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Review

Getting a decent (but sparse) signal to the brain for users of cochlear implants

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ABSTRACT

The challenge in getting a decent signal to the brain for users of cochlear implants (CIs) is described. A breakthrough occurred in 1989 that later enabled most users to understand conversational speech with their restored hearing alone. Subsequent developments included stimulation in addition to that provided with a unilateral CI, either with electrical stimulation on both sides or with acoustic stimulation in combination with a unilateral CI, the latter for persons with residual hearing at low frequencies in either or both ears. Both types of adjunctive stimulation produced further improvements in performance for substantial fractions of patients. Today, the CI and related hearing prostheses are the standard of care for profoundly deaf persons and ever-increasing indications are now allowing persons with less severe losses to benefit from these marvelous technologies. The steps in achieving the present levels of performance are traced, and some possibilities for further improvements are mentioned.

This article is part of a Special Issue entitled <Lasker Award>.

1. Introduction

This paper describes the surprising finding that a decidedly sparse and unnatural input at the auditory periphery can support a remarkable restoration of hearing function. In retrospect, the finding is a testament to the brain and its ability over time to utilize such an input. However, this is not to say that any input will do, as different representations at the periphery can produce different outcomes. The paper traces the steps that led up to the present-day cochlear implants (CIs) and the representations that are most effective. In addition, some remaining problems with CIs and possibilities for addressing those problems are mentioned. Portions of the paper are based on recent speeches by me and my essay (Wilson, 2013) in the special issue of *Nature Medicine* celebrating the 2013 Lasker Awards. The speeches are listed in the Acknowledgments section.

2. Five large steps forward

Today, most users of CIs can communicate in everyday listening situations by speaking and using their restored hearing in the absence of any visual cues. For example, telephone conversations are routine for most users. That ability is a long trip indeed from total or nearly-total deafness.

In my view, five large steps forward led to the modern CI: (1) proof-of-concept demonstrations that electrical stimulation of the auditory nerve in deaf patients could elicit potentially useful auditory sensations; (2) development of devices that were safe and

Abbreviations: AzBio, Arizona Biomedical Institute (as in the AzBio sentences); CA, compressed analog; CI, cochlear implant; CID, Central Institute for the Deaf (as in the CID sentences); CIS, continuous interleaved sampling; CNC, consonant–nucleus–consonant (as in the CNC words); CUNY, City University of New York (as in the CUNY sentences); EAS, electric and acoustic stimulation (as in combined EAS); F0, fundamental frequency; F1, first formant frequency; F2, second formant frequency; HINT, Hearing in Noise Test (as in the HIHT sentences); IP, interleaved pulses (as in the IP strategies); NIH, United States' National Institutes of Health; NU-6, Northwestern University Auditory Test 6 (as in the NU-6 words); Nuc/Han, Nucleus/Hannover; Nuc/USA, Nucleus/USA; SEM, standard error of the mean; SPIN, Speech Perception in Noise (as in the SPIN sentences); UCSF, University of California at San Francisco

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could function reliably for many years in the hostile environment of the body; (3) development of devices that provided multiple and perceptually separable sites of stimulation in the cochlea; (4) discovery of processing strategies that utilized the multiple sites far better than before; and (5) stimulation in addition to that provided by a unilateral CI, either with bilateral electrical stimulation or with combined electric and acoustic stimulation (EAS), the latter for persons with useful residual hearing in one or both ears. This paper is mainly but not exclusively about steps 4 and 5; more information about the preceding steps is presented in the essays by Professor Graeme M. Clark and by Dr. Ingeborg J. Hochmair in the special issue of *Nature Medicine* (Clark, 2013; Hochmair, 2013), and in Wilson and Dorman (2008a), Zeng et al. (2008), and Mudry and Mills (2013).

I note that, at the beginning, the development of the CI was regarded by many experts as a fool's dream or worse (e.g., as unethical experimentation with human subjects). For example, Professor Rainer Klinke said in 1978 that “From a physiological point of view, cochlear implants will not work.” He was among the chorus of vocal skeptics. Their basic argument was that 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 crude and undifferentiated stimulation of many neurons *en masse*, as would be produced by the early CI systems.

Of course, the naysayers were ultimately proven to be wrong as a result of the perseverance of pioneers in the face of vociferous criticism and the later development of CI systems that could stimulate different populations of neurons more or less independently and in effective ways. In addition, no one, including the naysayers, appreciated at the outset the power of the brain to utilize a sparse and distorted input. That ability, in conjunction with a reasonably good representation at the periphery, enables the performance of the present devices.

