



Cochlear Implants and Other Implantable Hearing Devices

SECOND EDITION

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Contents

<i>Foreword by Robert V. Harrison</i>	<i>vii</i>
<i>Preface</i>	<i>xi</i>
<i>Contributors</i>	<i>xiii</i>
Chapter 1. History of Implantable Hearing Devices <i>Marc D. Eisen</i>	1
Chapter 2. Designing and Building a Cochlear Implant Program <i>Linda S. Burg, David R. Friedland, and Christina L. Runge</i>	9
Chapter 3. Cochlear Implant Electrodes: Design and Characteristics <i>Jason A. Brant and Steven J. Eliades</i>	23
Chapter 4. Signal Processing Strategies for Cochlear Implants <i>Blake S. Wilson and Michael F. Dorman</i>	31
Chapter 5. Cochlear Implant Candidate Selection <i>René H. Gifford</i>	47
Chapter 6. Imaging of Cochlear Implantation <i>Suyash Mohan, Ellen G. Hoeffner, and Laurie A. Loevner</i>	63
Chapter 7. Cochlear Implants: Surgical Techniques, Special Considerations— Pediatric and Malformed Cochleae <i>Tiffany Chao and Luv Javia</i>	83
Chapter 8. Surgical Technique for Cochlear Implants in Adults <i>James G. Naples, Jason Brant, D. C. Bigelow, and Michael J. Ruckenstein</i>	109
Chapter 9. Hearing Preservation Cochlear Implantation and Electro-Acoustic Stimulation <i>Sandra Prentiss, Athanasia Warnecke, and Hinrich Staecker</i>	123
Chapter 10. Single-Sided Deafness <i>Margaret Dillon and Kevin Brown</i>	143
Chapter 11. Adult Cochlear Implant Programming: A Basic Introduction <i>Natalie R. Watts and Michelle L. Montes</i>	151
Chapter 12. Perspectives in Pediatric Cochlear Implant Programming <i>Michael Jackson</i>	161

Chapter 13. Measuring Auditory Outcomes of Cochlear Implant Use in Children with Behavioral and Electrophysiologic Tests <i>Karen A. Gordon and Blake C. Papsin</i>	175
Chapter 14. Treatment Outcomes of Adult Cochlear Implantation <i>David Low, Paul Mick, David Shipp, and Joseph Chen</i>	199
Chapter 15. Factors Influencing Cochlear Implant Performance <i>Saikrishna C. Gourishetti and Ronna Hertzano</i>	229
Chapter 16. Cochlear Implant-Mediated Perception of Environmental Sounds and Music <i>Yell Inverso</i>	239
Chapter 17. Auditory Neuropathy, Cochlear Nerve Deficiency, and Other Challenges in the Pediatric Population <i>Thierry Morlet and Robert C. O'Reilly</i>	257
Chapter 18. Cochlear Implant Reliability and Reimplantation <i>Cameron C. Wick and Craig A. Buchman</i>	271
Chapter 19. Advances in Auditory Brainstem Implantation <i>Elliott D. Kozin, Harrison W. Lin, and Daniel J. Lee</i>	283
Chapter 20. Bone-Conduction Hearing Devices <i>Jennifer W. Lee, Robert B. A. Adamson, and Manohar L. Bance</i>	313
Chapter 21. Middle Ear Implantable Hearing Devices: Present and Future <i>Hossein Mahboubi, Autefeh Sajjadi, Jeffery J. Kuhn, and Hamid R. Djalilian</i>	337
Chapter 22. Cochlear Implants—The Future <i>Michael J. Ruckenstein</i>	361
<i>Index</i>	365

Foreword

If you ask a seasoned academic to write the Foreword to a text relating to one of his (or her) career interests, you risk getting a personal historical perspective. This is no exception.

The year was (circa) 1975. It was past-midnight and I was busy with cochlear nerve recording experiments in the lab when a visiting Fellow to our Institute popped his head into my room. With some excitement he announced that he just had an important phone call, and had to arrange a flight home to Australia immediately! This visitor was the guest of speech scientist Bill Ainsworth and auditory physiologist Ted Evans in the Institute of Communication and Neuroscience, at the University of Keele (UK), and at the time he was exploring different ideas about how to process speech signals for a cochlear implant device. Our visitor (as you may have guessed) was Graeme Clark. His stay in the UK was cut short with the news that very substantial government funding had been granted to further develop and commercialize his cochlear implant device. He was on a plane home the following day; he had to be back in the driving seat!

