The Early History of the Cochlear Implant

A Retrospective

Albert Mudry, MD, PhD; Mara Mills, PhD

Importance: Histories of cochlear implant (CI) technology have often been inaccurate owing to the confusion of terms and anatomical situations or to biased reporting. This retrospective, published shortly after the death of inventor William F. House—and more than 50 years after placement of the first CI—offers a precise account of the early experimental period.

Objective: To clarify the first steps in the development of the CI, ie, an electrical stimulating device partially inserted into the cochlea.

Evidence Review: Literature review based on published data, oral history material, interviews, and written contact with protagonists.

Findings: The first CI was implanted by William House and John Doyle of Los Angeles, California, in 1961. In 1964, Blair Simmons and Robert White of Stanford University, Stanford, California, placed a 6-channel electrode through the promontory and vestibule directly into the modiolus. The next step in the development of the CI was its clinical trial on a cohort of patients. Robin Michelson, Robert Schindler, and Michael Merzenich at the University of California, San Francisco, conducted these experiments in 1970 and 1971. In 1973, the first international conference on the "electrical stimulation of the acoustic nerve as a treatment for profound sensorineural deafness in man" was organized in San Francisco. At the same time, Claude Henry Chouard in France and Graeme Clark in Australia began their research. The final step in the establishment of CI as a clinically feasible technology involved the independent evaluation of implant users. The first such evaluation—the result of a 1975 request from the National Institutes of Health—was published in 1977 by Robert Bilger and coworkers at the University of Pittsburgh, Pittsburgh, Pennsylvania.

Conclusions and Relevance: Inspired by French experiments with electrode implantation at the VIII nerve, the initial practical development of the CI is nonetheless a Californian story, divided between the House group at Los Angeles and teams at Stanford University and UCSF.

JAMA Otolaryngol Head Neck Surg. 2013;139(5):446-453

THE COCHLEAR IMPLANT (CI) is the successful realization of electrical stimulation of the ear to produce the sense of sound. A CI is a device that converts sound into an electrical current able to stimulate hearing. It may be partially or totally surgically implanted, but to be classified as CI the electrode must be inserted into the cochlea for a period longer than that of a temporary perioperative stimulation test. The implantation time can, however, be variable, related to such factors as patient tolerance. The development of the CI proceeded through 3 "anatomical" stages: extra-auricular, intra-auricular, and intracochlear. The profusely published history of CI has often been inaccurate because of the confusion of these different anatomical situations, along with other common misconceptions: the characterization of perioperative stimulation tests as implantation; conflation of animal and human studies; the use of unpublished or retrospective data as references; and personal biases on the parts of certain protagonists. The improper use of terminology has obfuscated other historical accounts, which fail to differentiate between concepts such as *wire* (ie, physical matter conducting electricity, also a synonym of electrode because 1 wire is 1 electrode), *electrode* (ie, functionality of a wire), *channel* (ie, path by which electricity is conducted in the wire or the electrode, with 1 channel in 1 wire), *multiwire electrode* (ie, many wires bundled into 1 coated array forming 1 electrode and often referred to as the electrode), *multielectrode* (ie, many insulated and separated arrays of electrodes), and *multichannel* (ie,

See Invited Commentary at end of article

Author Affiliations: Department of Otolaryngology–Head & Neck Surgery, Stanford University School of Medicine, Stanford, California (Dr Mudry); and Media, Culture, and Communication, New York University, New York, New York (Dr Mills).

many channels of conduction, or the capacity to deliver different signals to different wires in the electrode array that can be simultaneously, consecutively, or sequentially organized). Moreover, the reaction of the Deaf community has commanded the attention of historians and ethicists, who have tended to neglect the technical history of CI.[1]

The invention of the CI went against the paradigm that an "opened" inner ear could no longer function. This paradigm was first weakened with the replacement of extracted stapes by an artificial prosthesis in 1956.[2] The next definitive step was the introduction of an electrode into the cochlea, in 1961, which literally initiated cochlear implantation. The aim of this study is to clarify this history by referring only to available and published primary and secondary data; oral history material (Archives of the John Q. Adams Center for the History of Otolaryngology–Head and Neck Surgery); interviews or written contacts with some protagonists, notably William House, Robert Schindler, Robert White, Graeme Clark, and the patient Charles Graser; and by taking into account the preceding remarks about the precise definition of CI. Three periods can be isolated in this history: the experimental period, the initial period of application on a cohort of patients (until the National Institutes of Health evaluation in 1977), and the commercialization period. Only the first 2 periods are detailed here.

EXPERIMENTAL PERIOD

The invention of the first electrical capacitor in 1745, the Leyden jar, provided a great stimulus to the medical application of electricity. The first extra-auricular electrical stimulation dates to at least as early as 1748, with a report made by the English portraitist and electricity researcher Benjamin Wilson, who described his experiment on a deafened woman as follows[3(p202)]:

> The covered vial being electrised by two turns of the wheel only, I applied the end of a thick wire, which was fastened to the covering of the vial, to the left temple, just above the ear; then I brought the end of that wire, which was in the vial, towards the opposite part of her head, and there ensued a small explosion. She was much surprized, and perceived a small warmth in her head, but chiefly across it, from ear to ear. I repeated the experiment four times, and made the electrical shock stronger each trial.