We as a field and our patients owe the greatest debt of gratitude to the pioneers, and most especially to William F. House, D.D.S., M.D., who was foremost among them. Without his perseverance the development of the CI certainly would have been delayed or perhaps not even started.

A telling quote on the wall of his office before he died is “Everything I did in my life that was worthwhile, I caught hell for” (Stark, 2012). He took most of the arrows but remained standing.

3. Place and temporal codes for frequency

Most of the early CI systems used a single channel of sound processing and a single site of stimulation in or on the cochlea. Those systems could convey temporal information only. However, the information was enough to provide an awareness of environmental sounds and an aid to lipreading (Bilger et al., 1977). And in some cases, some recognition of speech from open sets (lists of previously unknown words or sentences) was achieved (Hochmair-Desoyer et al., 1981; Tyler, 1988a, 1988b).

These “single channel” systems had strong adherents; they believed that much if not all of the frequency information in sounds was represented to the brain in the cadences of neural discharges that were synchronized to the cycles of the sound waveforms for single or multiple frequencies. Indeed, this possible temporal coding of frequencies was the “volley” theory of sound perception (Wever and Bray, 1937), which was one of two leading theories at the time.

The other leading theory was the “place” theory, in which different sites (or places) of stimulation along the helical course (length) of the cochlea would represent different frequencies in the sound input. This theory had its genesis in first the supposition and then the observations that sound vibrations of different frequencies produced maximal responses at different positions along the length of the basilar membrane (von Helmholtz, 1863; von Békésy, 1960).

In one of the most important studies in the development of CIs, F. Blair Simmons, M.D., and his coworkers demonstrated that both codes can represent frequency information to the brain (Simmons et al., 1965; Simmons, 1966). Simmons implanted a deaf-blind volunteer with an array of six electrodes in the modiolus, the axonal part of the auditory nerve. Simulation of each electrode in isolation at a fixed rate of pulse presentations produced a distinct pitch percept that was different from the percepts elicited by stimulation of any of the other electrodes. The different electrodes were inserted to different depths into the modiolus and thus addressed different tonotopic (or cochleotopic) projections of the nerve. The differences in pitch according to the site of stimulation affirmed the place theory.

In addition, stimulation of each electrode at different rates produced different pitches, up to a “pitch saturation limit” that occurred at the rate of approximately 300 pulses/s. For example, presentation of pulses at 100/s produced a relatively low pitch for any of the electrodes, whereas stimulation at 200 pulses/s invariably produced a higher pitch. Further increases in pulse rate could produce further increases in pitch, but increases in rate beyond about 300 pulses/s did not produce further increases in pitch.

The finding that the subject was sensitive to manipulations in rate at any of the single electrodes affirmed the volley theory, but only up to a point, the pitch saturation limit. Results from subsequent studies have shown that the limit can vary among subjects and electrodes within subjects, with some subjects having limits up to or a bit beyond 1 kHz for at least one of their electrodes (Hochmair-Desoyer et al., 1983; Townshend et al., 1987; Zeng, 2002), for placements of electrodes on or within the cochlea. Such abilities are unusual, however, and most subjects studied to date have limits of around 300 pulses/s for pulsatile stimuli and 300 Hz for sinusoidal stimuli.

The results from the studies by Simmons et al. were important not only for the subsequent development of CIs (and especially processing strategies for multisite CIs), but also for auditory neuroscience. The debate about the volley *versus* place theories had been raging for decades, in large part because the two codes are inextricably intertwined in normal hearing, i.e., for a given sinusoidal input the basilar membrane responds maximally at a particular position along its length but also vibrates at the frequency of the sinusoid at that position. Thus, separation of the two variables – volleys of neural discharges and place of maximal excitation – is not straightforward in a normally hearing animal or human subject and definitive experiments to test the theories could not be easily conducted if at all. In contrast, the variables can be separated cleanly in the electrically stimulated auditory system by varying site and rate (or frequency) of stimulation independently. These stimulus controls allowed confirmation of both the place and volley theories and demonstrated the operating range of each code for frequency, at least for electrical stimulation of the auditory nerve. (The ranges may well be different for acoustic stimulation of the normally hearing ear; see, e.g., Moore and Carlyon, 2005. However, the confirmation of both theories was made possible by the unique stimulus controls provided with electrical stimulation.)

4. Status as of the late 1980s

By the late 1980s, steps 1 and 2 had been achieved and step 3 had been largely achieved (Wilson and Dorman, 2008a; Zeng et al., 2008). Both single-site and multisite systems were being applied clinically. Claims and counterclaims about the performances of different devices and about the “single channel” *versus* “multichannel” systems were in full force. The debates prompted the United States' National Institutes of Health (NIH) to convene its first consensus development conference on cochlear implants in 1988