That phone call (late-night in UK, daytime in Australia) to Graeme Clark informed him that his cochlear implant device could soon become a clinical reality. I had the feeling that I had witnessed the birth of the Cochlear (then Nucleus) device. I say the birth and not the conception because, of course, there had been many ideas and trials of cochlear implant devices beforehand, but most did not manage to achieve widespread clinical application. I was later to experience first-hand the enormous gap to be crossed when taking an experimental device through to commercialization and approval for clinical use. In the 1980s I took charge of a national Canadian initiative to develop a cochlear implant device. For a decade, we had eight University teams across the country working on electrode design, an implantable stimu-

lator, sophisticated speech processing with the latest microprocessor chip, and so forth. We produced a working experimental device, but it was never manufactured and commercialized. This translational stage is arguably more difficult to accomplish than inventing and testing the original design concepts. With this in mind I take my hat off to the companies that make, sell, and support the various cochlear implant systems and other implantable devices. Their achievements in getting product to market match, if not exceed, those involved in the early experimental conception and design.

I will return to Professor Clark later, but need to give mention to other pioneers in the field of cochlear implantation. I remind you that this is not a comprehensive history—simply my own recollections and perspective. I give this rider in advance because I know how irritated some can become if an important name has been missed. I saw this attitude surface a little when I worked in France (at the University of Bordeaux with Michael Portmann and Jean-Marie Aran). It was felt that the contributions of important French pioneers in cochlear implantation had been overlooked, notably the work of Andre Djourno and Charles Eyries in 1957 on a “permanently inserted” auditory prosthesis for electrical stimulation of the auditory nerve. (Some credit these authors as being the “inventors” of the cochlear implant.)

On the other side of the Atlantic, a different team had been credited with performing the earliest cochlear implantation, that of Bill House and John Doyle (House Ear Institute, Los Angeles). In 1961 they implanted patients with a single channel electrode device that was later (1972) developed and marketed by 3M. Also in California, at Stanford University, Blair Simmons and Bob White had implanted (in 1964) a multichannel device, but this did not see full commercialization.

Back in France, in the early 1970s Claude-Henri Chouard and Patrick Macleod published papers on a “trial of cochlear implantation with multiple electrodes.” As with many experimental teams, even those implanting human subjects, work was not continued or commercialization was not feasible. Elsewhere in Europe, other teams were experimenting, including Ingeborg and Erwin Hochmair in Austria, who produced a device that was implanted in 1977. These pioneers did manage the full “knowledge translation” and started the MED-EL company in 1989.

With no disrespect to other pioneers and device competitors, the Australian device has always been my favorite. I have always had an admiration for the very systematic approach that Graeme Clark and his team made in the quest to develop a cochlear implant device. This can be appreciated from reading just the titles of a series of papers he published, ranging from experimental concepts, “*A Hearing Prosthesis for Severe Perceptive Deafness—Experimental Studies*” (1973), covering practical matters, “*A Surgical Approach for a Cochlear Implant: An Anatomical Study*” (1975), and detailing device development, “*A Multiple-Electrode Array for a Cochlear Implant*” (1976). His Australian device was first implanted in 1978 and became widely available after U.S. FDA approval for use in adults in 1984.

In 1989, I had the privilege/task of establishing the pediatric cochlear implant program at the Hospital for Sick Children in Toronto. My initial instinct was to use only the Nucleus (later Cochlear) device. Our program was aca-

demically, meaning that all children implanted also became experimental subjects. In studying outcome measures, we chose to use only the Cochlear device to reduce any variance resulting from pooling data from patients with different equipment. The pediatric CI program is now directed by Blake Papsin and Sharon Cushing, and I sit on the sidelines and marvel at how far we have come in a few decades.

As a newly minted auditory neuroscientist in the 1970s, there was much academic excitement about cochlear implantation. Research and clinical meetings started to feature new studies and new ideas for cochlear implant devices. There were multiple groups in Europe, in North America, and obviously in Australia working on devices and a huge “derivative” field of academics tackling related problems.

For over four decades I have lived through an exciting period with regard to auditory science relating to cochlear implantation. Allow me to briefly outline two “paradigm shifts” that occurred in this period that I feel were significant.