Wilson repeated the experiment a few times during the next days, resulting in an improvement of the woman's hearing. He tried the experiment on 6 other deaf individuals, however, without any success. After him, similar attempts were made in France, Sweden, Italy, and England. The Italian physicist Alessandro Volta tackled his own ear in 1800, concluding, "The disagreable sensation, which I apprehended being dangerous, of shock in the brain, prevented me from repeating the experiment."[4] Despite Volta's discouraging remarks, other scientists continued on with attempts to electrically stimulate hearing during the 19th century,[5] notably Guillaume-Benjamin-Amand Duchenne de Boulogne in France in 1855[6] and Rudolf Brenner in Germany in 1868.[7] In 1905, the American La Forest Potter[8] patented an electrical stimulating system applicable to the mastoid bone:

> My invention relates, among other things, to improvements in means for passing an electric current through the mastoid bones and through the natural ear-passages of the human head and also of means for transmitting phonetic excitement to such media by the use of an electric current.

By 1930, Ernst Glen Wever and Charles Bray of Princeton observed that an amplified output from an electrode placed intracranially in the acoustic nerve of a cat produced a copy of the speech waveform in both frequency and amplitude.[9] In 1940, the Americans Clark Jones, Stanley Smith Stevens, and Moses Lurie placed electrodes directly into the middle ears of 20 patients lacking tympanic membranes, most of whom had undergone radical mastoid operations with removal of the drum and ossicles of the middle ear. Because of the proximity of these electrodes to the inner ear and the resulting production of sounds, the idea that direct stimulation of the auditory nerve might result in hearing was again hypothesized.[10] In 1950, the Swedish neurosurgeon Lundberg stimulated a patient's auditory nerve with a sinusoidal electric current during a neurosurgical operation and discovered that the sinusoidal current was perceived not as a tone but as a noise.[11]

The French team of André Djourno, electrophysiologist, and Charles Eyriès, otolaryngologist, are generally credited as the first to have implanted a CI. This is not strictly true because, as Djourno and Eyriès themselves report, they saw a small segment of the VIII nerve during a surgical procedure to graft a facial nerve on a deafened patient. (This patient had previously undergone temporal bone resection for a cholesteatoma, which had damaged his facial nerve.) On February 25, 1957, they placed an electrode in contact with a segment of the vestibular nerve[12(p424),13]:

> This procedure, undertaken by Dr Eyries revealed such dreadful damage that after a 5 cm graft of the facial nerve, we hesitated for a while to place the appliance. What we did was really for understandable psychological reasons and because we saw that a small segment of the eighth cranial nerve, measuring a few millimeters, was accessible without any additional risk. It belonged to the vestibular nerve. The induction device was 2.5 cm in length and 3.5 mm in diameter, including its coating. It had two stainless steel wires suitably orientated. One was insulated with polyethene just to its tip, and was placed in contact with a small segment of nerve. The other was bare and was connected to the temporalis muscle, in which was placed the micro-coil.

In another report published 5 months later, they wrote, "a very small nervous segment was accessible, through a labyrinthine opening."[14] The cochlea was never mentioned in their writings, and the electrode was certainly placed somewhere in the internal auditory canal where a few millimeters of the vestibular nerve was accessible. Nevertheless, Djourno and Eyriès must be considered the first to have implanted an electrode intra-auricularly to electrically stimulate the auditory nerve. Moreover, they predicted the imminent development of the CI, concluding in their first report, "The electrical stimulation of the cochlea itself, in analogous conditions, would without doubt allow the construction of a possible mechanism for electrical hearing."[12(p425)] Soon thereafter, however, Djourno lost interest in sensory stimulation experiments.

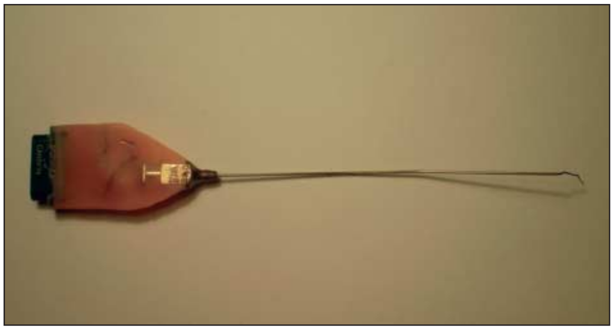

Figure 1. Doyle and House's cochlear implant prototype (Archives of the John Q. Adams Center for the History of Otolaryngology–Head and Neck Surgery). Copyright 2013. Reprinted with permission from the American Academy of Otolaryngology–Head and Neck Surgery Foundation.

The first true CI was implanted by the American otologist William (Bill) House of the House Clinic and the neurosurgeon John Doyle of Los Angeles, California, on January 9, 1961, as reported by Leland House[15(p996)] (not a family relation) in 1987:

Doctors Doyle and House surgically placed a single wire electrode in the scala tympani through an opening anterior to the round window. On February 1, 1961, in the same patient, the single wire electrode was replaced by a four-channel probe.

William House[16(p5)] described, in 1976, the operation as follows (**Figure 1**):

Using . . . a postauricular approach, the skin of the canal and the inferior one-half of the annulus were elevated. A gold wire electrode was placed in the scala tympani through the opening anterior to the round window.

William House[17(p1884)] later described how he became interested in the development of such a device:

Some years ago during the early part of 1957 [probably in 1958 as mentioned in another statement[18]], a patient brought me a two or three paragraph news clipping about what I considered to be a remarkable thing. It was a story about a patient in Paris who was totally deaf until a wire was placed into the region of his inner ear. Through this he was able to perceive a sensation of sound. This stimulated me a great deal, and I began to search the literature to find out what I could about this. The implanted wire mentioned in the news article was the result of work done by Djourno and Eyries. All this was the start of the cochlear implant.

