Toward better representations of sound with cochlear implants

Blake S Wilson

"From a physiological point of view, cochlear implants will not work."

This statement by Professor Rainer Klinke in 1978 was not the first criticism of efforts to develop a treatment for deafness using electrical stimulation of the auditory nerve. Klinke was accompanied and preceded by a chorus of experts in otology and hearing science who proclaimed that such an idea was a fool's dream. The cochlea, with its exquisite mechanical machinery, its complex arrangement of more than 15,000 sensory hair cells, and its 30,000 neurons, could not possibly be replaced by a crude and undifferentiated stimulation of many neurons *en masse*. The argument was a good one. However, the pioneers in the field persevered in the face of the vociferous criticism. Foremost among these pioneers was William F. House, who developed with Jack Urban the first cochlear implant system that could be safely applied over a patient's lifetime and that generally provided an awareness of environmental sounds and an aid to lipreading[1]. This achievement was a huge step forward.

The House system and other early systems used a single channel of processing to transform sound sensed by a microphone into patterns of electrical stimulation, as well as a single site of stimulation in or on the cochlea. Many or most surviving neurons were stimulated synchronously and in more or less the same way with the single site of stimulation. Only temporal information could be conveyed with these early implants, but it was enough to provide the aforementioned benefits, and it was sufficient in other single-site systems to support some speech recognition for some patients, most notably in the early systems developed by Ingeborg and Erwin Hochmair.

Some of the early developers believed that temporal information was paramount for auditory perception, but other early developers believed that representation of different frequencies with different sites of stimulation in the cochlea was also important, if not the dominant or even the sole code for frequencies. These latter persons included, but were not limited to, Graeme Clark, Donald Eddington, and Michael Merzenich, as well as their respective teams[2].

My entry into the field

I was trained initially as an electrical engineer but became interested in hearing research first through my solo project to recreate the perception of three-dimensional hearing from the two tracks of information in a stereo long-play (LP) record. I learned aspects of auditory psychophysics in the project and was fascinated by the intricacies of hearing.

I later became keenly aware of the problems of deafness and severe hearing losses through another project, which aimed to provide supplementary information for deaf persons automatically and in real time to disambiguate the challenges of lipreading. This project involved analyzing speech with a small computer and relaying the output of the speech analysis to a set of light-emitting diode (LED) displays mounted on the stems of eyeglasses, such that the LED displays projected virtual images that the user could see to either side of the lips of a person speaking to her or him. This second project was directed by Robert L. Beadles and was conducted at the Research Triangle Institute (RTI) in the Research Triangle Park in North Carolina, USA, where I also was employed. I assisted Bob in the project from 1974 through much of 1978.

Figure 1 The RTI team in 1986. From left to right are Charles Finley, Blake Wilson and Dewey Lawson.

In 1977 I applied for and won an RTI professional development award to visit three of the four centers in the United States that were then active in the development and first applications of cochlear implants. I wanted to learn more about what these centers were doing and whether I could be helpful in any of their ongoing efforts, such as in the area of speech analysis.

I visited Bill House and members of his team in Los Angeles; Blair Simmons, Robert White, and other members of the team at Stanford University; and Mike Merzenich and his team at the University of California at San Francisco (UCSF). The visits were in 1978, the same year Professor Klinke made the statement I quoted above. After my visit to UCSF, Mike asked me to be a consultant for the project there. I happily agreed, and that was the beginning of my direct involvement in the field of cochlear implants.

'Speech processors' projects

A few years later, in 1983, I won the first in a series of seven contiguous projects to develop cochlear implants, with an emphasis on design and evaluation of novel processing strategies for implants. These projects were supported

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through the Neural Prosthesis Program at the US National Institutes of Health (NIH), and they spanned 23 years. Advances we made in these projects are among the advances being honored by the 2013 Lasker~DeBakey Clinical Medical Research Award.

Our first studies with implant patients were conducted at UCSF. Mike Merzenich and many others there were our gracious hosts, and they all helped us mightily in getting started.

In late 1984, I received a call from Joseph C. Farmer Jr., who was an otologic surgeon at Duke. Joe mentioned that he had heard about our work at UCSF and wondered whether we might want to work a little closer to home, at Duke University, less than ten miles from the RTI. Of course, I thought Joe's idea was wonderful and welcomed it, so long as we could continue our partnership with UCSF, which we did for many years. We built a laboratory at Duke in 1985 and conducted most of our patient studies there for the next ten years, at which point we built two new laboratories at the RTI, one for speech-reception studies and the other for evoked-potential studies. We made a transition to the RTI laboratories over the next two years and all subsequent studies were conducted at the RTI.