The first related to “processing” of the speech signals prior to electrode stimulation. There were two schools of thought. Given the limited channel capacity of any device, there were those who suggested that the processor should select out the most important cues in speech signals, and pass that information to appropriate electrodes. Following this idea, the earliest Nucleus/Cochlear devices were designed to select vowel formant frequency information (F1 and F2) and stimulate the appropriate frequency-place cochlear positions. The other school of thought, (which has prevailed), was to recognize the ability of auditory brain to do its own speech cue recognition as required. Just send in as much information as possible and in a way that most emulates normal cochlear function, and let the plasticity of brain function sort out what is relevant and useful information.

The second important shift in thinking (in my opinion) related to age at implantation in the congenitally deaf child. Studies of brain plasticity were informing us that sensory stimulation, particularly during early developmental periods, would act to establish neural path-



Justin McManus/The Age

ways through synaptic strengthening and other Hebbian mechanisms. In the field of cochlear implantation, this meant that neural activation patterns evoked by electrical stimulation of the cochlea were important to establish brain networks responsible for hearing function. More importantly, this developmental plasticity was greatest during an early postnatal period, and that early implantation in the congenitally deaf infant gave the best outcomes for speech understanding and language development. It can be argued that the advent of the cochlear implant as an intervention for the deaf child, and the recognition of the need for early intervention, was a major incentive for adopting universal newborn hearing screening.

Perhaps the single, most satisfying aspect of being academically involved in the field of cochlear implantation is the diversity of expertise that has and continues to contribute to the field. Just look at the chapters in this text to see the multiple backgrounds and affiliations of the authors. The development of cochlear implant

devices has required scientists and engineers from a wide range of disciplines, including biomaterial and biomedical sciences, electrical engineering, and computer programming. Those directly involved in cochlear implant programs will immediately understand the range of health care professionals involved, including otology, audiology, speech-language pathology, radiology, genetics, social work, AV therapists, and nurses. In the educational realm, we have teachers of various specialty areas who need to understand the special needs of children with hearing challenges. Providing some guiding force and new discoveries for implantable devices, we also have academic physiologists, neuroscientists, psychophysicists, and perhaps for the future, molecular biologists.

I wonder what other area of clinical endeavor has involved such a wide range of engagement and expertise? With that, I congratulate all of the contributing authors, and all those who will consult this text, for being a part of a truly rich and diverse academic field.

Robert V. Harrison, PhD, DSc

Preface

During my residency, I had the pleasure of attending several miniseminars dedicated to cochlear implants offered at the annual AAO-HNSF meeting. Cochlear implants had just been approved by the FDA, and as a young clinician-scientist with a background in auditory physiology, I was very excited to learn about these devices that restored hearing. Most of the speakers at the seminars provided detailed scientific data that documented the outcomes in patients who had received cochlear implants. One speaker, however, presented little science. He expounded on the wonder of restoring hearing, how it changed people's lives, how "miraculous" it was to participate in the process! At the time I remember dismissing this speaker's presentation as unscientific anecdotalism. However, as I have progressed through my career, I often hearken back to that early "anecdotal" talk. Although the necessity of scientific study is undisputed, it has become clear to me that the process of restoring hearing is somehow bigger than what the scientific data can convey. It is a

true honor and privilege to be involved in the field of cochlear implantation, and it is from these feelings that this book emanates.

I have assembled a group of authors who are true experts in the field and I am truly grateful to each and every one of them for taking the time to contribute to this effort. This book is organized in what I hope is a logical way. The chapter topics were chosen to be practical, providing the student with the necessary background to understand, and hopefully one day contribute, to this exciting area of study. The recent advances in the field of middle ear implantable hearing devices are extremely exciting, and we attempt to provide readers with an introduction to this rapidly evolving field.

As always, I am very grateful to my editor, Nicole Hodges, who manages to be extraordinarily pleasant while very effectively pushing for completion of a book! All the people at Plural are wonderful to work with, and I have enjoyed the process immensely.

