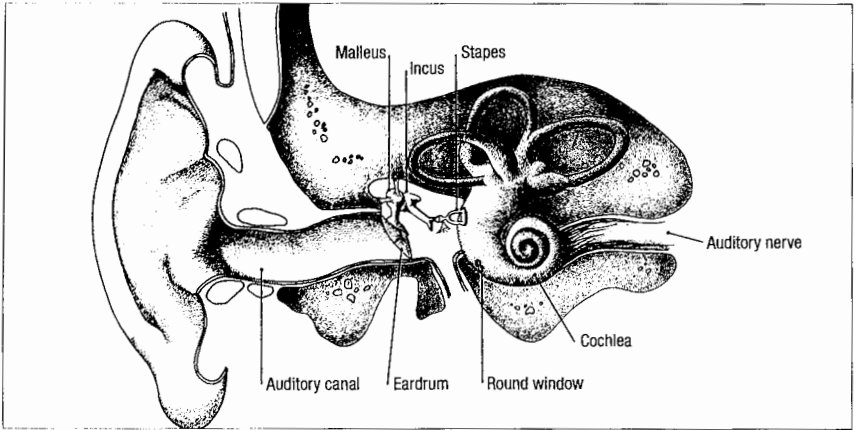
**Figure 1. Components of a cochlear implant. The numbers indicate the sequence of steps from pickup of a signal by the microphone to stimulation of electrodes in the inner ear.**

2,100 Hz. The vowel in “bit” is characterized by frequencies of 400 and 1,800 Hz. The signatures of the two vowels differ by only a few hundred Hz. Overall, then, an implant must transmit a range of frequencies and must have sufficient resolution for frequencies within that range so that the sounds of the language can be individually identified. It is the latter job, the resolution of small differences between sounds, that is the most difficult to accomplish.

## Anatomy and Physiology

Two facts about normal hearing make a cochlear implant possible. The first is that the frequency of a sound is coded by where, or the place at which, stimulation occurs in the inner ear. The second is that the neural fibers that respond to where stimulation occurs can be jolted into responding by an electrical current as well as by the normal, somewhat involved, means. Thus, if electrodes can be placed at several places in the inner ear of a completely deaf individual, and if there are neural fibers left to stimulate, the component frequencies of sounds can be coded and, in the best case, speech understanding can be restored.

Normally it is the job of the peripheral auditory system to transmit to the brain the acoustic signatures of speech sounds. The structures that make up

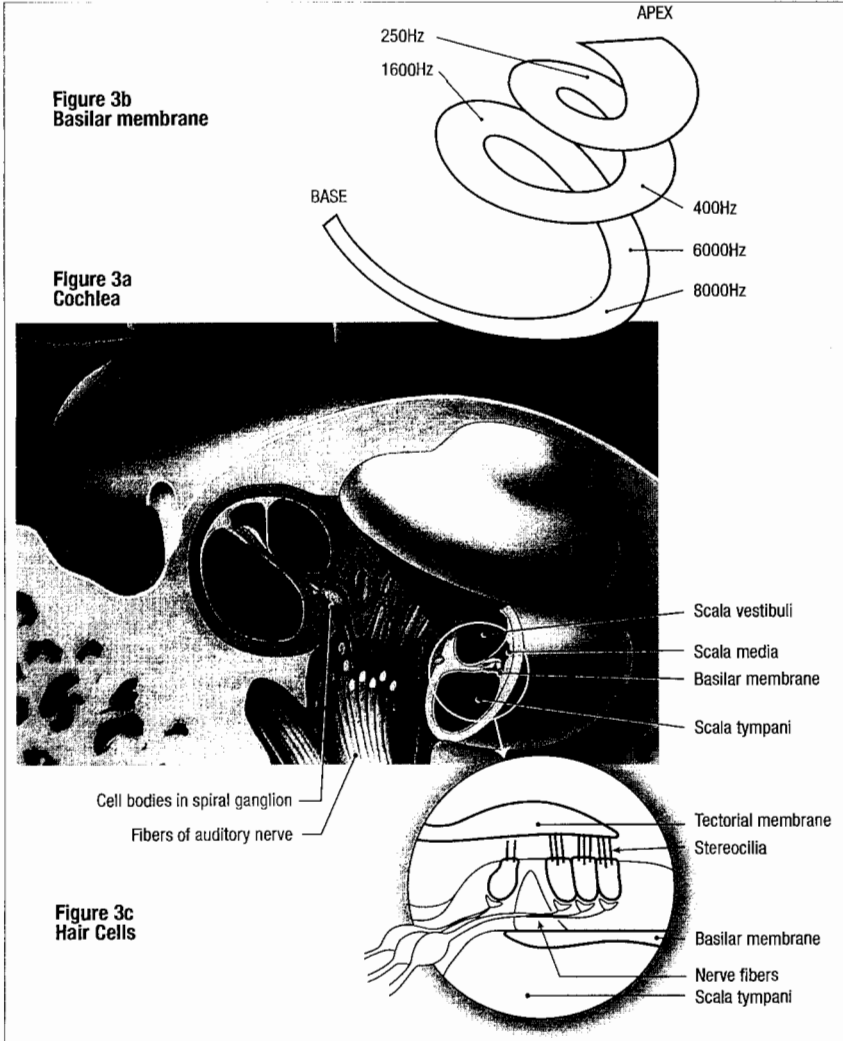


**Figure 2. Structures composing the peripheral auditory system. (Figure reproduced with permission of Harcourt Brace and Company.)**

the peripheral auditory system are shown in Figure 2. Sounds first travel down the external auditory canal and cause the tympanic membrane, or eardrum, to vibrate. This vibration is transmitted by the three middle ear bones—the malleus, the incus, and the stapes—to the oval window of the cochlea, or inner ear. The inward and outward movement of the stapes in response to the vibration at the eardrum causes fluid in the bony, hard-walled cochlea to be displaced.

