The Remarkable Cochlear Implant and Possibilities for the Next Large Step Forward

Blake S. Wilson

Address:
2410 Wrightwood Avenue
Durham, North Carolina 27705
USA

Also at:
Duke University
Chesterfield Building
701 West Main Street
Room 4122, Suite 410
Durham, North Carolina 27701
USA

Email:
blake.wilson@duke.edu

The modern cochlear implant is an astonishing success; however, room remains for improvement and greater access to this already-marvelous technology.

Introduction

The modern cochlear implant (CI) is a surprising achievement. Many experts in otology and auditory science stated categorically that pervasive and highly synchronous activation of neurons in the auditory nerve with electrical stimuli could not possibly restore useful hearing for deaf or nearly deaf persons. Their argument in essence was "how can one have the hubris to think that the exquisite machinery of the inner ear can be replaced or mimicked with such stimuli?" They had a point!

However, the piece that everyone, or at least most everyone, missed at the beginning and for many years thereafter was the power of the brain to make sense of a sparse and otherwise unnatural input and to make progressively better sense of it over time. In retrospect, the job of designers of CIs was to present just enough information in a clear format at the periphery such that the brain could "take over" and do the rest of the job in perceiving speech and other sounds with adequate accuracy and fidelity. Now we know that the brain is an important part of the prosthesis system, but no one to my knowledge knew that in the early days. The brain "saved us" in producing the wonderful outcomes provided by the present-day CIs.

And indeed, most recipients of those present devices use the telephone routinely, even for conversations with initially unfamiliar persons at the other end and even with unpredictable and changing topics. That is a long trip from total or nearly total deafness!

Now, the CI is widely regarded as one of the great advances in medicine and in engineering. Recently, for example, the development of the modern CI has been recognized by major international awards such as the 2013 Lasker~DeBakey Clinical Medical Research Award and the 2015 Fritz J. and Dolores H. Russ Prize, just to name two among many more.

As of early 2016, more than half a million persons had received a CI on one side or two CIs, with one for each side. That number of recipients exceeds by orders of magnitude the number for any other neural prosthesis (e.g., retinal or vestibular prostheses). Furthermore, the restoration of function with a CI far exceeds the restoration provided by any other neural prosthesis to date.

Of course, the CI is not the first reported substantial restoration of a human sense. The first report, if I am not mistaken, is in the Gospel of Mark in the New Testament (Mark 7:31-37), which describes the restoration of hearing for a deaf man by Jesus. The CI is the first restoration using technology and a medical intervention and is similarly surprising and remarkable.

A Snapshot of the History

The courage of the pioneers made the modern CI possible. They persevered in the face of vociferous criticism, and foremost among them was William F. House, MD, DDS, who with engineer Jack Urban and others developed devices in the late 1960s and early 1970s that could be used by patients in their daily lives outside the laboratory. Additionally, the devices provided an awareness of environmental sounds, were a helpful adjunct to lipreading, and provided limited recognition of speech with the restored hearing alone in rare cases. “Dr. Bill” also developed surgical approaches for placing the CI safely in the cochlea and multiple other surgical innovations, described in his inspiring book (House, 2011). House took most of the arrows from the critics and without his perseverance, the development of the modern CI would have been greatly delayed if not abandoned. He is universally acknowledged as the “Father of Neurotology,” and his towering contributions are lovingly recalled by Laurie S. Eisenberg (2015), who worked closely with him beginning in 1976 and for well over a decade thereafter and stayed in touch with him until his death in 2012.