The first written report of this operation was published on March 9, 1957, in *Compte-rendus des séances de la Société de Biologie*.[12] The *New York Times* related this successful operation by "French surgeons" in 1958,[19] followed by an announcement in *JAMA* in 1959.[20] William House subsequently collaborated, and financed research,[18] with the Doyles to replicate this experiment, as reported by Leland House[15(p996)]:

In December 1960, Dr. John Doyle, a neurosurgeon, his brother Jim Doyle, an electronics engineer, and Doctor William House, our own well-known otologic surgeon, worked together testing the electrical activity of the surgically exposed eighth nerve.

In a 1976 report of the same operation, William House[16(p5)] wrote,

On February 1, the single electrode implant was removed. . . . and five wire electrodes were inserted, tested, and then withdrawn . . . A five wire electrode induction coil system was inserted on March 4, 1961. . . . a postauricular incision through a mastoid-facial recess approach was made. The round window was exposed and the electrodes were placed in the scala tympani. The induction coils were seated in the bone in the postauricular area. . . . On March 15, 1961, the device was removed, with uneventful healing.

These facts are corroborated in an oral history interview that Phillip Seitz conducted with John and Jim Doyle in 1993.[21] Before this first implantation, the Doyles and William House had gained some experience in the observation of electrical activity of the VIII nerve, by the temporary placement of an electrode during surgical sectioning of the vestibular nerve in patients who presented symptoms characteristic of Ménière's disease. Other experiments were also conducted during stapes surgery, with the electrode being placed into the perilymph through the opened oval window.[16]

A second patient also underwent implantation on January 9, 1961, as described by William House[16(p5)] in 1976:

through a middle fossa approach. . . . a gold wire electrode placed in the scala tympani in the superior part of the basal coil of the cochlea in the region of 3000 Hz. The wire was led along the bone of the middle fossa and brought out through a skin incision. . . . After two test periods, however, the amount of current necessary for stimulation increased. Because it was thought infection or edema might be occurring, the wire was removed [2 weeks later].

No reports of these 2 patients were made in the medical literature at that time.

The partnership between the Doyle brothers and William House soon ended for at least 2 reasons, the first being that the Doyles shared the details of these experiments with the press. William House[22(p505)] recalled,

We began to be deluged by calls from people who had heard about the implant and its possibilities. The engineer who had constructed the implant exercised bad judgment and encouraged newspaper articles about the research we were doing.

The second reason was that the Doyle brothers refused to share the full reports on the electronics and material they had developed. William House quoted Jim Doyle: "I'm not going to give you this material. There was no written contract between us and as far as I am concerned, it's mine."[18(p68)] For William House, as quoted by his brother Howard House, "It was one of the most depressing moments I ever had in medicine. . . . Now I would need to start all over again."[23(p303)]

The Doyle brothers continued their research, performing implantation in another patient the next year (on November 23, 1962), the surgeon being this time the otolaryngologist Leland House of the White Memorial Hospital of Los Angeles, California, with another otolaryngologist, Frederick Myles Turnbull. A preliminary report was made by John Doyle, and discussed by William House, at the 16th clinical meeting of the American Medical Association, held in Los Angeles on November 27, 1962,[24] followed by another report a few months later to the Los Angeles Neurological Society[25(p150)]:

An induction coil which had been previously imbedded in a plastic case (methyl methacrylate) was inserted in a craniectomy defect in the squamous position of a temporal bone of a patient suffering from essentially total congenital perceptive hearing loss. The active electrode was passed through a tunnel of bone into the middle ear and through a fenestra in the promontory of the cochlea between the oval and round windows.

The procedure was also reported to the American Academy of Ophthalmology and Otolaryngology on October 19, 1963.[26]

After William House and Jim Doyle introduced implantation at the cochlea, fundamental physiological research began, notably in Germany and in the United States. The German otologist Fritz Zöllner, who visited Djourno in March 1962 and who was aware of the work of the Doyles and William House, published in 1963 an article dealing with the transmission of sound by electrical stimulation of the acoustic nerve.[27] Zöllner perioperatively conducted stimulation tests of 2 patients by inserting an electrode through the oval window into the scala tympani (no precise date was given).

On July 26, 1962, the Stanford University team of otolaryngologist Blair Simmons and engineer Robert White perioperatively conducted stimulation tests through a posterior craniotomy, with an electrode placed on the acoustic nerve, and then displaced on the inferior colliculus with less success.[28] The stimulating device, fixed on the head, consisted of a bipolar electrode placed on the nerve and held there with a micromanipulator (**Figure 2**). The patient was "in a supported sitting position using local anesthesia without premedication."[28(p561)] On May 7, 1964, they placed a permanent transcutaneous 6-channel electrode through the promontory and vestibule directly into the modiolus by means of a transmastoid approach. It is noteworthy that the incus was removed, and the electrode was slid through the epitympanic recess; the stapes being also removed, the medial wall of the vestibule was exposed, upon which the anterior ridge of the saccular recess could be seen.[29(p12)]

Using this landmark as a guide, a preliminary 2 mm hole was made in the promontory approximately 3 mm anterior and 1 mm inferior to the superior margin of the oval window. . . . Next a 0.1 mm hole was drilled through the modiolar bone, using the oval window for visualization and the promontory opening for the drill shank. Nerve-like tissue could be seen through the modiolar hole. . . . A six-electrode array was then successfully passed through the promontory hole and into the modiolar hole to a depth of about 3-4 mm.