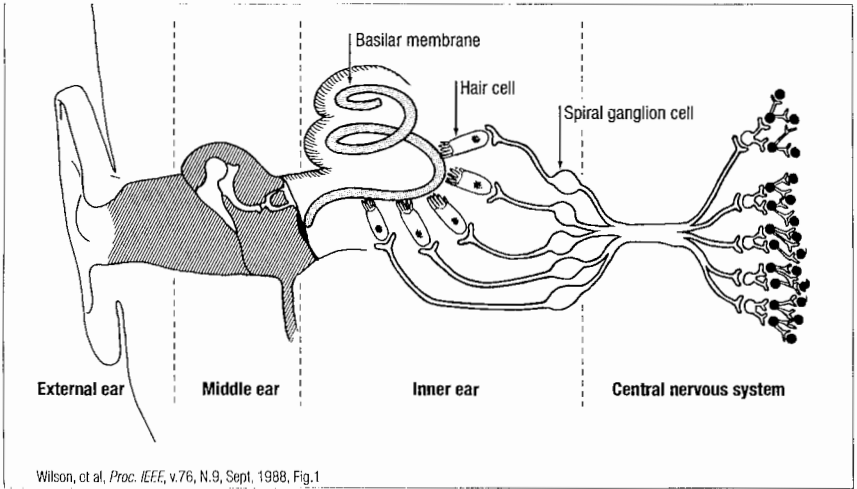
As shown in Figures 3a and 3c, the coiled cochlea is composed of three fluid-filled compartments separated by two membranes. The basilar membrane is of crucial importance. When the fluid in the cochlea is displaced by the movement of the stapes (remember, the stapes moves because it follows the movement of the eardrum), the basilar membrane moves up and down and the place along the coil where the movement is greatest varies with the frequency of the sound. High-frequency sounds cause a maximum movement near the oval window, or the base, of the cochlea, and low-frequency sounds cause a maximum movement near the far end of the cochlea, or the apex (Georg von Békésy received the Nobel prize in 1961 for, among other discoveries, his demonstration of this effect). The relationship between the place of maximum movement and the frequency of the incoming sound is shown in Figure 3b. The 4,000 to 6,000 Hz energy in “s” causes a maximum displacement toward the base of the cochlea. The 300 Hz energy in “m” causes a maximum displacement much farther toward the “top” of the cochlear spiral. Thus, the basilar membrane acts as a frequency analyzer and begins the chain of events that leads to the perception of the sounds of our language.

Between the basilar membrane and the tectorial membrane are two groups of cells—the inner and outer hair cells. As shown in Figure 3c and, in cartoon



**Figure 3.** Anatomy of the inner ear: (a) cutaway drawing of structures in the cochlea (illustration courtesy of Cochlear Corporation and Ed Zilberts); (b) frequency locations along basilar membrane; (c) enlargement of a portion of the cochlea.

fashion, in Figure 4, protruding from the top of these cells are thin rods of protein named stereocilia—the “hairs” of hair cells. When the basilar membrane moves up and down, the stereocilia move as if hinged where they exit from the body of the hair cell. The movement of the stereocilia starts a series of electrochemical events that generate a brief electrical discharge—an action



**Figure 5**  
**Electrode**

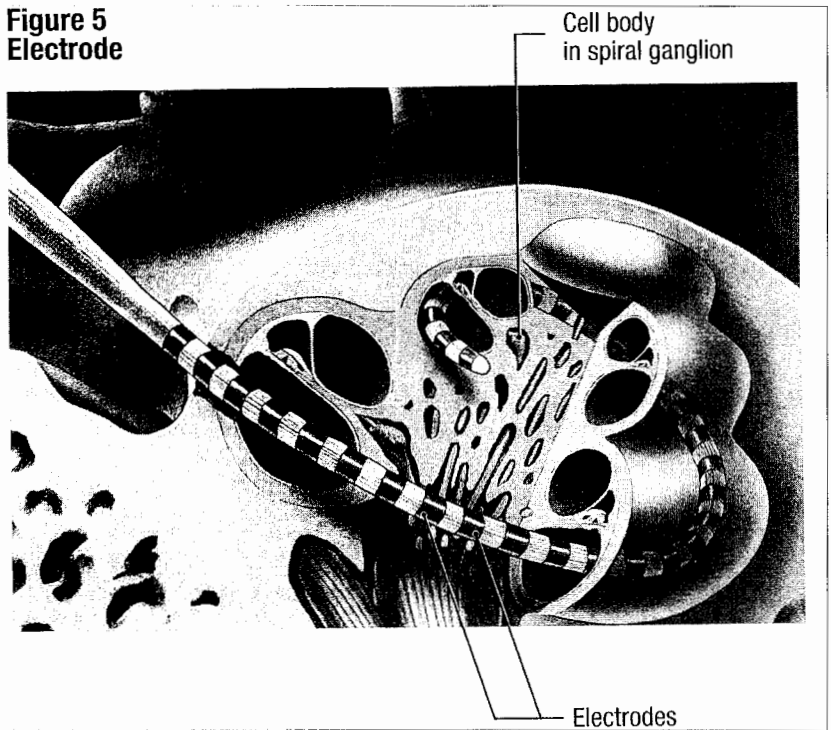


Figure 4. Schematic illustration of structures involved in hearing.  
Figure 5. An electrode with twenty-two rings inserted into the scala tympani (illustration courtesy of Cochlear Corporation and Ed Zilberts). The current from the electrodes stimulates the nerve fibers and cell bodies in the spiral ganglion.

potential, or spike discharge—along the fibers that terminate at the bottom of the hair cells. These fibers form the auditory nerve and, after making many connections in the brain stem, reach the auditory area in the cortex of the brain. When the electrical discharge, which began at the level of the cochlea, reaches the brain stem and cortical centers, we “hear.”

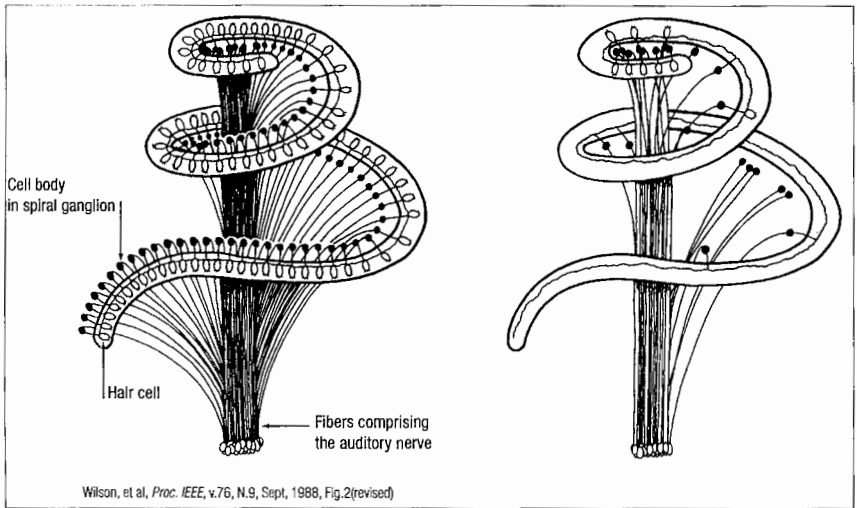
As noted above, one of the aspects of physiology that makes the restoration of hearing possible for individuals who are deaf is that an electrical discharge can be started in the fibers of the auditory nerve either by the normal mechanism, that is, the movement of the stereocilia and the resulting electrical and chemical events, or by passing an electrical current across the fibers. The brain doesn’t know how the electrical discharge was started—it knows only that a discharge took place. And because frequency is coded by *which* fibers “fire” at a given time (the ones at the base of the spiral, which code high frequencies, or the ones at the “top” of the spiral, which code low frequencies), if electrodes, inserted through the round window, can be placed at different locations along the cochlear spiral, as is shown in Figure 5, the perception of different frequencies can be restored to individuals who are deaf.