Joe, I and others also founded the Cochlear Implant Program at Duke in 1985, which was one of the first such programs in the US. The first two implants in the program were experimental devices provided by UCSF. The implant recipients who were fit with these devices were studied intensively in the Duke laboratory and in close cooperation with investigators at UCSF.

A comprehensive description of the seven NIH projects—and the studies in the UCSF, Duke and RTI laboratories—is presented in a recent book[3].

Figure 2 Members of the RTI team in 2001, along with a research subject and his wife. From left to right are Jeannie Cox, Stefan Brill, Reinhold Schatzer, Denis Fitzgerald (the research subject), Heather Fitzgerald (Denis's wife), Robert Wolford, Dewey Lawson and Blake Wilson. Not shown is team member Lianne Cartee. The Fitzgeralds visited the RTI laboratories from their home in St. Asaph, Wales, UK.

Composition of the teams

The projects started small, but they grew in scope and size across the years. By the fall of 1984 we had a core team of three investigators (**Fig. 1**) and a part-time administrative assistant. In late 1990 the core team included four investigators and a full time administrative assistant, and by 1996 the number of investigators had grown to five and then in 2000 to six. The team in 2001 along with two visitors is shown in **Figure 2**, and the changing composition of the teams over the years is depicted on page 7 in ref. 3.

Although our focus was on the development of better processing strategies for implants, the work also included tool building and many other areas of research that are listed on pages 16 and 17 in ref. 3. A hallmark of the projects was joint efforts with many investigators worldwide. These partnerships greatly extended the reach of our core teams.

Continuous interleaved sampling

We developed and tested many processing strategies during the projects, and many of the strategies are in widespread clinical use today. However, one strategy towers above the rest in terms of the improvement in performance over its predecessors and in terms of impact. That strategy is the continuous interleaved sampling (CIS) strategy, invented in 1989 and tested with an initial set of cochlear implant patients in 1989 and 1990. The results from those studies were published in *Nature* in 1991 (ref. 4). This publication became the most highly cited publication in the specific field of cochlear implants at the end of 1999 and has remained so ever since.

By 1989, groups in Australia, Europe and the US had developed multielectrode arrays that could be safely inserted into the scala tympani of the cochlea and that could excite different sectors (or tonotopic regions) of the auditory nerve, depending on which intracochlear electrode or which closely spaced pair of intracochlear electrodes was activated. Thus, stimulation of an electrode near the basal end of the cochlea would elicit a high-pitched percept, stimulation at the other end of the cochlea would elicit a low-pitched percept, and stimulation at intermediate positions would elicit intermediate pitches.

The status of the field at that time is accurately expressed in the conclusions from the first NIH Consensus Development Conference on Cochlear Implants, which was convened in 1988. Two of these conclusions were that multisite systems were more likely to be effective than single-site systems, and that "about 1 in 20 patients could carry out a normal conversation without lipreading," using the best of the multisite systems[5]. The introduction of the multisite systems was another great step forward for cochlear implants, but even moderate levels of speech recognition using the restored hearing alone were still rare.

CIS was a breakthrough in sound processing that used the multiple sites far better than before, and thereby enabled high levels of speech recognition for the great majority of cochlear implant users. Unlike some prior strategies (including strategies we developed), this new strategy did not make any assumptions about how speech is produced or perceived, or about what might be important in the input. That is, the new strategy did not extract and then represent any specific features in the input, such as the fundamental frequency of voiced speech sounds, the periodicity or aperiodicity of inputs, or an inferred resonance frequency of the vocal tract in producing a speech sound. Instead, the strategy was designed to reproduce as many aspects of the input as possible, and then to allow the user's brain to decide what was (or was not)

Figure 3 The payoff: what the intervention and associated technology can do for deaf and severely hearing-impaired persons. A user of a cochlear implant is conversing with the author. The joy in the exchange is obvious, and she clearly is not having any difficulty in understanding me even though she is not looking at my lip movements and the conversation included many different and unpredictable topics. The cochlear implant user is Lilo Baumgartner from Vienna, Austria; the photo was taken at an outside location near our RTI laboratories in September 2003.

important in the input. This design decision proved to be crucial, as considerable information that could be perceived was discarded in the previous approaches, and the accuracy of feature extraction was very poor in typical acoustic environments with noise, reverberation and multiple talkers, even when using the most advanced signal processing techniques of the time.