The electrode was percutaneously connected with the external device. The patient was then regularly observed and examined. This was the first implantation of a multichannel CI.

This procedure was reported in *Science* in 1965,[30] and the following year Simmons' team published the first extensive article on the different aspects of electrical stimulation of the auditory nerve in humans.[29] On March 27, 1967, during a workshop on microsurgery of the ear held in Chicago, Illinois, Simmons[31(p61)] stated, "My own personal and probably too optimistic opinion is that an artificial inner ear will eventually be able to provide at least marginal hearing for some persons with sensorineural deafness." It seems that this was the first time the term *cochlear implant*, which Simmons used in the title of his presentation, was used in a scientific publication to describe the artificial inner ear. William House, present at the meeting, commented, "Simmons has done what I consider to be probably the most difficult problem facing us today in otology."[31(p68)] A last work was published by the Stanford group in 1970, comparing the electrical and acoustic stimulation of the cat ear.[32]

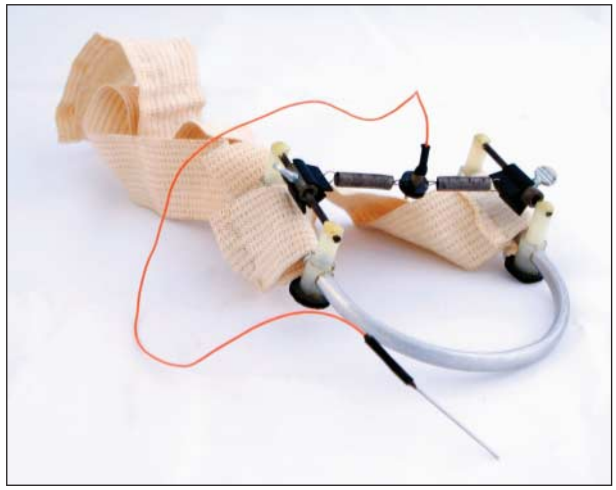

Figure 2. Simmons' stimulation electrode (reprinted with permission from Virginia Commonwealth University Tompkins-McCaw Library, Special Collections and Archives).

By 1967, William House and Jack Urban, an electrical engineer, had worked out the details for a new approach to the CI. Instead of placing an induction coil beneath the skin, they developed a percutaneous button containing an induction coil. In early 1969, conditions were ripe to try new implantations on 3 patients.[23] In particular, the miniaturization of electronics components, the development of new surgical plastics, and the success of the implanted artificial pacemaker prepared the way for this new round of CIs. As reported in 1976, William House performed implantation on a patient on September 24, 1969, using a silver multiple hard wire electrode. This patient was tested "periodically at Urban's laboratory for the remainder of 1969 and 1970."[16(p9)] He received a new device on October 18, 1974. In 1970, House added 2 other patients. The first one received the implant on October 10, 1970: "a multiple electrode system was inserted. Unfortunately, after several weeks, the button loosened in the bone, resulting in the failure of the system."[16(p9)] It is worth noting that this patient had been transiently stimulated on May 11, 1961. The second patient received his implant in the right ear, on June 18, 1970. Two years later, this patient also underwent implantation at the left ear with a multielectrode CI (**Figure 3**).[33] All these electrodes were effectively composed of a single channel of stimulation.

The relationship between the CI innovators during this period was collaborative, as well as competitive. The physicians met regularly, also in private.[34] William House[18(p69)] wrote that Simmons and Robin Michelson

became interested in implants, and the three of us found mutual support in being able to discuss implants in what was becoming a subject considered by some to be quackery. We formed an informal "West coast" implant group.

In 1973, William House and Urban published their first article about the long-term results of electrode implan-

Figure 3. House and Urban with the patient Charles Graser (Archives of the John Q. Adams Center for the History of Otolaryngology–Head and Neck Surgery). Copyright 2013. Reprinted with permission from the American Academy of Otolaryngology–Head and Neck Surgery Foundation.

tation and electronic stimulation of the cochlea in 1 patient. The article was presented and discussed at the meeting of the American Otological Society, April 6 to 7, 1973. William House[22(p510)] concluded his study by stating,

> We feel that the electronic cochlea is now ready for more widespread testing and development. . . . We present this evidence in the hope that teams . . . will commence as soon as possible to investigate this new possibility and continue to refine these techniques.

In commenting on this article, Richard Marcus added, "We will also hope that someday it will be successful for most of our severely deafened patients."[22(p514)] When William House presented the same article at the Collegium Oto-Rhinol-Laryngologicum, however, he met with a hostile audience. The main critique of these first, mostly single-channel CI prototypes was the difficulty with insulating the electrode.

INITIAL APPLICATION PERIOD ON A COHORT OF PATIENTS

The next step in the development of the CI was its use in clinical practice on a cohort of patients. The team at the University of California, San Francisco (UCSF), under the supervision of otolaryngologist Robin Michelson and with the collaboration of otolaryngologist Robert Schindler and neurophysiologist Michael Merzenich, became interested in the development of a CI. Merzenich conducted various studies at the turn of 1970 on cats[35] and was interested, contrary to Michelson, in the development of a multichannel CI. After these animal experiments, the UCSF team selected 4 patients who were tested with an electrode placed temporarily in the lower scala under local anesthesia. Two of these patients finally received a totally implanted CI in 1970. A transcanal approach was used to place the single bipolar electrode[36(p321)]:

> A shallow groove was cut in the posterior canal wall deep enough to receive the leads from the intracochlear electrode. The electrode was then inserted through the round window into the lower scala . . . The lead terminated in a tiny amplitude-modulated radio receiver placed beneath the skin.