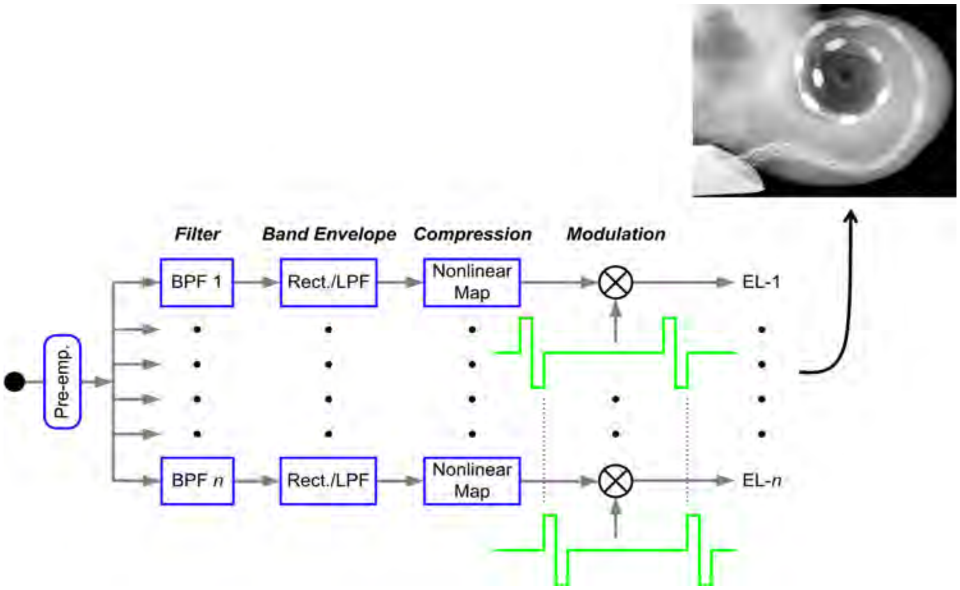

***Figure 1**. Block diagram of the continuous interleaved sampling (CIS) processing strategy for cochlear implants. **Circles with “x,”** multiplier blocks; **green lines,** carrier waveforms. Band envelopes can be derived in multiple ways and only one way is shown. **Inset:** X-ray image of the implanted cochlea showing the electrode array in the scala tympani. Each channel of processing includes a band-pass filter (BPF); an envelope detector, implemented here with a rectifier (Rect.) followed by a low-pass filter (LPF); a nonlinear mapping function, and the multiplier. The output of each channel is directed to intracochlear electrodes, EL-1 through EL-*n, where* n *is the number of channels. The channel inputs are preceded by a high-pass preemphasis filter (Pre-emp.) to attenuate the strong components at low frequencies in speech, music, and other sounds. Block diagram modified from Wilson et al. (1991), with permission; inset from Hüttenbrink et al. (2002), with permission.*

In my view, five large steps forward led to the devices and treatment modalities we have today. Those steps are

(1) proof-of-concept demonstrations that a variety of auditory sensations could be elicited with electrical stimulation of the auditory nerve in deaf persons;

(2) the development of devices that were safe and could function reliably for many years;

(3) the development of devices that could provide multiple sites of stimulation in the cochlea to take advantage of the tonotopic (frequency) organization of the cochlea and ascending auditory pathways in the brain;

(4) the discovery and development of processing strategies that utilized the multiple sites far better than before; and

(5) stimulation in addition to that provided by a unilateral CI, with an additional CI on the opposite side or with acoustic stimulation in conjunction with the unilateral CI.

This list is adapted from a list presented by Wilson (2015). Step 1 was taken by scientist André Djourno and physician Charle Eyriès working together in Paris in 1957 (Seitz, 2002) and step 5 was taken by Christoph von Ilberg in Frankfurt, Joachim Müller in Würzburg, and others in the late 1990s and early 2000s (von Ilberg et al., 1999; Müller et al., 2002; Wilson and Dorman, 2008). Bill House was primarily responsible for step 2, and the first implant operation performed by him was in 1961. Much more information about the history is given by Wilson and Dorman (2008, 2018a), Zeng et al. (2008), and Zeng and Canlon (2015).

A Breakthrough Processing Strategy

Among the five steps, members of the Acoustical Society of America (ASA) may be most interested in step 4, the discovery and development of highly effective processing strategies. A block diagram of the first of those strategies and the progenitor of many of the strategies that followed, is presented in **Figure 1**. The strategy is disarmingly simple and is much simpler than most of its predecessors that included complex analyses of the input sounds to extract and then represent selected features of speech sounds that were judged to be most