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*To Sean, Jennifer, and Laura—who bring
magic to my life on a daily basis!*



Chapter 1

History of Implantable Hearing Devices

MARC D. EISEN

INTRODUCTION

Generally, an implantable hearing device is designed to capture sound and present it to the auditory system to rehabilitate hearing, where at least part of the device is surgically implanted in the patient receiving it. In order to create a framework with which to systematically address the history of implantable hearing devices, we subdivide implantable by their invasiveness. Least invasive are the bone-conduction aids. These function by oscillating the temporal bone and transmitting the vibration of sound directly to the cochlea. The bone-anchored hearing aid (Baha[®]) is the archetypal example of this technology. Next, is the group of aids whose sound transmission is through the middle ear anatomy. The implantable middle ear portion of the aid is driven either by an external microphone and processor (semi-implantable) or by an implantable microphone and processor (fully-implantable). Finally, the cochlear implant bypasses the cochlea to stimulate the cochlear nerve fibers directly.

BONE-CONDUCTION DEVICES

The fact that sound can be conducted through the skull base to reach the cochlea, bypassing the middle ear, has been understood for millennia.¹ There are several very early descriptions of nonimplanted auditory prostheses that utilized the teeth as bone conductors. In 1812,

J.M.G. Itard, for example, described a wooden rod that had a narrow and broader end. The speaker would speak with the narrow end between her teeth, and the listener held the broader end against the teeth.¹ *Implanted* bone-conduction prostheses had an unlikely precursor: Andrija Henry Karl Puharich (1918–1995) owned the patents to a “miniature tooth radio.” Puharich was an eccentric who received his medical doctorate from Northwestern University, but spent little time practicing medicine. He proposed an “alternative” neural pathway that he called the “facial system,” a theoretical pathway from the mandibular teeth through to the central auditory areas that bypasses the

inner ear completely. Theoretically, stimulating the facial system with sound would give hearing to the deaf, and one entry point to the pathway was at the teeth. His U.S. Patent #2,995,633, “Means for Aiding Hearing,” describes this parallel neural pathway, as well as the receiver and piezoelectric stimulator implanted into a tooth.² A second patent³ improves on the design of the implanted “miniature tooth radio,” still claims that it functioned as a neural stimulator. In reality, the miniature tooth radio could have functioned as an implanted bone-conduction device. The miniature tooth radio would have needed a microphone and transmitter, but this was not described in the patent. There is no evidence that the miniature tooth radio was ever manufactured.

Bone-conduction hearing aids play sound through the skin behind the ear to oscillate the temporal bone. An inherent inefficiency with this design is the damping effect of the skin and soft tissue, and the need to hold the device with pressure against the skin. The *bone-anchored* hearing aid was developed to overcome these two drawbacks of bone-conduction hearing aids by affixing the device to the skull. The technologic advancement that allowed this concept to be developed was the discovery that titanium integrates with bone without a connective tissue interface, which was described by Per-Ingvar Branemark in Sweden in the 1970s. Such integration led to the idea that the bone-conduction aid be attached to the titanium implant that penetrated through the skin, completely removing the damping effect of the skin. Anders Tjellstrom collaborated with Branemark and developed the first bone-anchored hearing aid, which was first implanted in a human in 1977.⁴ With FDA approval in 2002 and subsequent acceptance by third-party payers, the Baha[®] gained wide acceptance and use.

J.V.D. Hough developed a semi-implantable bone conduction device initially for conductive loss, called the Audiant Bone Conductor. For this device, the implantable portion consisted of an assembly of a rare-earth magnet surrounded by a titanium screw unit. The titanium osseointegrated. The external portion comprises a micro-

phone and speech processing unit that drives the subcutaneously placed internal portion with electromagnetic induction. The FDA approved marketing for the Audiant in 1986. Although several thousand patients were implanted with the Audiant in the following decade, production of the device ended in the 1990s. Unlike the Baha[®], the Audiant has no transcutaneous components. It was never covered by third-party payers, and it never reached the mainstream.

IMPLANTABLE MIDDLE EAR HEARING DEVICES

Implantable middle ear hearing devices are designed to drive the ossicular chain directly. The advantages of implantable middle ear hearing devices over conventional hearing aids, then, should be improved fidelity, freedom from feedback, more discrete or hidden hardware, and removal of the occlusion effect that conventional aids create. Goode laid out these potential advantages in 1969.⁵ Several direct-drive designs emerged in the later part of the 20th century, which generally fall into two types: piezoelectric drivers and electromagnetic drivers. A piezoelectric driver contains a crystal that expands and contracts when an electrical field is passed across it. When one piezoelectric element is fixed, and one is free, either on the stapes superstructure or the footplate, the free element will transmit motion (ie, the vibration of sound) and stimulate the middle ear. One piezoelectric-based partially implantable device was developed at Ehime University in Japan, with the Rion and Sanyo Electric Companies. A prototype was available in 1983 whose ossicular vibrator (the Ehime [E]-type ossicular vibrator) was implanted through the mastoid. The external components stimulated the internal vibrator by transcutaneous induction. The complete device, the Rion Device E-type, was first implanted in a human in 1984.⁶ After a number of complications with this initial device, a second-generation device was developed that improved on the first.⁷ The device was implanted