A preliminary report was published in 1971, followed by a more complete one that was presented a few months later during the American Otological Society Meeting in San Francisco, May 28 to 29, 1971.[37] Michelson added 1 more patient to his report; this was the first published article dealing with 3 patients implanted with a single-channel CI. This article was discussed with much skepticism by Moses Lurie, Harold Schucknecht, and Joseph Hawkins, leading Michelson to conclude, "It has been said that the investigator's best friend is his severest critic. I seem to have a number of friends here today."[37(p919)] William House was more optimistic in his comments on the article: "It is possible that some day we may be able to overcome the problem of sensory deafness."[37(p919)]

In June 1973, the first international conference on electrical stimulation of the acoustic nerve as a treatment for profound sensorineural deafness in humans was organized in San Francisco. Notably, Blair Simmons, Robert White, William House, Jack Urban, the complete UCSF team, and the French otolaryngologist Claude Henri Chouard—a colleague of Eyriès—participated in the meeting. The reports of this first congress were published 1 year later and specially distributed to the participants.[38] By this point, the term *cochlear implant* had been definitively introduced into the medical literature.

Confronted with the low level of success in speech discrimination with a single electrode, other types of devices were developed with multiple electrodes. After 3 years of laboratory work with the physiologist Patrick MacLeod, Chouard[39-41] reported 6 implantations of a device with 7 electrodes on patients presenting total bilateral deafness in 1976.[40(p1746)]

> Each electrode was introduced into the cochlea through a separate fenestration of the scala tympani. An electrically isolated compartment was made in the scala for each electrode by means of little pieces of silastic.

On September 22, 1976, Chouard completed his first implantation.[42] It was a quite complicated and time-consuming surgical procedure. On March 16, 1977, a patent (French 77 07824; US 4 207 441) for this device was deposited with the main claim being[43]

> A system with n sets of electrodes implantable in the cochlea at n different locations so chosen that when they are stimulated the electrodes allow the brain to identify n different frequencies comprised in the audible range.

This device prompted other researchers to continue the development of a multichannel CI, and they were not limited by Chouard's patent. In 1978, Chouard organized, in Paris, the first international course on the multielectrode CI. William House, Michelson, and Schindler were participants.

In Melbourne, Australia, the Australian otologist Graeme Clark began to be interested in CI in 1967.[44-46] He was convinced that[47(p51)]

> stimulating hearing nerves with a single electrode at the same time rate as the sound frequency would not be effective, and the place of coding of frequency would be needed. This required inserting multiple electrodes in the inner ear to excite the separate groups of hearing nerves that convey different pitch sensations.

He then regularly published reports of his research, mainly on cats, first regarding "the types of electrodes that should be used, and the most appropriate methods of implantation,"[48(p944)] then on the possibility "that an electrode array can be passed along the whole length of the cochlea,"[49(p792)] and finally about the production of a constant current stimulation, in the form of a "stimulating pulse shape that minimizes the production of toxic substances and loss of metal from the electrodes."[50(p943)] Clark implanted his first multi-electrode CI hearing prosthesis in 1978.[51-53] It became the first successful commercialized multichannel CI, under the name of Cochlear/Nucleus.

Another crucial step in this period involved the independent evaluation of CI. The first such evaluation was published in 1977 by the audiologist and neurophysiologist Robert Bilger and coworkers[54] from Pittsburgh. This study was the result of a request from the National Institutes of Health dated March 1975. Over the course of 5 days, Bilger's group evaluated 13 patients with implants (11 who had undergone implantation by William House with a single-channel electrode, and 2 by Michelson) and remarked that "[t]he implant surgical procedures were well-tolerated by the subjects and did not disrupt middle ear function."[54(p3)] The patients "did score significantly higher on tests of lipreading and recognition of environmental sounds with their prostheses activated than without them."[54(p4)] They concluded as follows: "To the extent that the effectiveness of single-channel auditory prostheses has been demonstrated here, the next step lies in the exploration of a multichannel prosthesis."[54(p9)] This conclusion astounded William House[18(pp81-82)] because it was

> based entirely on theory and not the actual study . . . but was made before any wearable multiple electrodes devices or patients were available for clinical use or testing, and there were no data provided to support such conclusions.

William House organized an electroanatomy conference at what is now known as the House Ear Institute in Los Angeles in 1977. This meeting was intended to include all of the staff working on CI projects.

The future of CI technology would in fact be dominated by the multichannel single-wire electrode initiated by Simmons and White and implanted by Michelson's team in 1974 (**Figure 4**), as well as by Clark in 1978 (**Figure 5**). Clinical results were published beginning in 1978, by Clark for 2 patients[55-58] and by Michelson for 1 patient,[59] along with the speech discrimination tests necessary to study these results. These experiments definitively launched the commercialization period. In Germany, Belgium, and Austria, other groups began to conduct new experiments on electrical stimulation of the ear in animals and humans in order to develop and produce new multichannel devices (**Table**). This required close collaboration between surgeons and engineers; moreover, the commercialization period coincided with the increase in prevalence of university-industry partnerships and the growth of medical electronics as a field. Priority of patents and the possibility for commercial development were for some groups the indisputable motor. The industrial transformation is evident in the House Ear Institute collaboration with Nucleus (Cochlear) in Australia, 3M Company in the United States, and with the creation of other firms such as Med-El in Austria, Chorimac in France, Laura in Belgium, Clarion, and Ineraid in the United States.