## Best-Case and Worst-Case Physiology

The hair cells, the cell bodies in the spiral ganglion, or central core of the cochlea, and the fibers that make up the auditory nerve are shown in cartoon fashion in Figure 6. On the left side of the figure is a “normal” cochlea, without the bony shell, in which there is a full complement of hair cells and fibers. On the right side of the figure is a cochlea from an individual with a long-standing, profound hearing loss. Almost all of the hair cells have died, and as a consequence, the fibers that terminated at the bottom of the hair cells have degenerated. Restoring hearing to the cochlea on the left would be relatively straightforward, since all of the neural elements are available to be stimulated. Restoring hearing to the cochlea on the right would be very difficult, since there are few fibers or cell bodies to stimulate. Unfortunately, there are no tests to determine the state of neuronal survival before a patient is implanted with a device to restore hearing. Thus, no matter how good the device, there will always be some people who receive little or no speech understanding from an implant.

## The First Cochlear Implants

Cochlear implants got off to a very modest start in the United States in the early 1960s. The first report of an implant in 1957, by Djourno and Eyries, was written in French and appears to have been unnoticed on this side of the



**Figure 6. On left: schematic drawing of basilar membrane, hair cells, cell bodies in the spiral ganglion, and fibers of the auditory nerve in the inner ear of an individual without hearing damage. On right: structures remaining in the cochlea of an individual with long-term deafness; there are few cell bodies or nerve fibers to stimulate.**

Atlantic. A patient brought a newspaper account of the article to Bill House, a Los Angeles surgeon. In 1961 House implanted one patient with a single-electrode device and implanted another patient first with a single-electrode device and then with a five-electrode device.

Both patients reported a sensation of “hearing” when the speech signal, picked up by a microphone, was directed to the electrode. Neither patient was able to understand speech. The devices were removed within weeks of implantation due to a concern over infection or a reaction to the silicone covering of the electrode bundle. Encouraged by the outcome—that both patients reported “hearing”—House and an engineering colleague, Jack Urban, spent the next several years improving the design of both the external and the implanted electronics.

In 1964 Blair Simmons, at Stanford, in an attempt to directly stimulate cell bodies in the spiral ganglion (see Figure 3a), inserted a six-electrode array into the central core of the cochlea. The patient could hear changes in pitch up to a frequency of 300 pulses per second and could recognize speech signals as speech. The patient did not receive any speech understanding. Perhaps as interesting as the modest results was the reaction by other researchers to the results: few appeared to care. Worse, when the results were submitted for presentation at a meeting in 1965 for surgeons, the paper was turned down as being too controversial.

## First Generation Implants

By 1969 House and Urban had sorted out some of the bioengineering issues connected with implantation. In that year, House began another series of tests with patients. After experimenting with five electrode systems and finding no better performance than with a single-electrode system, House settled on a single-electrode system. Single-electrode systems were also implanted by Robin Michelson at the University of California at San Francisco (UCSF). As in the early experiments, the patients did not report that they could understand speech. One patient wrote: "Speech reminds me of a long-distance, short-wave transmission with too weak a signal, or off-frequency radio setting that prevents intelligible speech. Music reminds me of listening to the Mormon choir years ago on an old radio with poor reception."<sup>1</sup>

Although the single-channel implant did not allow speech understanding by sound alone, the implant was a godsend to most patients. A patient wrote:

I was deaf for 12 years, but now I hear. This is a modern miracle to me with strong religious overtones. Using the new device has opened the world to me. My current progress can be described as changing from profoundly deaf to just hard of hearing. (Tonight for the first time in all these years I can hear the bell that tells me I am at the right hand margin as I type). ... I get tremendous help and enjoyment hearing the bells at school, traffic noises on the highway, a mockingbird calling, the cat meowing, a twig breaking under foot, bacon frying, the doorbell ringing, and on and on. ... Now when I am camping and hear the chipmunk stealing the peanuts out of the sack beside me, I know that I am no longer deaf.<sup>2</sup>

If patients' reactions to implants were enthusiastic, professional reaction was cautious. Part of the caution stemmed from the absence of articles in professional journals on the performance of implant patients. Implant patients received a fair amount of publicity in the media, which prejudiced the case for implants in the view of scientists who wanted to see "real data," not television interviews. Indeed, as late as 1978, applications for funding for research on cochlear implants from the National Institutes of Health were turned down on "moral" grounds.

The need for an independent review of the performance of cochlear implant patients led to a landmark study of House's and Michelson's patients' directed by Bob Bilger of the University of Illinois and published in 1977, the report confirmed that, for some patients, implants (1) improved scores on tests of speech understanding when the patient could both watch and hear the speaker, (2) increased the awareness and recognition of environmental sounds, and (3) aided in the control of the speaking voice.<sup>3</sup> The publication of this report made implants respectable.

## Second Generation Implants

The first single-electrode implants provided very little or no speech understanding by sound alone. Although the preliminary experiments by House hadn't shown any benefit of multiple electrodes, it was clear that if speech was to be understood, multiple electrodes would have to be used to stimulate different sections of the cochlea and thus stimulate the different frequency regions necessary for the coding of the frequency components in speech. In the 1970s, research groups in several countries began work on multiple-electrode (or multichannel) implants. In the United States, researchers at the University of California at San Francisco, at Stanford University, and at the University of Utah developed implants with multiple channels. Multiple-channel devices were also developed at the University of Melbourne, Australia, and in Paris. By the early 1980s, several of the projects had shown sufficient promise that commercial companies were formed.