in about 100 patients until its manufacture ceased in 2005 due to lack of profitability.⁸

Electromagnetic designs of the ossicular driver involve rare earth magnets placed on the tympanic membrane or on the umbo, and driven by coils placed in the ear canal.⁹ One simple design was to implant a magnetic ossicular replacement (either a PORP or TORP) that could be driven via an ear canal electromagnet.^{10,11} This driver's disadvantage was that it was worn in the ear canal, creating the occlusion effect. The magnetic element with this design is also relatively large compared to other middle ear magnets. J.V.D Hough was inspired by Aram Glorig¹² and Jack Vernon¹³ to pursue implantable magnetic elements placed on an intact ossicular chain. Out of these efforts came the SOUNDTEC Direct Drive Hearing System. It consisted of a barrel-shaped magnet held by a collar on the incudostapedial joint. The microphone, processor, and power supply were contained in a behind-the-ear device, from which electrodes led to a deeply placed canal coil. The coil created the oscillating magnetic field that drove the implanted element. Although the initial design¹⁴ tended to break down in situ, results in clinical trials were favorable compared to conventional hearing aids.^{15,16}

Richard Goode introduced a “floating mass transducer” that was developed by Jeff Ball and incorporated into the Symphonix Devices Corporation's Vibrant Soundbridge.¹⁷ The Vibrant Soundbridge had the transducer and receiver both implanted, the transducer affixed to the stapes and the receiver into the mastoid.¹⁸ The Food and Drug Administration approved the Vibrant Soundbridge for marketing and production in the United States in 2000.

The Otologics middle ear transducer (“MET”) ossicular stimulator was developed by John Fredrickson at Washington University in St. Louis. The MET device consisted of an implanted receiver/transducer unit that is anchored to the mastoid and whose probe inserts into the incus directly. An external processor was worn behind the ear.^{19,20} Direct-drive electromagnetic devices appear to have better fidelity and efficient energy transfer. Technical problems, a

greater expense compared to conventional aids, and the need for surgical implantation are challenges that the implantable hearing aids have to overcome.

THE COCHLEAR IMPLANT

Many fields have contributed to the development of the cochlear implant over the course of the past half century. As a result of these efforts, we now have reliable, mass-produced devices expected to last a lifetime; we have a safe outpatient procedure to implant the device that is a routine part of otologic training programs; and we have rehabilitation and ongoing management of the cochlear implant by audiologists that is a routine part of the curriculum in audiology training programs. Individual contributions to the development of the cochlear implant cannot be considered in isolation, but this section highlights benchmarks in cochlear implant development by breaking them down into several categories. These categories include a proof of concept that electrical stimulation of the cochlea would yield audition, development of the hardware of the implant, development of the safety of the device, advances that allowed its mass production, advancement of speech processing strategies, and finally, the relaxation of candidacy requirements.

PROOF OF CONCEPT— ELECTRICAL STIMULATION YIELDS AUDITION

Electrical stimulation of the auditory pathway has roots back to Alessandro Volta, who found that current passed across his own head created auditory sensations.²¹ This and other similar attempts over the next 150 years to stimulate the auditory system electrically, however, did not systematically address which neuroanatomic structure in the auditory pathway was stimulated. Specific candidates included the organ of Corti and the auditory nerve fibers. Stevens had

described in the 1930s that an intact organ of Corti will respond to electrical stimuli with a mechanical response, thus stimulating the normal release of neurotransmitter from cochlear hair cells onto fibers of the auditory nerve. This phenomenon was termed “electrophonic hearing,”²² and required an intact, functioning organ of Corti. This type of stimulation would not be helpful in the deaf ear, where the organ of Corti is nonfunctional.