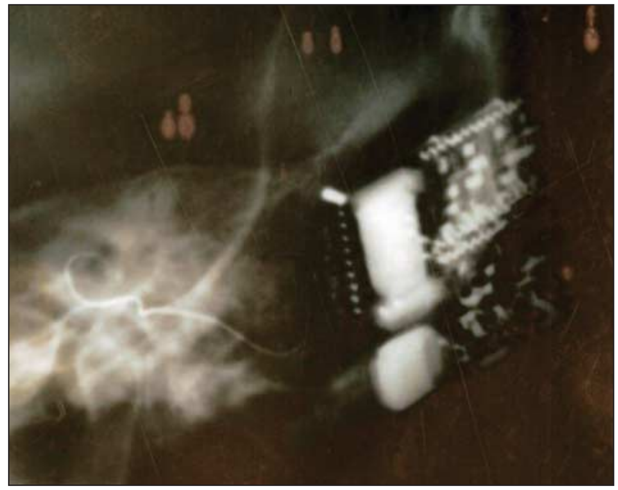

Figure 4. Radiograph of a cochlear implant inserted in 1974 (reprinted with permission from Robert Schindler).

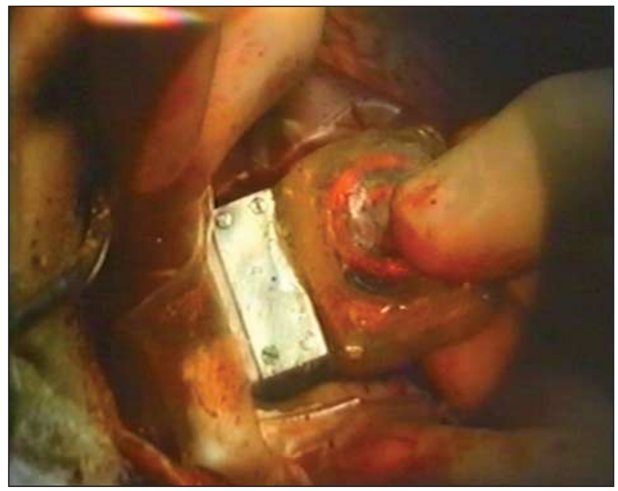

Figure 5. Clark's first cochlear implant in situ (reprinted with permission from Graeme Clark).

HISTORICAL PERSPECTIVE

Djourno and Eyriès's work, dating to 1957, definitively spurred the development of the CI. Strictly speaking, the history of CIs began in the early 1960s with the experiments of William House, the Doyle brothers, Leland House, Frederick Turnbull, Robert White, and Blair Sim-

Table. Chronological Table

Date	Investigators	Milestone
1748	Wilson	First extra-auricular electrical stimulation
1800	Volta	Discouraging experiments stimulating own ear
1905	Potter	Patent for mastoid electrical stimulator
1930	Wever & Bray	Stimulated acoustic nerve in cats can produce a copy of speech waveform
1940	Stevens & Lurie	Possible direct electrical stimulation of the inner ear with electrode placed in the middle ear during ear surgery
1950	Lundberg	Sinusoidal current perceived as noise by direct stimulation of the auditory nerve during neurosurgery
1957	Djourno & Eyriès	First implantation of an electrode near the VIII nerve
1961	House & Doyles	First 2 implantations of a single-channel electrode inside the cochlea through the round window
1964	Simmons & White	Implantation of a 6-channel electrode through promontory
1969	House & Urban	3 Implantations with a single-channel electrode
1969	Clark	First publication on stimulation of the auditory nerve of cats
1970	UCSF team	2 Implantations of a single-channel electrode
1973	UCSF team	First international conference on CI, San Francisco, California
1974	UCSF team	Implantation of a multielectrode device
1976	Chouard et al	6 Implantations of a 7 separated-electrode device
1977	Chouard et al	French patent for a multielectrode device
1977	Bilger et al	Independent evaluation of CI for NIH
1978	Clark	Implantation of first commercialized multielectrode device
1978	Chouard et al	First international course on multielectrode CI, Paris, France
1978	Various teams	Beginning of second wave of CI development

Abbreviations: CI, cochlear implant; NIH, National Institutes of Health; UCSF, University of California, San Francisco.

mons in California. It took more than 10 years before the application of CI on a cohort of patients was realized by the UCSF team, also in California. This led to the organization of the first international meeting on CI in San Francisco in 1973, which introduced this new technology to an even wider audience. Ultimately, the establishment of clinical feasibility for CI, as well as the commercialization of the technology, intensified the competitiveness between the various research groups, leading Simmons[60(p6)] to write in 1985,

> There is a certain reluctance about openly sharing results. Implants are dramatic research. I suspect that there are more than a few workers in this field who secretly suspect that a Nobel Prize lurks somewhere just beyond the next success. I hope these attitudes will not encumber solving the problems.