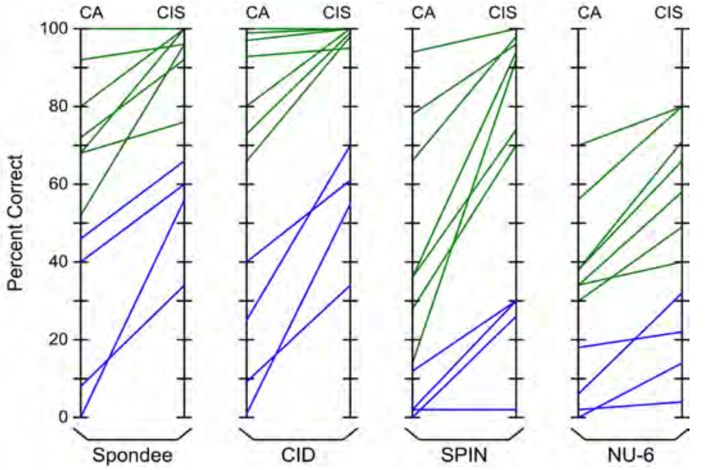

***Figure 2**. Results from initial comparisons of the compressed analog (CA) and CIS processing strategies. **Green lines,** scores for subjects selected for their exceptionally high levels of performance with the CA strategy; **blue lines,** scores for subjects selected for their more typical levels of performance with that strategy. The tests included recognition of two-syllable words (Spondee); the Central Institute for the Deaf (CID) everyday sentences; sentences from the Speech-in-Noise test (SPIN) but here without the added noise; and the Northwestern University list six of monosyllabic words (NU-6). From Wilson and Dorman (2018a), with permission.*

important for recognition. Instead, the depicted strategy, continuous interleaved sampling (CIS; Wilson et al., 1991), makes no assumptions about how speech is produced or perceived and simply strives to represent the input in a way that will utilize most or all of the perceptual ranges of electrically evoked hearing as clearly as possible.

As shown, the strategy includes multiple channels of sound processing whose outputs are directed to the different electrodes in an array of electrodes implanted in the scala tympani (ST), one of three fluid-filled chambers along the length of the cochlea (see X-ray inset in **Figure 1**, which shows an electrode array in the ST). The channels differ only in the frequency range for the band-pass filter. The channel outputs with high center frequencies for the filters are directed to electrodes at the basal end of the cochlea, which is most sensitive to high-frequency sounds in normal hearing (the tonotopic organization mentioned in **A Snapshot of the History**), and the channel outputs with lower center frequencies are directed to electrodes toward the other (apical) end of the cochlea, which in normal hearing is most sensitive to sounds at lower frequencies.

The span of the frequencies across the band-pass filters typically is from 300 Hz or lower to 6 kHz or higher, and the distribution of frequencies is logarithmic, like the distribution of frequency sensitivities along the length of the cochlea in normal hearing. In each channel, the varying energy in the band-pass filter is sensed with an envelope detector, and then the output of the detector is “mapped” onto the narrow dynamic range of electrically evoked hearing (5-20 dB for pulses vs. 90 dB or more for normal hearing) using a logarithmic or power-law transformation. The envelope detector can be as simple as a low-pass filter followed by a rectifier (full wave or half wave) or as complex as the envelope output of a Hilbert Transform. Both are effective. The compressed envelope signal from the nonlinear mapping function modulates a carrier of balanced biphasic pulses for each of the channels to represent the energy variations in the input. Those modulated pulse trains are directed to the intracochlear electrodes as previously described. Implant users are sensitive to both place of stimulation in the cochlea or auditory nerve and the rate or frequency of stimulation at each place (Simmons et al., 1965).

Present-day implants include 12-24 intracochlear electrodes; some users can rank all of their electrodes according to pitch, and most users can rank at least a substantial subset of the electrodes when the electrodes are stimulated separately and one at a time. (Note, however, that no more than eight electrodes may be effective in a multichannel context, at least for ST implants and the current processing strategies; see Wilson and Dorman, 2008.) Also, users typically perceive increases in pitch with increases in the rate or frequency of stimulation, or the frequency of modulation for modulated pulse trains, at each electrode up to about 300 pulses/s or 300 Hz but with no increases in pitch with further increases in rate or frequency (e.g., Zeng, 2002). For that reason, the cutoff of the low-pass filter in each of the processing channels usually is set at 200-400 Hz to include most or all of the range over which different frequencies in the modulation waveforms can be perceived as different pitches. Fortuitously, the 400-Hz choice also includes the full range of the fundamental frequencies in voiced speech for men, women, and children. The pulse rate for each channel is the same across channels and is usually set at four times the cutoff frequencies (which also are uniform across channels) to minimize ambiguities in the perception of the envelope (modulation) signals that can occur at lower rates (Busby et al., 1993; Wilson et al., 1997).

