

The multichannel cochlear implant for severe-to-profound hearing loss

Graeme M Clark

It is a great and unexpected honor to receive the Lasker~DeBakey Award for Clinical Medical Research. My research team and I consider it a privilege to be able to give hearing and speech understanding to severely or profoundly deaf people.

My interest in helping people with severe hearing loss started as a teenager when I assisted my deaf father at his pharmacy. Customers would ask for confidential items, and he would have to ask them to speak up; thus, all those present would know a customer's needs. When he was in his 90s I asked him what it had been like. He said, "Deafness has been an enormous handicap. It affects your whole life; there's nothing so embarrassing as not being able to hear people properly and having to work" (Fig. 1).

To help severely deaf people, I commenced training in 1962 as an ear surgeon but soon came to realize what little we could do, even with powerful hearing aids. This realization led me to start research on auditory neurophysiology at the University of Sydney in 1967. My aim was to see how well electrical stimulation of the auditory pathways could code environmental sounds and speech.

Back then, a leading scientist had said that "direct stimulation of the auditory nerve fibers with resultant perception of speech is not feasible"¹, and this was because the nerves were too complex. Nevertheless, undeterred, I decided to undertake systematic studies to see how sounds were coded.

Two key features of how sound is represented in the brain are temporal coding and place coding (Fig. 2). Temporal coding refers to the fact that brain cells fire in phase with the sound waves. And, in the case of place coding,

the pitch depends on the site of stimulation because the brain centers that respond to sound are arranged tonotopically. It was crucial to incorporate these two features into our attempts to use electrical stimulation to generate sound.

In studying how to reproduce the temporal coding of frequency, I first discovered that the neural responses to electrical stimulation were markedly reduced at 300 Hz, which is much less than the 4,000 Hz needed for speech understanding. Then it became necessary to see how the animal as a whole responded and not just groups of cells in the brain stem. The behavioral studies in the cat confirmed the physiological findings that there was an electro-neural 'bottleneck' at the interface between electrodes and the brain².

In addition, our research showed that the animal could discriminate low rates of stimulation for electrodes in the apical, or low-frequency, region of the cochlea, as well as in the basal, or high-frequency, region. This indicated that temporal and place coding occurred along separate processing channels.

After my initial research, I came to the conclusion that "if pure tone reproduction is not perfect, meaningful speech may still be perceived if it can be analyzed into its important components, and these used for electrical stimulation. More work is required to decide which signals are of the greatest importance in speech perception"³. I am grateful to the University of Melbourne for appointing me as the Chair of Otolaryngology in 1970, thus enabling me to continue this research (Fig. 3).

During the course of our studies, we discovered (i) that it would be necessary to transmit the coded signals through the intact skin by radio waves in order to avoid the risk of infection³, (ii) that electrical currents could be localized to groups of neurons with appropriate electrode placement and current flow³⁻⁶ and (iii) that intra-cochlear electrodes could be



Figure 1 Graeme Clark with his father, Colin, at age 90.

placed opposite the ganglion cells transmitting the mid to low speech frequencies³⁻⁶. In addition, passing electrodes into the cochlea also represented a safety issue. Surgeons had said that the inner ear was inviolable and should not be operated on. The main issues were that surgical trauma and the electrical stimuli could damage the very nerves we hoped to excite and that infection could enter into the inner ear from the middle ear and lead to meningitis. We addressed these concerns systematically in the experimental cat and rat and temporal bone laboratory^{3,5,7,8}.

While working to resolve the biological issues, we developed the multichannel implant so that we could study speech coding in patients. The engineering was undertaken primarily in the Department of Otolaryngology in collaboration with the University of Melbourne's Department of Electrical Engineering³ (Fig. 4a). Two deaf people came forward of their own volition to allow us to test the implants. When I selected the first patient (Fig. 4b), he said, "I would like to be able to hear again; it's a nightmare being deaf. If it helps with speech, I will be very grateful."