By the end of the 1980s, CI became the predominant treatment for profound deafness in the United States, Europe, and Australia, bringing about a new controversy over the "origins" of the technology, as well as controversy about its application among the Deaf community.[61]

Submitted for Publication: February 8, 2012; final revision received August 30, 2012; accepted January 15, 2013.
Correspondence: Albert Mudry, MD, PhD, Department of Otolaryngology–Head & Neck Surgery, Stanford University School of Medicine, 801 Welch Rd, Stanford, CA 94305-5328 (amudry@ohns.stanford.edu).
Author Contributions: Dr Mudry had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. *Study concept and design:* Mudry. *Acquisition of data:* Both authors. *Analysis and interpretation of data:* Mudry. *Drafting of the manuscript:* Both authors. *Critical revision of the manuscript for important intellectual content:* Both authors. *Administrative, technical, and material support:* Mills. *Study supervision:* Mudry.
Conflict of Interest Disclosures: None reported.
Additional Contributions: We thank William House, Robert White, Robert Schindler, and Graeme Clark for their remarks and suggestions in the preparation of this manuscript. We also thank Robert Jackler and Nik Blevins for their critical review of the text.

REFERENCES

1. Mills M. Do signals have politics? inscribing abilities in cochlear implants. In: Pinch T, Bijsterveld K, eds. *The Oxford Handbook of Sound Studies.* Oxford, England: Oxford University Press; 2011:320-346.
2. Shea JJ Jr. Fenestration of the oval window. *Ann Otol Rhinol Laryngol.* 1958;67(4):932-951.
3. Wilson B. *A Treatise on Electricity.* 2nd ed. London, England: Davis; 1752:202-208.
4. Volta A. On the electricity excited by the mere contact of conducting substances of different kinds. *Philos Trans.* 1800;90:403-431.
5. Shah SB, Chung JH, Jackler RK. Lodestones, quackery, and science: electrical stimulation of the ear before cochlear implants. *Am J Otol.* 1997;18(5):665-670.
6. Duchenne GBA. *De l'électrisation localisée et de son application à la physiologie, à la pathologie et à la thérapeutique.* Paris, France: Baillière; 1855:73, 807-813.
7. Brenner W. *Untersuchungen und Beobachtungen über die Wirkung elektrischer Ströme auf das Gehörorgan im gesunden und kranken Zustande.* Leipzig, Germany: Giesecke & Devrient; 1868.
8. Potter LF, inventor. Electric ostephone. US patent 792162. June 13, 1905.
9. Wever EG, Bray C. The nature of acoustic response: the relation between sound frequency and frequency of impulse in the auditory nerve. *J Exp Psychol.* 1930;11:373-387.
10. Jones RC, Stevens SS, Lurie MH. Three mechanisms of hearing by electrical stimulation. *J Acoust Soc Am.* 1940;12(2):281-290.
11. Gisselson L. Evidence favouring a possible humoral transmission in the inner ear. *Acta Otolaryngol.* 1950;38(suppl 82):9-23.
12. Djourno A, Eyries C, Vallancien B. De l'excitation électrique du nerf cochléaire chez l'homme, par induction à distance, à l'aide d'un micro-bobinage inclus à demeure. *C R Seances Soc Biol Fil.* 1957;151:423-425.
13. Eisen MD. Djourno, Eyries, and the first implanted electrical neural stimulator to restore hearing. *Otol Neurotol.* 2003;24(3):500-506.
14. Djourno A, Eyries C. Prothèse auditive par excitation électrique à distance du nerf sensoriel à l'aide d'un bobinage inclus à demeure. *Presse Médicale.* 1957;65(63):1417.
15. House LR. Cochlear implant: the beginning. *Laryngoscope.* 1987;97(8, pt 1):996-997.
16. House WF. Cochlear implants. *Ann Otol Rhinol Laryngol.* 1976;85(3, pt 2)(suppl 27):1-93.
17. House WF. Goals of the cochlear implant. *Laryngoscope.* 1974;84(11):1883-1887.
18. House W. *The Struggles of a Medical Innovator: Cochlear Implants and Other Ear Surgeries.* Lexington, KY: CreateSpace; 2011.
19. Hillaby J. Electrical ears restore hearing. *New York Times.* Aug 3, 1958:29.
20. Artificial hearing aids. *JAMA.* 1959;171(7):1024.
21. Seitz P. Interview with John and Jim Doyle, August 22, 1993. 612-OH-9. Coch-