The principal multichannel implants in the United States in the 1980s were devices with radically different designs. One was the design of the group originally at the University of Melbourne. This implant, marketed by Cochlear Corp. as the Nucleus 22, had twenty-two electrodes placed very close together (.75 mm apart) to give good frequency resolution; it used a microphone, a signal processor, an external radio frequency transmitter, and an implanted receiver to deliver signals to the electrodes. The other design was that of the group originally at the University of Utah. This design, marketed first by Symbion Inc. as the Ineraid, delivered stimulation, picked up by a microphone and processed into four frequency bands, to electrodes spaced relatively far apart (4 mm) in the cochlea. The microphone and the sound processor were connected to the implanted electrodes by a graphite connector, approximately the size of the nail on your little finger, which protruded through the skin above the ear. The through-the-skin, or percutaneous, connector was used so that only the electrode wires were implanted. This was thought to be a good idea because there were no implanted electronics that could fail, thus requiring additional surgery.

By 1985 it became clear that another independent study of the effectiveness of cochlear implants was needed, since there were, once again, many claims about the effectiveness of the new commercial devices offered in the United States. For example, the very first patient implanted with the commercial Ineraid device in 1983 turned out, in retrospect, to be one of the best-performing patients with any device, including devices marketed today. He promptly was whisked off on an around-the-world trip to promote the device. Given the specter of publicity before science, the National Institutes of Health awarded a grant to Bruce Gantz and Richard Tyler at the University of Iowa Hospital to conduct an independent test of single-channel and multichannel devices. The design of the study eliminated the possibility of assigning a given

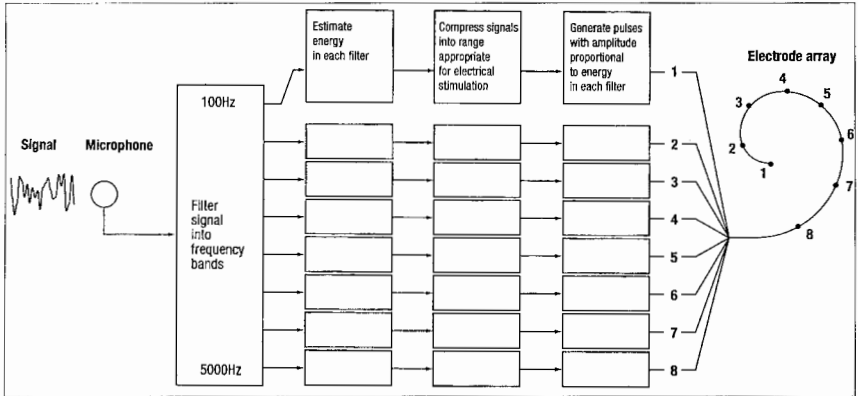
implant only to patients who might do well with the device. The early results were straightforward—patients who were implanted with the multichannel devices performed far better than patients implanted with single-channel devices. Indeed, performance with the single-channel devices was so poor that implantation of the single-channel systems at Iowa was terminated.

In spite of the differences in design, the two multichannel devices (the Ineraid and the Nucleus 22) produced very similar scores on tests of speech understanding. The average score for words in sentences was around 30 percent correct. Importantly, however, the *range* of scores was 0 to 92 percent correct. Some patients, then, could understand sentences with near perfect accuracy by means of either device. The scores for the Nucleus device were not a surprise because the device used twenty-two electrodes to stimulate a wide range of fibers in the cochlea. However, the similar scores for the Ineraid patients were puzzling because of the relatively few (four) channels of stimulation. How could four channels produce speech-understanding test scores that were equal to the scores produced by twenty-two channels? We will return to this story later.

## Third-Generation Implants

In 1982 the Neural Prosthesis Program (NPP) of the National Institutes of Health awarded a contract to develop new speech processors to a group of researchers at Research Triangle Institute (RTI), North Carolina, headed by Blake Wilson. The new processors were originally designed for the multichannel implant patients at the University of California, San Francisco. At the same time the NPP awarded contracts to Graham Clark at the University of Melbourne and to Robert White at Stanford University to continue work on the multichannel implants developed at those universities. These contracts led to the signal processors now used in the cochlear implants marketed in the United States.

The design of a “generic” signal processor is shown in Figure 7. An incoming speech signal is picked up by a microphone and is directed to filters that cover the range of frequencies in the speech signal. The energy in each filter is estimated and is then squeezed, or compressed, into a range appropriate for electrical stimulation. This is necessary because the tolerable range of electrical stimulation is much smaller than the range of intensities of sounds in the speech signal. Then a pulse is generated in each channel with an amplitude that represents the energy in the channel. This operation codes the intensity of the signal in each channel. Pulses from low-frequency filters go to electrodes at the “top,” or apex, of the cochlea, and pulses from high-frequency filters go to electrodes at the “bottom,” or base, of the cochlea. The pulses are sent in sequential fashion, one after the other, to the electrodes. This



**Figure 7. The design of a “generic” cochlear-implant signal processor.**

interleaving of the pulses is important because pulses sent at the same time can interfere with each other and distort the representation of the frequencies in the speech signal.

The devices originally produced by Clark’s group at the University of Melbourne, and now marketed by Cochlear Corporation, have undergone many changes since their beginnings in the 1970s. The hallmark of the present devices is the use of twenty filters connected to twenty electrodes. The energy in each filter is estimated, and the six to ten channels with the most energy are determined every few milliseconds. This operation is designed to pick out the multiple frequencies that characterize each of the sounds of English.

Wilson’s group at RTI first developed a number of processing strategies for patients with the University of California at San Francisco (UCSF) multichannel device. Among the strategies was a “peak picking” strategy very similar to the one described above for the present University of Melbourne/Cochlear Corporation device.

Some of the UCSF patients had through-the-skin (percutaneous) connectors; others used a transmitter-receiver to send signals from the signal processor to the electrodes. The transmitter-receiver system proved unwieldy for research because it limited the types and ranges of stimuli that could be specified for the electrodes. In contrast, the direct electrical connection from the processor to the electrodes provided by the percutaneous connectors imposed no such limitations.

In 1986–87 the RTI group turned to patients who used the Ineraid’s through-the-skin connector and six intracochlear electrodes in order to develop new signal-processing strategies. The result of many years of work was the continuous interleaved sampling (CIS) strategy—a strategy that is now implemented in one way or another on most commercial implants. (Even though all implant systems now offered commercially use a transmitter-receiver link, that

link is adequate in most cases for support of a CIS strategy. The Ineraid system, with its percutaneous connector, is no longer manufactured or marketed.)