We implanted the multichannel receiver-stimulator on 1 August 1978 (Fig. 4c). When the patient recovered, my first aim was to find

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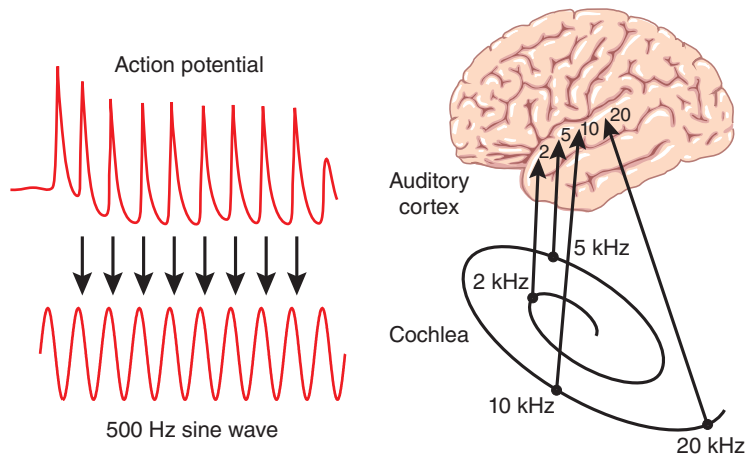


Figure 2 Temporal and place coding of sound. In temporal coding, neurons fire action potentials in phase with the sound waves (left). Place coding (right) refers to the perception of pitch depending on the site of stimulation. This is possible because the brain centers that respond to sound are arranged tonotopically—cells located at different sites along the auditory system respond to different sound frequencies in a highly organized fashion that is projected in an identical pattern through the pathway, from the cochlea to the cerebral cortex.

out what sensations he experienced with electrical stimulation. Were they like the sounds he had known before? And did temporal and place coding occur as predicted from acoustic neurophysiology? The four basic areas of psychophysics we explored were melody, rate and place pitch, timbre (the quality of a sound that distinguishes two musical instruments playing the same note) and loudness.

To test melody, we first presented Australia's unofficial national anthem, "Waltzing Matilda," which the patient recognized immediately. But key questions were how well he could perceive pitch and whether pitch was conveyed by place as well as by frequency of stimulation. We discovered that rate of stimulation was perceived as a true pitch sensation, but pitch only increased with rates up to ~300 Hz for all electrodes, reaching then a plateau (**Fig. 5a**). This helped establish that the neural response rate is an important code for low frequencies, which could not be determined with acoustic stimulation alone as this affects the rate and site of stimulation together.

For different places of stimulation along the cochlea, the patient also experienced different pitch sensations, and they increased from low- to high-frequency electrodes. The perceptions of pitch for rate and place of stimulation influenced each other, suggesting that the brain has a 'pitch perception processor' for temporal and place pitch⁹. Both pitch and timbre were perceived depending on the place of stimulation. In the low-frequency area it was described as dull and in the high-frequency region as sharp. We also found that timbre could be scaled according to the place-frequency response from low- to high-frequency electrodes, and this allowed us to

select the correct electrode to stimulate for an effective speech code¹⁰.

In trying to develop a way to code speech, my first aim was to model the physiology of the auditory nervous system^{3–5}. But, overall, speech understanding was very limited because the electrical fields around each electrode overlapped, and it was difficult to predict loudness with simultaneous stimulation. So, we reverted to our alternative idea of analyzing the most important components for speech understanding and maximizing their transmission through the electro-neural bottleneck³.

Selecting the right information for a speech code emerged by finding that, when we stimu-

lated different sites in the ear, the patient not only described the sensation as sharp or dull but also referred to it as a vowel sound (**Fig. 5b**). This gave us an important clue on how to develop a speech-processing strategy that would be effective in his daily life.