lear implants, 1961-1965 Collection. Located at: John Q. Adams Center for the History of Otolaryngology–Head and Neck Surgery, Alexandria, VA.
22. House WF, Urban J. Long term results of electrode implantation and electronic stimulation of the cochlea in man. *Ann Otol Rhinol Laryngol*. 1973;82(4):504-517.
23. Hyman S. *For the World to Hear: A Biography of Howard P. House.* Pasadena, CA: Hope; 1990.
24. Scientific program (Los Angeles Clinical Meeting). *JAMA*. 1962;182(4):471-481.
25. Doyle JB Jr, Doyle JH, Turnbull FM, Abbey J, House L. Electrical stimuation in eighth nerve deafness: a preliminary report. *Bull Los Angel Neuro Soc*. 1963; 28:148-150.
26. Doyle JH, Doyle JB Jr, Turnbull FM Jr. Electrical stimulation of eighth cranial nerve. *Arch Otolaryngol*. 1964;80:388-391.
27. Zoellner F, Keidel WD. Gehörvermittlung durch electrische Erregung des Nervus acusticus. *Arch Ohren Nasen Kehlkopfheilkd*. 1963;181:216-223.
28. Simmons FB, Mongeon CJ, Lewis WR, Huntington DA. Electrical stimulation of acoustic nerve and inferior colliculus. *Arch Otolaryngol*. 1964;79:559-568.
29. Simmons FB. Electrical stimulation of the auditory nerve in man. *Arch Otolaryngol*. 1966;84(1):2-54.
30. Simmons FB, Epley JM, Lummis RC, et al. Auditory nerve: electrical stimulation in man. *Science*. 1965;148(3666):104-106.
31. Simmons FB. Cochlear implants. *Arch Otolaryngol*. 1969;89(1):61-69.
32. Simmons FB, Glattke TJ. Comparison of electrical and acoustical stimulation of the cat ear. *Ann Otol Rhinol Laryngol*. 1972;81(5):731-737.
33. Johnson RE. Cochlear implant: a decade of progress. *Oto Review*. 1972;5(1): 3-5.
34. House W. A personal perspective on cochlear implants. In: Schindler RA, Merzenich MM, eds. *Cochlear Implants.* New York, NY: Raven Press; 1985:13-16.
35. Merzenich MM, Michelson RP, Pettit CR, Schindler RA, Reid M. Neural encoding of sound sensation evoked by electrical stimulation of the acoustic nerve. *Ann Otol Rhinol Laryngol*. 1973;82(4):486-503.
36. Michelson RP. Electrical stimulation of the human cochlea: a preliminary report. *Arch Otolaryngol*. 1971;93(3):317-323.
37. Michelson RP. The results of electrical stimulation of the cochlea in human sensory deafness. *Ann Otol Rhinol Laryngol.* 1971;80(6):914-919.
38. Merzenich MM, Schindler RA, Sooy FA. Proceedings of the First International Conference on Electrical Stimulation of the Acoustic Nerve as a Treatment for Profound Sensorineural Deafness in Man. San Francisco, CA: Velo-Bind; 1974.
39. Chouard CH, Mac Leod P. La réhabilitation des surdités totales: essai de l'implantation cochleaire par électrodes multiples. *Nouv Presse Med*. 1973; 2(44):2958.
40. Chouard CH, MacLeod P. Implantation of multiple intracochlear electrodes for rehabilitation of total deafness: preliminary report. *Laryngoscope*. 1976;86 (11):1743-1751.
41. Chouard CH, Mac Leod P, Meyer B, Pialoux P. Appareillage electronique implanté chirurgicalement pour la réhabilitation des surdités totales et des surdi-mutité. *Ann Otolaryngol Chir Cervicofac*. 1977;94(7-8):353-363.
42. Chouard CH. Histoire de l'implant cochléaire. *Ann Otorhinolaryngol Chir Cervicofac*. 2010;127:288-296.
43. Ricard CFF, Chouard C-H, MacLeod P, inventors; Bertin & Cie, assignee. Auditory prosthesis equipment. US patent 4,207,441. June 10, 1980.
44. Clark GM. Hearing due to electrical stimulation of the auditory system. *Med J Aust*. 1969;1(26):1346-1348.
45. Clark GM. Responses of cells in the superior olivary complex of the cat to electrical stimulation of the auditory nerve. *Exp Neurol*. 1969;24(1):124-136.
46. Clark GM. *Middle Ear and Neural Mechanisms in Hearing and in the Management of Deafness* [thesis]. Sydney, NSW, Australia: University of Sydney; 1969.
47. Clark GM. *Sounds from Silence*. St-Leonards, NSW, Australia: Allen & Unwin; 2000.
48. Clark GM. A hearing prosthesis for severe perceptive deafness—experimental studies. *J Laryngol Otol.* 1973;87(10):929-945.
49. Clark GM, Hallworth RJ, Zdanius K. A cochlear implant electrode. *J Laryngol Otol*. 1975;89(8):787-792.
50. Clark GM, Tong YC, Black R, Forster IC, Patrick JF, Dewhurst DJ. A multiple electrode cochlear implant. *J Laryngol Otol*. 1977;91(11):935-945.
51. Clark GM. *Cochlear Implants: Fundamentals and Applications.* New York, NY: Springer; 2003.
52. Epstein J. *The Story of the Bionic Ear*. Melbourne, VIC, Australia: Hyland House; 1989.
53. Clark GM, Pyman BC, Bailey QR. The surgery for multiple-electrode cochlear implantations. *J Laryngol Otol.* 1979;93(3):215-223.
54. Bilger RC, Black FO. Auditory prostheses in perspective. *Ann Otol Rhinol Laryngol*. 1977;86(suppl 38):3-10.
55. Clark GM, Tong YC, Bailey QR, et al. A multiple-electrode cochlear implant. *J Otolaryngol Soc Austral.* 1978;4:208-212.
56. Tong YC, Black RC, Clark GM, et al. A preliminary report on a multiple-channel cochlear implant operation. *J Laryngol Otol*. 1979;93(7):679-695.
57. Tong YC, Clark GM, Seligman PM, Patrick JF. Speech processing for a multiple-electrode cochlear implant hearing prosthesis. *J Acoust Soc Am*. 1980;68(6): 1897-1898.
58. Clark GM, Tong YC, Martin LFA, Busby PA. A multiple-channel cochlear implant: an evaluation using an open-set word test. *Acta Otolaryngol.* 1981;91(3-4): 173-175.
59. Michelson RP, Schindler RA. Multichannel cochlear implant: preliminary results in man. *Laryngoscope*. 1981;91(1):38-42.
60. Simmons B. History of cochlear implants in the United States: a personal perspective. In: Schindler RA, Merzenich MM, eds. *Cochlear Implants.* New York, NY: Raven Press; 1985:1-6.
61. Blume S. *Artificial Ear: Cochlear Implants and the Culture of Deafness.* New Brunswick, NJ: Rutgers University Press; 2010.