In addition, unlike some other previous strategies, the new strategy did not stimulate the multiple electrodes in the implant simultaneously but instead sequenced brief stimulus pulses from one electrode to the next until all of the used electrodes had been stimulated. This pattern of stimulation across electrodes was repeated continuously, and each such 'stimulus frame' presented updated information. This decision also proved to be crucial, in that the simultaneous stimulation produced spurious interactions ('cross talk') among the electrodes and thereby greatly degraded the perception of the 'place of stimulation' (frequency-based) cues.

A further departure from the past was that, for pulsatile processors, the rate of stimulation was very much higher than had been used previously. The high rates allowed a fine-grained representation of temporal information at each of the used electrodes; thus, both place information and temporal information were represented with CIS, up to or near the limits of perception for both codes.

Many additional aspects and features of CIS are listed on page 10 in ref. 3, and details about the design are presented elsewhere in the same book and in refs. 2 and 4. In broad terms, CIS combined the best elements from disparate prior strategies and added some new elements as well. The combination produced unprecedented levels of speech recognition with cochlear implants. After this and other advances, the NIH convened another conference in 1995, the Consensus Development Conference on Cochlear Implants in Adults and Children[6]. A principal conclusion from that conference was that "A majority of those individuals with the latest speech processors for their implants will score above 80 percent correct on high-context sentences, even without visual cues."[6]

The introduction of CIS into widespread clinical use in the early 1990s was soon followed by exponential growth in the number of implant recipients, which persists to this day. CIS is still used and is the basis for many of the strategies developed subsequently, which also no doubt helped to fuel the growth in implant numbers. Even today, CIS remains the standard against which other promising strategies are compared.

In retrospect, those of us who designed implant systems had to 'get out of the way' and allow the brain to do its work. Once given a relatively clear and unfiltered input, the brain could do the rest.

From speech to sound processors

At the beginning of our work, we were delighted when a research subject could recognize, with hearing alone, even short fragments of ongoing speech or more than two or three single-syllable words in a list of 50. The sole emphasis of our group and others was to convey more information about speech. We designers did not think about other sounds.

Happily, those early days are history and today many patients score at or near 100% correct in recognizing sentences and above 80% correct in recognizing single-syllable words, with the speech items presented in quiet and using the restored hearing alone. In fact, we are now at the point at which investigators are calling for more difficult tests because the standard audiological tests are no longer sufficiently sensitive to detect differences among implant systems, patients or processing strategies, at least for the top-performing patients[7]. Such a lack of sensitivity (due to ceiling effects) is a happy problem to have.

With these great advances in prosthesis design and performance, the emphasis has shifted to music reception and to recognition of speech in especially adverse acoustic environments, such as noisy restaurants or workplaces. We now think in terms of sound processors rather than speech processors. The present goal is to represent sound as faithfully as possible so that the brain will have access to the greatest possible amount of information, and not just to speech information or features abstracted from speech. This shift in emphasis is a sign of the progress that has been made.

A lucky engineer

Ronald Vale wrote a wonderful essay[8] for last year's special issue of *Nature Medicine* celebrating the Lasker Awards. The title of his essay was: 'How lucky can one be? A perspective from a young scientist at the right place at the right time.' The essay resonated with me, as I experienced many of the same feelings and learned some of the same lessons Ron so eloquently described. I would only substitute the word 'engineer' for the word 'scientist' to describe my own experience. I had the great fortune to work on a problem that so adversely affected millions of people, and to do that work in the company of spectacular colleagues.

A few further lessons learned along the way

Further lessons I learned that pertain more directly to the development of neural prostheses are:

- Persevere: the experts are not always correct.

• Try not to make assumptions about what the brain might need for optimal perception.

• Know that a surprisingly sparse representation may be adequate for a substantial restoration of function with neural prostheses.

• However, also know that a threshold of quality and quantity of information probably needs to be exceeded before the brain can do its work or at least work effectively.

• Respect the brain for its enormous capabilities and work to forge a good partnership between the brain and the prosthesis.

• Evaluate many ideas, because only a tiny fraction may emerge as good ones in practice; as Alfred Nobel famously said, "If I have 300 ideas in a year and just one turns out to work I am satisfied."

• Multidisciplinary teams are needed to create successful neural prostheses.

Concluding remarks

Even though I have been working in the field of cochlear implants for well over 30 years, I am as excited as ever about the possibilities for the future[2,9,10]. The work has been one incredible ride and among the great adventures of my life. The best parts have been the interactions with patients (**Fig. 3**) and seeing them flourish with their restored hearing.

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COMPETING FINANCIAL INTERESTS

The author declares no competing financial interests.

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