Our research thus aimed at using electrical stimulation to reproduce the basic neural-response patterns crucial for understanding speech. Formants, for example, are concentrations of frequency energy that are important for speech intelligibility. F_0 would be the fundamental or voicing frequency. In the case shown in **Figure 5c**, for the word 'wit', the first (F_1), second (F_2) and third (F_3) formants are shown as the continuous line, and the electrical pulses for the speech-coding strategy are the vertical bars. As F_2 is the most critical cue for consonants, it was the only one we coded with the initial strategy. For the /w/ sound, there is a rising F_2 . So, the site of stimulation for place coding shifted upward to higher-frequency regions in the cochlea. The vowel /i/ is steady and voiced. Therefore, the vertical bars do not change in position and are proportional to the voicing frequency. Finally, the noise in /t/ had random sound frequencies, and they were presented as a place code.

To ensure this strategy was effective, there were still some questions to answer: Would the F_0/F_2 formant coding strategy benefit other English speakers and people who spoke other languages, or had we hit upon some particular code that suited this one person only? Would the memory for speech sounds be retained by people who had been deaf for many years?

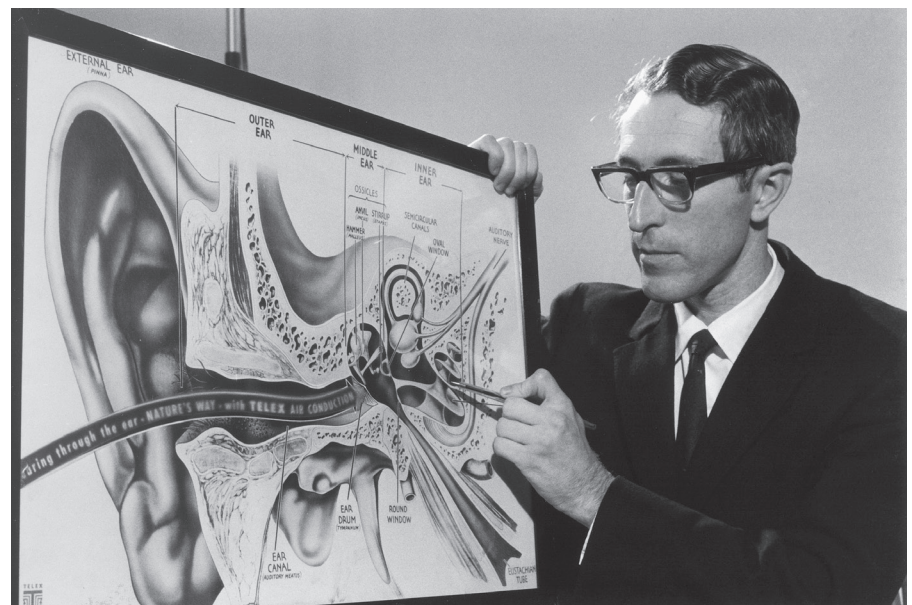


Figure 3 Graeme Clark, with a diagram of the cochlea, explaining his proposed research when appointed in 1970 as the University of Melbourne's first William Gibson Chair of Otolaryngology, situated at the Royal Victorian Eye & Ear Hospital.



Figure 4 Early implants. (a) Jim Patrick and Ian Forster with the silicon chip design for the first multichannel implant developed in the Department of Otolaryngology, University of Melbourne, 1977. (b) Communicating with Rodney Saunders—Graeme Clark's first patient—in 1978. (c) The completion of the first multichannel implant operation at the Royal Victorian Eye & Ear Hospital by the leaders of the University of Melbourne's surgical team, Graeme Clark and Brian Pyman, with the receiver-stimulator placed in its bed.

To help answer these questions, in 1979 I operated on my second patient (**Fig. 6a**), who had been deaf for 17 years. The fact that the stimuli immediately sounded like the speech he remembered was very significant. It showed not only that other people could benefit by using our approach but also that the neural connections could remain functional after prolonged lack of exposure to sound.

With funding from the Australian government, and the creation of the biomedical firm Cochlear Pty. Ltd., our speech code was implemented for a world clinical trial through a partnership between our university and the industry. The trial was first managed through the University of Melbourne's cochlear implant clinic at the Eye & Ear Hospital and then with international clinics. The trial established that Cochlear had successfully implemented the university's speech code. In 1985, ours was the first multichannel implant (**Fig. 6b**)

to be approved by the US Food and Drug Administration (FDA) for postlingually deaf adults.