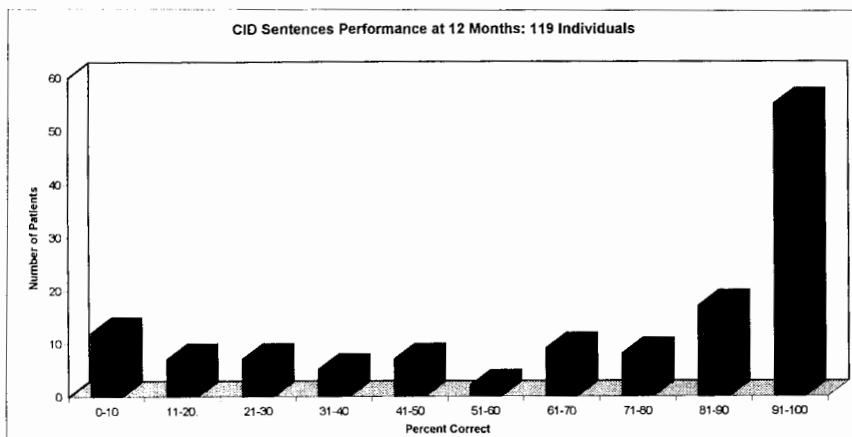
The hallmark of the CIS strategy is that pulses are sent out at a very fast rate in a staggered order to the electrodes. The high rate of stimulation defines the variation in time of the components of the speech signal better than a low stimulation rate.

As happens only sometimes in science, spectacular results were obtained with the first Ineraid patient tested with the CIS system. The patient obtained nearly perfect scores on tests of sentence understanding. These scores, given previous data, were not particularly surprising. What was surprising was a score of 80 percent correct on a very difficult test of words presented in isolation. Further refinement in the CIS processor boosted the patient's single-word score to 98 percent correct, a score well within the range of scores for normal-hearing listeners. Of course, not all patients did this well—scores on the test of words in isolation ranged from 5 to 94 percent correct—but Wilson and his colleagues were clearly on the right track.

It is worth noting that the RTI made a decision early in its work to donate all results from its NIH-sponsored research on cochlear implants to the public domain. This has facilitated use of the technology by manufacturers of implant systems and thereby helped bring the benefits of the technology to recipients of cochlear implants. CIS or CIS-like processors are now offered in implant systems manufactured by Advanced Bionics Corporation of Sylmar, California (the Clarion devices); Med El Corporation of Innsbruck, Austria (the COMBI 40 and COMBI 40+ devices); Cochlear Pty. Ltd. of Sydney, Australia (as a processing option in its new CI24M device); and Bionic Systems of Antwerp, Belgium (the LAURA device). Ironically, the manufacturer of the Ineraid device decided not to utilize this technology and instead discontinued the Ineraid product line, thus denying the benefits of the technology to the very patients with whom the technology was developed!

## **The Current State of the Art**

How well do patients understand speech with the current generation of cochlear implants? Scores for words in sentences for patients who use the eight-channel Clarion CIS processor are shown in Figure 8. The most common score is 90–100 percent correct. Similar scores are found for patients who use Cochlear Corporation's Nucleus 22–Spectra processor, which is the most widely used processor in the world (with over 15,000 units worldwide). However, for any device used, some patients, perhaps 10 percent, score in the 0–10 percent correct range. As we noted in the section on anatomy and physiology, inevitably some patients will have very few fibers to stimulate and, as a consequence, will not be able to code the multiple frequencies in the speech signal.



**Figure 8. Identification of words in sentences by 119 adults fit with a cochlear implant. Slightly more than half of the individuals achieved scores between 80 and 100 percent correct.**

Even the best-performing patients do not get all the information in the speech signal. Patients who achieve scores in the sentence test of between 90–100 percent correct average only 58 percent correct when tested with individual words without sentence context (the best-performing patients achieve scores between 70 and 90 percent correct). Thus, it appears that the best-performing patients recognize many, perhaps most, individual sounds and rely on sentence context to fill in the identity of the sounds they cannot resolve.

What does an implant sound like to the best-performing patients? One patient writes: “Speech sounds perfectly natural to me now. ...it is easy to distinguish voices, even over the telephone. Also important, I can hear all the little intonations and inflections in speech with which we color the mood and meaning of what we say. I would say that speech is very clear, although I find that when I begin to listen to someone with a heavy accent, it takes me a bit before I get a good grip on what they are saying.”<sup>4</sup> Another patient wrote:

In my everyday situation ... I deal with customers in person and on the phone. ... I really don't run into any problems at work except for some children who might ask me a question, or a customer who is looking in the opposite direction and is talking to me. So I have to ask the person to turn around and face me. With the telephone I can understand at least 90 percent of the time. Sometimes I have to have them spell their names for me when they are reserving movies and ... kids at certain age levels are hard for me to understand. The only other situation [in which I have trouble] is when we are with a lot of people and everyone is talking.<sup>5</sup>

A patient with *average* scores on tests of word intelligibility wrote: “I receive a sharp clear signal when the person articulates properly. I don't do

well with mumblers and foreign accents. [I don't hear] as well as I would like in everyday situations ... [but] most are very satisfactory. [I don't hear as well as I would like] in group meetings [but] do pretty well with an FM system when [I can] move the microphone around."<sup>6</sup>

One patient with *very poor* speech understanding wrote:

It [the implant] is incredibly useful for environmental sounds ... the doorbell, the microwave signal, the two different phone lines at home (one is a TDD) ... and so on. I was thrilled to hear crickets again—even though everyone else with normal hearing seems to complain about them. It is just wonderful to hear birds again and when I was in Belgium on vacation last year I heard a rooster crow. It was the first rooster I had heard since I was a child. I also enjoyed listening to the train whistles and ... the wonderful church bells. I would stop in the middle of a street to listen in wonder to those bells! I recognized speech as such when I heard it for the first time, but it sounded to me like when I was little and was sent to bed ... when we had company. I'd strain my ears to hear what the adults were talking about through closed doors. I couldn't understand what they were saying but could recognize the voices. ... I can tell men's voices from women's. I can tell singing from speech.<sup>7</sup>

## Results for Adults Who Were Deafened at Birth

The results described above were for patients who had been deafened relatively late in life and who had memories of what speech sounds like. What happens if an adult (as distinguished from a child) who has *never* heard before is given an implant? There are several reasons to suspect that understanding speech by means of the implant would be very difficult for these individuals. First, the individual would have no memory of what the consonants and vowels of language sound like. Second, it is likely that the individual's auditory system would have been damaged as a result of the deprivation of sound. It has been well documented that the size of cell bodies in the core of the cochlea and in the central nervous system shrink, or atrophy, as a consequence of not being stimulated by sound. Furthermore, stimulation during infancy drives, or shapes, the formation of neural connections in the central nervous system. Neural interconnections will not develop normally in the absence of stimulation. This does not suggest that the auditory system will not respond to sound following a long period of deprivation but rather suggests that the neural responses to sound will be abnormal. Thus, we should expect that adults who were deafened at birth and who receive an implant as an adult will "hear" but will have great difficulty, perhaps unsurmountable difficulty, in understanding speech.