Stimulating the auditory nerve in a deaf patient to generate hearing was first demonstrated in Paris in the 1950s. André Djourno (1904–1996) and Charles Eyriès (1908–1996) collaborated in Paris in 1957 to implant the first auditory prosthesis. Djourno was a basic scientist, an electrophysiologist in the Department of Anatomy and Physiology at the Faculté de Médecine of Paris, with a special interest in developing implantable induction coils that stimulated nerves. Eyriès was a clinician, Chief of Otorhinolaryngology and Head and Neck Surgery at L’Institut Prophylactique (later L’Institut Arthur Vernes) in Paris, with a special interest in facial reanimation surgery. When Eyriès was consulted for facial reanimation in an unfortunate patient with bilateral deafness and facial paralysis after extensive cholesteatoma surgeries, Djourno convinced him to implant one of his induction coils during surgery to see whether the patient would hear. On February 25, 1957, Eyriès performed the surgery. The induction coil was implanted into the mastoid cavity, and a wire placed in close proximity to the cochlear nerve stump. Stimulation through the implant was tested intraoperatively and then postoperatively during testing sessions. The patient described auditory sensations, and the patient was able to discriminate lower frequency (described as “burlap tearing”) from higher frequency (described as “silk ripping”) stimuli. He appreciated environmental noises and several words, but could not understand speech.^{23,24} The work of Djourno and Eyriès was published only in French, and development of a commercial device was never pursued. Their work would likely have remained in obscurity

were it not for a patient who brought the work to the attention of his otologist.

DEVELOPMENT OF THE HARDWARE OF THE IMPLANT

Around 1960, William F. House, MD, DDS, was in the earliest years of his practice with his half-brother Howard House, MD, at the Otolologic Medical Group in Los Angeles. One of Bill House’s patients brought him an article in the French lay press about the work of Djourno and Eyriès. Their work inspired House to pursue a cochlear implant of his own.²⁵ Over the ensuing year, he collaborated with two brothers, John (a neurosurgeon) and James Doyle (an electrical engineer), respectively, on developing a cochlear implant for human patients. The first two deaf volunteers received a simple gold wire electrode inserted through the round window and brought out through the skin.²⁶ Like the patient of Djourno and Eyriès, electrical stimulation generated hearing. These early results were encouraging, but were tempered by local infections that warranted early wire removal. One of the patients was re-implanted with a multi-electrode wire array connected to an induction device seated underneath the skin, but again local tissue reaction forced Dr. House to remove the device for the concern of infection. Despite limited success at stimulating hearing and genuine concerns about biocompatibility raised by these two patients, the lay press made overly optimistic and premature claims of a pending artificial ear.^{27,28} The cochlear implant suffered from a lack of legitimacy among scientists and engineers involved in hearing science.

Two other otologists in the 1960s experimented with cochlear implants in human patients. F. Blair Simmons, then chairman of Otolaryngology at Stanford, implanted an electrode into the modiolus of a deaf patient in 1964. Following the procedure, the patient underwent auditory testing sessions to assess the implant’s capabilities. Given the man’s comorbidity of being blind, however, assessment of the subject’s hearing

generated by the device was exceedingly difficult.²⁹ Simmons's enthusiasm for the viability of the cochlear implant waned.³⁰ The other clinician who began experimenting with implants in the 1960s was Robin Michelson. The consummate tinkerer, Michelson began working on a cochlear implant on his own as a private practitioner in Redwood City, California. He moved to the University of California at San Francisco under the leadership of Francis Sooy. Michelson implanted several subjects with fully-implantable single electrode devices and reported their experiences at national forums.^{31,32}

DEVELOPMENT OF THE SAFETY OF THE DEVICE

The nascent efforts above were aimed at demonstrating proof of the concept that electrical direct stimulation of the auditory nerve in deaf patients could rehabilitate hearing. Manufacturing a viable, safe cochlear implant was a tremendous hurdle that then stood in the way. Societal pressures in the 1970s led to tighter regulation on device manufacturing. The emergence of much more stringent Food and Drug Administration (FDA) regulations of new devices in 1976 meant that efficacy and safety would have to be proven before a new device could be marketed.

The early 1970s brought more controversy to the cochlear implant than excitement. The basic science community in general adamantly opposed cochlear implantation on the grounds dictated by the current understanding of auditory physiology that cochlear implants would yield no useful hearing. Furthermore, they argued that before humans should be implanted, rigorous scientific method be applied and devices verified in animal models.