While participating in this trial, we undertook a series of perceptual studies to see how the more complex stimuli underpinning speech could be perceived. In the course of these studies, we discovered that voiced sounds were coded as rate of electrical stimulation and that place of stimulation was best for the frequency glides in consonants^{10–12}. Our psychophysical studies^{3–5} and acoustic modeling of electrical stimulation¹³ have all been important in refining speech coding over more than 20 years. Now, severely to profoundly deaf people can understand speech as well as or better than a severely deaf person who uses a hearing aid^{3,5}.

As speech perception was achieved with a monaural cochlear implant speech code, I decided to see if the benefits of two ears (or binaural hearing), could improve hearing,

especially in noisy conditions. This required either bilateral implants or bimodal hearing; that is, an implant in one ear and a hearing aid in the other. In 1989, I operated on our first deaf person to receive bilateral implants (**Fig. 6c**), and the procedure helped the patient localize sound and hear speech in noise¹⁴. Then, in 1990, an adult patient was the first person to have bimodal hearing, and, in 1991, we operated on the first child to receive bilateral implants.

The speech codes I have described were discovered for deaf people who had lost hearing after their brain connections had been optimized by exposure to speech sounds. The next challenge was to determine whether young deaf children could use these codes before their brain pathways had been exposed to sound and matured. The first three young children to receive the multichannel cochlear implant were 14, 10 and 5 years old (**Fig. 6d**).