The data support the prediction. Tests conducted in several countries indicate, overwhelmingly, that patients who were deafened at birth and who were

implanted as adults obtain little speech understanding by means of an implant.<sup>8</sup> Of all the patients reported in the literature, only a few individuals achieve speech understanding scores at a level above chance. Yet many individuals who obtain no speech understanding wear their implants daily and derive a high level of satisfaction with the devices. This is because (1) the implant allows them to “hear”; (2) the implant allows them to recognize some environmental sounds, such as a dog barking or a telephone ringing; (3) the implant provides improved self-monitoring for speech production, which leads to better voice quality; and (4) the implant assists with speechreading.

There is a growing population (primarily teenagers and young adults but some older adults), also deaf from birth, who are receiving cochlear implants. Generally, they are profoundly hearing-impaired, are considered good hearing aid users (in contrast to the individuals described in the previous paragraph, who did not wear hearing aids), communicate through auditory and oral means, and have been mainstreamed through their school years. These “borderline” cochlear implant candidates can articulate eloquently the differences between hearing with their hearing aids and hearing with their implants. This group is too new yet to have contributed to the pool of research data. Clinicians are finding that many—or even most—of these individuals understand speech with their implants.

## **Why Aren't Devices with More Electrodes Better?**

It was noted above that one of the puzzles about cochlear implants is that devices with a relatively small number of electrodes allow the same levels of speech understanding as devices with many more electrodes. The results of experiments at RTI and the House Ear Institute suggest that most patients cannot take advantage of more than a relatively small (perhaps six to seven) number of electrodes, or channels, in the course of speech understanding. The factors underlying this limitation are not well understood. Perhaps the current electrode designs restrict, for some unknown reason, the number of channels that can be accessed. If this is so, then perhaps different electrode designs would allow more channels to be accessed in the service of speech perception.

## **How Many Channels Are Needed?**

In the previous section we indicated that implants with relatively few channels allowed the same level of speech understanding as devices with rel-

atively many channels. We also indicated that the patients who achieve 90–100 percent scores on tests of word understanding in sentences average only 58 percent correct on tests of words in isolation. So, how many channels are needed to get a perfect, or near perfect, score on words in isolation, or alternatively, how many channels are necessary to correctly identify each of the sounds in an isolated word?

To answer this question, my colleague Philip Loizou and I have processed words through a simulation of a cochlear implant's signal processor with four, six, and eight channels and have presented the words to normal-hearing listeners for identification. The results indicate that eight channels of stimulation allow 95 percent of the sounds in the words to be identified. Thus, if an implant patient were able to extract from eight channels all the information that a normal-hearing individual could extract, eight channels, or eight electrodes, would be sufficient to allow a very high level of speech understanding.

## **Children and Implants**

An adult who loses his or her hearing and who then is fitted with a cochlear implant has a lifetime of linguistic knowledge to aid in the interpretation of the new, slightly degraded, or greatly degraded sounds delivered by the implant. Thus, the largely tacit, or unconscious, knowledge about what sequences of sounds are permissible in English and which words usually follow each other in a normal sentence has a large influence on the intelligibility of speech transmitted by an implant. A child who has acquired language, and subsequently loses hearing, may respond to an implant as well as an adult if the child has developed adult-like linguistic knowledge. However, the child deafened at birth does not have a set of linguistic rules to guide the interpretation of the impoverished sounds provided by the implant. Indeed, the child must discover the rules of spoken language by means of the degraded signal.

Learning a language by means of a degraded speech signal is not a circumstance unique to children with cochlear implants. Children with mild to profound hearing losses have always faced this challenge. We should imagine that the performance of hearing-impaired children on tasks of speech perception, speech production, and language acquisition could be used to generate a reasonable set of expectations for the performance of implanted children. However, the speech and language skills of “normal” hearing-impaired children vary widely. On the one hand, there are ample data to suggest that even a mild hearing loss, if undetected, can result in a delay in the acquisition of language skills. On the other hand, a relatively small number of individuals, such as the author of this book, have acquired speech and language skills—in this instance, the skills appropriate for a professor of law—and have acquired

those skills with the aid of very little hearing for a very short period of time. Nonetheless, the usual outcomes of losing hearing early and profoundly are delays in the acquisition of language skills and disorders in both speech production and, of course, speech perception.

The first children to receive implants were given single-channel devices by Bill House in 1980. The children obtained very little speech understanding by means of the device (remember that a single-channel device cannot represent the multiple frequencies that characterize each of the sounds of speech). The average level of speech-perception skill was being able to discriminate the difference between a one-syllable word and a two-syllable word. Understanding words in sentences by sound alone was near zero except for one or two children. The results for these single-channel patients are important for several reasons. One is that the results established that children could obtain some information even from a very impoverished signal. The second reason is that the relatively meager results have allowed those who do not approve of implants in children, on principle, to say that implants do not “work” in children or to say that “no child has acquired language by means of a cochlear implant.”

Of course, as implants improved from single-channel devices to second- and third-generation, multichannel devices, so also did the performance of implanted children. In the United States, large studies of the speech and language skills of implanted children who were deafened before they learned language (prelingually deafened children) have been conducted, and are still under way, at the University of Iowa, the University of Indiana School of Medicine, the Central Institute for the Deaf, and the New York University School of Medicine.