A turning point in the development of the cochlear implant came in 1975, when the NIH sponsored a thorough evaluation of the patients who had received cochlear implants up until that time. Thirteen subjects, all implanted with single-channel devices by either Robin

Michelson or William House, volunteered to go to Pittsburgh for extensive psychoacoustic, audiologic, and vestibular testing led by Robert Bilger. The report concluded that single channel devices could not create speech understanding, but that patients' speech production, lip reading, and quality of life were all enhanced with the device.³³ The study and its report marks the first time that an objective evaluation of patients by the scientific mainstream was performed. Benefits from implants were evident, and the concept that electrical stimulation of the auditory nerve could yield useful hearing was finally confirmed.

Cochlear implant research gained a foothold in the scientific mainstream in the later part of the 1970s. Work on the implant emerged from legitimate, well-established academic centers, and funding to perpetuate the work increased. The group at the University of California, San Francisco, led by Michael Merzenich and Robert Schindler, addressed the safety and feasibility of long-term electrical stimulation of the auditory nerve in a cat model, showing that scala tympani electrodes inserted atraumatically could stimulate the auditory nerve chronically without dramatic neural degeneration.^{34,35} The NIH contract mechanism pushed progress further by funding efforts to determine the most suitable materials for electrical biostimulation.³⁶ Two groups worked on the development of a multielectrode cochlear prosthesis—the UCSF group³⁴ and Graeme Clark and his group at the University of Melbourne in Australia.³⁷ These groups made substantial improvements in miniaturization of the receiver/stimulator device and improved safety and durability of the electrode array. The work of these two groups resulted eventually in the production of the Advanced Bionics Clarion and the Cochlear Corporation's Nucleus devices. At the same time, William House and his engineer colleague Jack Urban continued to pursue the development of the single-channel device. Manufactured by the 3M Corporation, the House 3M single-channel implant was the first FDA-approved implant, and more than 1,000 were implanted from 1972 into

the mid-1980s. FDA approval for the multichannel cochlear implant came in 1985 for adults and in 1990 for children as young as two years.

THE ADVANCEMENT OF SPEECH PROCESSING STRATEGIES

As the safety of the cochlear implant became well accepted, work on the cochlear implant focused on the understanding of speech. The superiority of multiple-channel devices over single-channel devices became clear, as demonstrated in large adult clinical trials.^{38,39} A speech-processing scheme based on a high rate of alternating electrode stimuli was introduced by a collaboration between the UCSF group and the Research Triangle Institute, and was shown in 1991 to be a significant boost to speech recognition performance.⁴⁰

RELAXATION OF CANDIDACY REQUIREMENTS

Candidacy was initially granted to adult patients with profound bilateral hearing loss (>100 dB thresholds) and no measurable open-set speech recognition with hearing aids. The 25 years that followed the initial FDA approval of the cochlear implant saw age requirements fall initially down to 2 years or older, and then 1 year or older in 2000. Through combined advances in universal newborn hearing screening and early diagnosis of deafness, education and rehabilitation of implantees, and greater acceptance of cochlear implantation by the deaf community, implantation of infants has become accepted and resulted in tremendous improvements in implant performance in these patients. Residual hearing requirements have also been liberalized to include patients with considerable residual hearing, both with pure tone threshold and with open-set speech recognition with hearing aids. As far as which ear is implanted, initial thought was that residual hearing implied better neural element preservation, which would lead to bet-

ter cochlear implant performance. A 2005 study from the Johns Hopkins cochlear implant center demonstrated that the degree of residual hearing did NOT correlate with the performance with the implant.⁴¹ The trend towards preservation of residual hearing, stimulating audition with both acoustic and electrical hearing in ears with residual hearing, and implanting deaf ears in patients with single-sided deafness have recently emerged as the envelope of cochlear implant applicability continues to expand.

CONCLUSIONS

The history of the development of implantable hearing devices closely follows the technologic advances of electronics, namely, miniaturization and sophistication of microcircuitry, materials, and sound processing. Although patient needs are the primary driving force behind implantable hearing devices, these concurrent technologic advancements borrowed from unrelated fields have been necessary to bring the vision of a few pioneering clinicians to fruition.

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8 Cochlear Implants and Other Implantable Hearing Devices

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