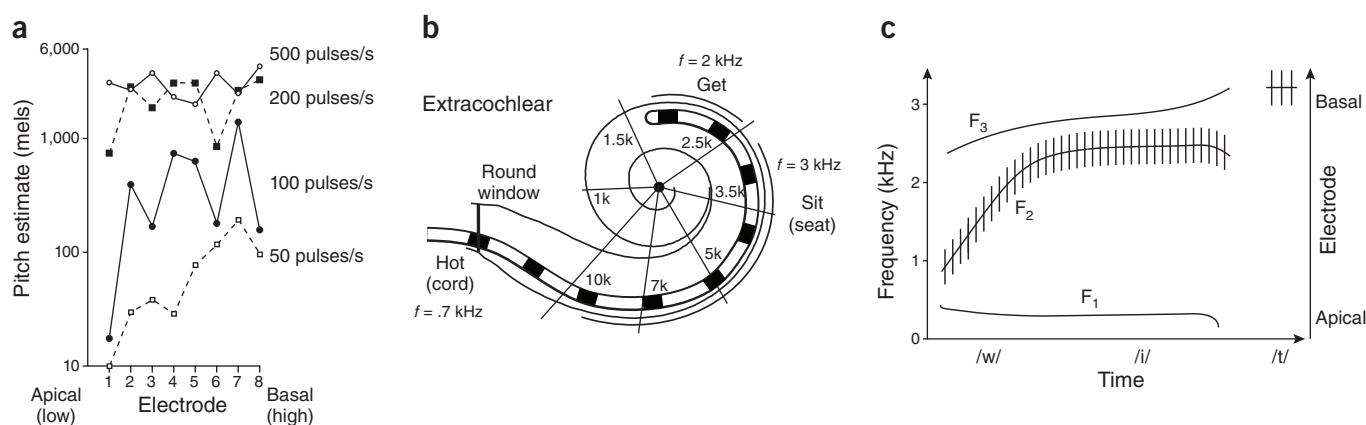


Figure 5 Psychophysical studies in the first patient. (a) Pitch versus rate and place of stimulation. The pitch increased from 50 pulses/s to 200 pulses/s and then reached a plateau. It also increased with place of stimulation from apical (#1) to basal (#8) electrodes. (b) Timbre and place of stimulation related to the vowels' second formant (F_2). The vowels like /e/ and /i/ originated from high-frequency regions, were perceived as sharp and had high second formants. Vowels like /o/ originated from low-frequency regions around the outside of the auditory nerve due to extra-cochlear current spread, were dull and had low second formants. (c) The speech feature/formant (F_0/F_2)-based speech code. For the word /wit/ the first (F_1), second (F_2) and third (F_3) formants over time are the continuous lines. Our successful inaugural feature extraction speech code is illustrated by the vertical bars that are the electrical pulses. The F_2 was extracted as it conveys most intelligibility. For /w/, as the F_2 increases in frequency, the site of stimulation moves upward; for the vowel /i/ it is steady; and for /t/ it stimulates a high-frequency site. The pulse rate is proportional to the voicing frequency, and for the noise in /t/ it is random.

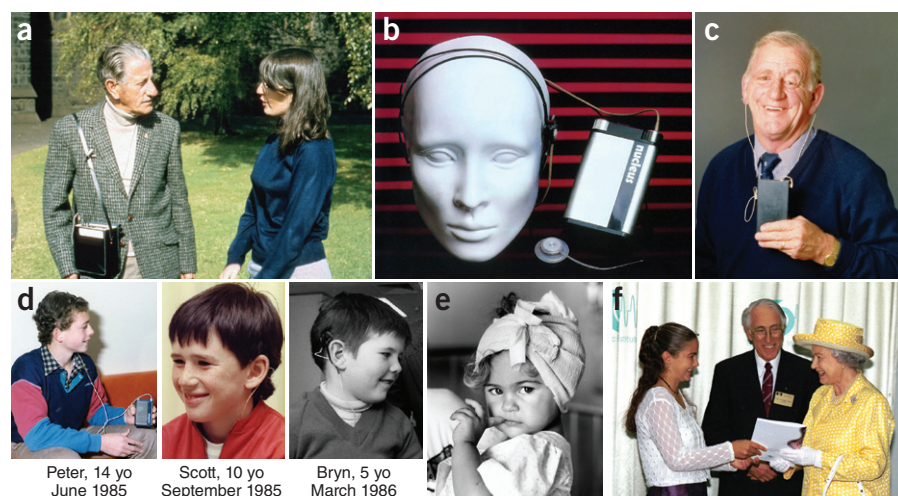


Figure 6 Other important milestones. (a) Graeme Clark's second patient, George Watson, wearing a speech processor and speaking with senior audiologist Lois Martin, 1979. (b) First Nucleus (Cochlear Ltd.) multichannel cochlear implant for clinical trial, 1982. (c) Peter Stewart, the first adult to have a bilateral cochlear implant. (d) The first children to receive the multichannel cochlear implant. (e) Sian Neame, our first young child with the implant, in 1990 at 2.5 years old. (f) Sian meeting Her Majesty Queen Elizabeth II in 2000 during a visit to the Bionic Ear Institute at the University of Melbourne.

The first two were operated on in 1985 and the third in 1986 (ref. 15). In 1990, the FDA announced that the 22-channel cochlear implant was safe and effective for deaf children 2–17 years old in understanding speech both with and without lip reading. It was the first cochlear implant to be approved for deaf children by any world regulatory body and the first major advance in helping deaf children communicate since Sign Language of the Deaf was developed 250 years ago at the Paris Deaf School.

After this announcement I began to operate on young children to achieve better speech and spoken language. The first (Fig. 6e) was just 2.5 years old when she had her implant. At 13 years old, her spoken language was at normal levels when she met Her Majesty Queen Elizabeth II in 2000 (Fig. 6f). Then, in 2007, she decided to have a second implant in her previously unoperated ear (thus receiving bilateral implants), and these are some of her comments: “At second switch on I burst into tears of joy because I had never heard sounds

through this ear; on the first day I was able to recognize voices; one of the most miraculous outcomes is that I am aware of the direction of sounds; this has been the best decision of my life.”

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COMPETING FINANCIAL INTERESTS

The author declares no competing financial interests.

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