Before the results of these, and other, studies are summarized, several factors that have affected the results need to be considered. First is the nature of the device used. For obvious reasons, very long-term data are available only from children who were implanted with either single-channel implants or early versions of multichannel implants. Second is the nature of the disorder that produced the deafness. Some pathologies damage parts of both the peripheral and the central nervous system. Thus, some implanted children must struggle with both a degraded signal and learning disabilities. Other pathologies result in a cochlea that is not fully developed and in which only a small number of electrodes can be inserted. The task of understanding speech will be especially difficult (but not necessarily impossible) for these children. Third is the age of the child at implantation. Given that early stimulation shapes the organization of neural connections from the auditory periphery to the cerebral cortex, it stands to reason that the earlier the children are implanted, the better their performance will be later in childhood. The population of children for whom there are the most data were implanted relatively late in childhood. Only recently have children age 2 years or younger received

implants. Fourth is the type and amount of rehabilitation and or parental attention the child receives. Studies have found that children in classrooms where hearing and listening are the sole means of communication score better on tests of speech intelligibility than do children in classrooms where listening and speaking are only one of the possible means of communication.<sup>9</sup> The more time spent in aural rehabilitation, the better is the performance. Finally, not all parents have had the time and the skills to aid their children in adapting to sound. Given the factors cited above, we should expect to find, and do find, a wide range of test scores in children. The current data on the speech and language skills of children with implants serve best as a hint as to the level of skills that will be acquired by children who will use advanced sound-processors, who will be implanted early in childhood (age 2 or before), and who will receive intensive rehabilitation.

## Speech Understanding by Prelingually Deafened Children

The results on a test of understanding common phrases for thirty prelingually deafened children fitted with third-generation cochlear implants are shown in Figure 9.<sup>10</sup> The children were implanted at ages 3.5 to 7.5 years and had used their implant for only a year. Ten of the thirty children achieved

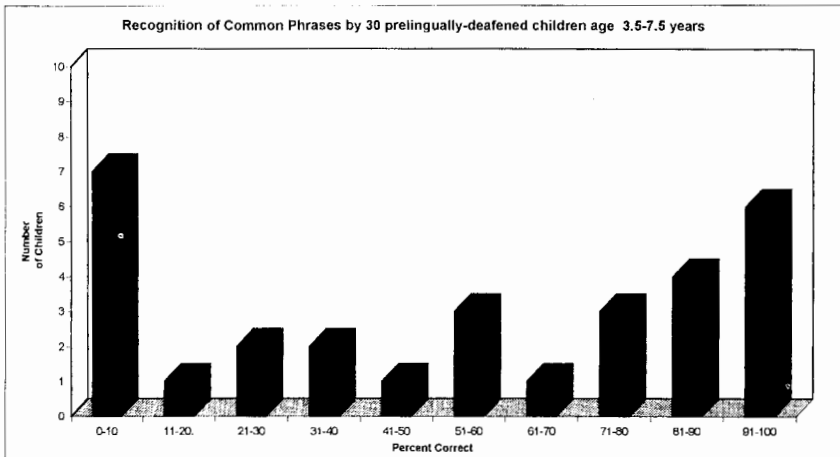


Figure 9. Identification of words in common phrases by thirty prelingually deafened children who were fit with an implant between the ages of 3.5 and 7.5 years and who had used the implant for a year. Thirty-three percent of the children achieved scores between 80 and 100 percent correct. Twenty-seven percent of the children achieved scores between 0 and 20 percent correct.

scores between 80 and 100 percent correct. However, seven of the thirty achieved scores between 0 and 10 percent correct. The low scores are not surprising given the number of factors working against acquiring speech-perception skills immediately following a long period of auditory deprivation. Moreover, data from other studies indicate that children who score 0 percent correct at one year after implantation can achieve scores of 100 percent correct two, three, four, or five years following implantation.<sup>11</sup> Indeed, a study of one hundred children in England reports that 85 percent of the children were able to understand common phrases three years after implantation.<sup>12</sup> Clearly, after a relatively short period of adaptation, many children are able to achieve high scores on tests of sentence understanding. Several chapters in this book provide further discussions of this topic.

## **The Intelligibility of Speech Produced by Prelingually Deafened Children**

The average intelligibility of speech produced by profoundly hearing-impaired children is about 20 percent. The intelligibility of speech produced by a sample of implanted children at the Central Institute for the Deaf—children, who use second-generation multichannel implants, who were implanted at age 4, who had used their implants for at least two years, and who attended oral schools—is 48 percent, with a range from 14 to 93 percent.<sup>13</sup> Like the scores for speech understanding, the scores for speech intelligibility vary greatly. And again, it is encouraging that some of the children achieved scores of 90 percent intelligibility or better. The study of one hundred children from England reports that five years after implantation, 83 percent of the children produce speech that is sufficiently intelligible and that the children use speech as their primary mode of communication.

## **Language Acquisition**

Children who are profoundly deaf generally develop language at less than half the rate of normal-hearing children, that is, at a rate of approximately five months' growth in one year. At age 5 years, for example, a profoundly deaf child may have the expressive language skills of a normal-hearing child of 2.4 years. As a consequence, children implanted at, for example, 5 years of age will be delayed in language structure, vocabulary, and language content. A critical issue, then, is whether an implant can restore a normal rate of language development. Recent results from the study at the Indiana University School of Medicine indicate that the answer to this question is "yes."<sup>14</sup> Children

implanted at age 4 years (on average) were tested for expressive language skills at six-month intervals for a period of two and one-half years following implantation. In each six-month interval, the implanted children's scores increased as much as the scores from a group of normal-hearing children. In contrast to the six-month gain in language score found for normal-hearing and implanted children in each six-month interval, the gain in language scores for a group of not-implanted, profoundly deaf children was approximately 2.5 months. The different rates of acquisition of language skills in the implanted and not-implanted children demonstrate the effectiveness of the implant in fostering the acquisition of spoken language. These data argue eloquently for early implantation of children—the earlier children are implanted, the less language delay they will have to overcome. The case studies provided later in this book reinforce this concept.

If an implant can restore a normal rate of language acquisition, is it the case that children implanted, for example, at age 5 years are doomed throughout childhood to be 2.6 years behind in language skills? The answer to this question is “no.” As documented in the case studies in this book, the language skills of implanted children can—and do—catch up with the language skills of normal-hearing children.

## **On Reading and Hearing**

Many studies have shown that there is an important relationship between reading skills and the ability to segment, or divide, the speech signal into syllables and sounds. Poor readers have more difficulty than good readers in identifying the number of syllables in words and the number of different sounds in words. It follows from this that children who cannot hear, or produce, the syllables and sounds in a language will begin the processes of reading at a marked disadvantage. Early poor reading skills act, in turn, to limit the addition of new words to a child's vocabulary (new words appear to be added to a vocabulary principally from reading new words and discovering their meaning from context). The third-grade reading level, on average, of profoundly deaf high school graduates documents the difficulty in learning to read when an individual does not have access to the sound system of his or her language. This is not to say that perceiving and producing speech auditorily is an absolute requirement for reading. However, it is undeniable that learning to read is enormously easier if an individual can hear or produce the speech sounds that most writing systems seek to mimic. And adding words to an individual's vocabulary is very much easier if the meanings of new words encountered in print can be inferred from an already large vocabulary.

Cochlear implants assist deaf children in improving their reading scores by providing the children with the ability to access our sound system. Thus,

as the case studies presented later in this text illustrate, implanted deaf children increasingly demonstrate reading scores at age-appropriate levels.

## The Look of Devices in the Near Future

One aspect of the near future is already clear—companies will offer smaller devices, ones that fit behind the ear like a hearing aid. It remains to be seen whether the smaller devices—with, perhaps, restricted computational power—will allow the same level of performance as the larger devices that are currently manufactured. The signal processing of the devices produced by different companies will, most likely, function in very similar ways. All will offer variable rates of stimulation, and all will use the continuous interleaved sampling (CIS) strategy or a version of this strategy. Each device will have a “feature” that distinguishes it from other devices. The newest device from Cochlear Corporation, the CI24m-ACE, features two new electrodes that allow the device to be run in one of a number of modes of stimulation (e.g., monopolar or bipolar electrode stimulation), and features a faster pulse rate than previous models. The Clarion device offers an electrode design that differs from other designs, and the device can be programmed with a variety of pulse-stimulation schemes or with the analogue signal as output to the electrode array. The Med El Combi 40+, which is currently being tested in the United States, offers an electrode array that can be inserted deeper into the cochlea than other electrodes and offers both a CIS stimulation scheme and a stimulation scheme similar to that of the Cochlear Corporation device. There is some evidence that each of the features of each of the devices might be of benefit to patients. At present, it is difficult to argue that any of these features will make a large difference in performance. However, all of the devices will provide the opportunity for individuals who have lost their hearing to hear once again and the opportunity for children, and some adults, who have never heard to hear for the first time.

## Further Reading and Viewing

Perhaps the best way to become acquainted with cochlear implants is to view videotapes of adults and children who use implants. An impressive tape is *The Story of David*, documenting Warren Estabrooks’s work with a child fitted with a cochlear implant. This tape can be obtained from Cochlear Corporation, 61 Inverness Drive East, Suite 200, Englewood, CO 80112. Another impressive, and short, tape is *Samples of Speech Production and Language in Children with Cochlear Implants* which documents the ability of several children who use cochlear implants. This tape can be obtained from Dr. Emily

Tobey, Callier Center for Communication Disorders, University of Texas at Dallas, 1966 Inwood Rd., Dallas, TX 75236. A video of adults who use cochlear implants is *Symphony of Life*. This tape can be obtained from Cochlear Corporation, 61 Inverness Drive East, Suite 200, Englewood, CO 80112.

Good sources of technical information about cochlear implants can be found in the following texts: R. Tyler (ed.), *Cochlear Implants: Audiological Foundations* (Singular Publishing Group, 1993); G. Clark, Y. Tong, and J. Patrick (eds.), *Cochlear Prostheses* (Churchill Livingstone, 1990); D. Allum (ed.), *Cochlear Implant Rehabilitation in Children and Adults* (Singular Publishing Group, 1996); G. Clark, R. Cowan and R. Dowell (eds.), *Cochlear Implantation for Infants and Children* (Singular Publishing Group, 1997); M. E. Nevins and P. Chute (eds.), *Children with Cochlear Implants in Educational Settings* (Singular Publishing Group, 1996); and A. Geers and J. Moog (eds.), "Effectiveness of Cochlear Implants and Tactile Aids for Deaf Children: The Sensory Aids Study at Central Institute for the Deaf," *Volta Review* 96, no. 5 (1994).

Each company that manufactures cochlear implants has publications describing its products. The address for Advanced Bionics Corporation is 12740 San Fernando Road, Sylmar, CA 91342. The address for Cochlear Corporation is 61 Inverness Drive East, Suite 200, Englewood, CO 80112. The address for Med El Corporation is P.O. Box 14183, Research Triangle Park, NC 27709. In addition, information and referrals may be obtained from the Alexander Graham Bell Association for the Deaf, 3417 Volta Place NW, Washington, DC, 20007 (202-337-5220), and from Auditory-Verbal International, 2121 Eisenhower Ave., Suite 402, Alexandria, VA 22314 (703-739-1049).

## NOTES

1. W. House, "Case Histories," *Annals of Otology, Rhinology, and Laryngology* 86 (supp. 38) (1977).

2. *Ibid.*

3. R. Bilger, F. Black, N. Hopkinson, E. Myers, J. Payne, and N. Stenson, "Evaluation of Subjects Presently Fitted with Implanted Auditory Prosthesis," *Annals of Otology, Rhinology, and Laryngology* 86 (supp. 38) (1977): 1-176.

4. Personal communication to M. Dorman.

5. *Ibid.*

6. *Ibid.*

7. *Ibid.*

8. T. Zwolan, P. Kileny, J. Kemink, C. Spak, and L. Loughheed, "A Closer Look at Cochlear Implant Use by Prelingual Adults" (paper presented at the Third International Cochlear Implant Symposium, Innsbruck, Austria, 1993).

9. M. Osberger, A. Robbins, S. Todd, and A. Riley, "Speech Intelligibility of Children with Cochlear Implants," *Volta Review* 96, no. 5 (1994): 169-80.

10. Data provided by Dorcas Kesler of Advanced Bionics Corporation.

11. S. Waltzman, N. Cohen, R. Gomolin, J. Green, W. Shapiro, R. Hoffman, and J. T. Roland, *American Journal of Otology* 18 (1997): 342–49.
12. Gerald M. O'Donoghue, Queens Medical Center HHS Trust, Nottingham, England, personal communication.
13. Osberger, et al., "Speech Intelligibility."
14. A. Robbins, M. Svirsky, and K. Kirk, "Implanted Children Can Speak, but Can They Communicate?" (paper presented at the Sixth Symposium on Cochlear Implants in Children, University of Miami School of Medicine, Miami, 1996).