A further aspect of the processing is to address the effects of the highly conductive fluid in the ST (the perilymph) and the relatively distant placements of the intracochlear electrodes from their neural targets (generally thought to be the spiral ganglion cells in the cochlea). The high conductivity and the distance combine to produce broad spreads of the excitation fields from each electrode along the length of the cochlea (length constant of about 10 mm or greater compared with the ~35-mm length of the human cochlea). Also, the fields from each electrode overlap strongly with the fields from other electrodes. The aspect of processing is to present the pulses across channels and their associated electrodes in a sequence rather than simultaneously. The nonsimultaneous or "interleaved" stimulation eliminates direct summation of electric fields from the different electrodes that otherwise would sharply degrade the perceptual independence of the channels and electrodes. CIS gets its name from the continuous (and fixed rate) sampling of the mapped envelope signals by interleaved pulses across the channels.

The overall approach is to utilize the perceptual space fully and to present the information in ways that will preserve the independence of the channels and minimize perceptual distortions as much as possible. Of course, in retrospect, this approach also allowed the brain to work its magic. Once we designers "got out of the way" in presenting a relatively clear and unfettered signal rather than doing anything more or more complicated, the brain could take over and do the rest.

Some of the first results from comparisons of CIS with the best strategy in clinical use at the time are presented in **Figure 2**. Results from four tests are shown and range in difficulty from easy to extremely difficult for speech presented in otherwise quiet conditions. Each subject had had at least one year of daily experience with their clinical device and processing strategy, the Ineraid™ CI and the "compressed analog" (CA) strategy, respectively, but no more than several hours of experience with CIS before the tests. (The CA strategy presented compressed analog signals simultaneously to each of four intracochlear electrodes and is described further in Wilson, 2015.) The ***green lines*** in **Figure 2** show the results for a first set of subjects selected for high performance with the CA strategy (data from Wilson et al., 1991), which was fully representative of the best performances that had been obtained with CIs as of the time of testing. The ***blue lines*** in **Figure 2** show the results for a second set of subjects who were selected for their more typical levels of performance (data from Wilson et al., 1992). The scores for all tests and subjects demonstrated an immediate and highly significant improvement with CIS compared with the alternative strategy.

Not surprisingly, the subjects were thrilled along with us by this outcome. One of the subjects said, for example, "Now you've got it!" and another slapped the table in front of him and said, "Hot damn, I want to take this one home with me!" All three major manufacturers of CIs (which had more than 99% of the market share) implemented CIS in new versions of their products in record times for medical devices after the results from the first set of subjects were published (Wilson et al., 1991), and CIS became available for widespread clinical use within just a few years thereafter. Thus, the subjects got their wish and the CI users who followed them benefitted as well.

Many other strategies were developed after CIS, but most were based on it (Fayad et al., 2008; Zeng and Canlon, 2015; Zeng, 2017). CIS is still used today and remains as the principal "gold standard" against which newer and potentially beneficial strategies are compared. Much more information about CIS and the strategies that followed it is presented in recent reviews (Wilson and Dorman, 2008, 2012; Zeng et al., 2008). Additionally, most of the prior strategies are described in Tyler et al. (1989) and Wilson (2004, 2015).

Performance of Unilateral Cochlear Implants

The performance for speech reception in otherwise quiet conditions is seen in **Figure 3**, which shows results from two large studies conducted approximately 15 years apart. In **Figure 3**, the ***blue circles and lines*** show the results from a study conducted by Helms et al. (1997) in the mid-1990s and the ***green circles and lines*** show the results from tests with patients who were implanted from 2011 to mid-2014 (data courtesy of René Gifford at the Vanderbilt University Medical Center [VUMC]). For both studies, the subjects were postlingually (after the acquisition of language in childhood with normal or nearly normal hearing) deafened adults, and the tests included recognition of sentences and monosyllabic words. The words were comparable in difficulty between the studies, but the low-context Arizona Biomedical (AzBio) sentences used in the VUMC study were more difficult than the high-context Hochmair-Schultz-Moser (HSM) sentences used in the Helms et al. (1997) study. Measures were made at the indicated times after the initial fitting of the device, and the means and standard error of the means (SEMs) of the scores are shown in **Figure 3**. Details about the subjects and tests are presented in Wilson et al. (2016).

The results demonstrate (1) high levels of speech reception for high-context sentences; (2) lower levels for low-context sentences; (3) improvements in the scores for all tests with increasing time out to 3-12 months depending on the test; (4) a complete overlapping of scores at every common test

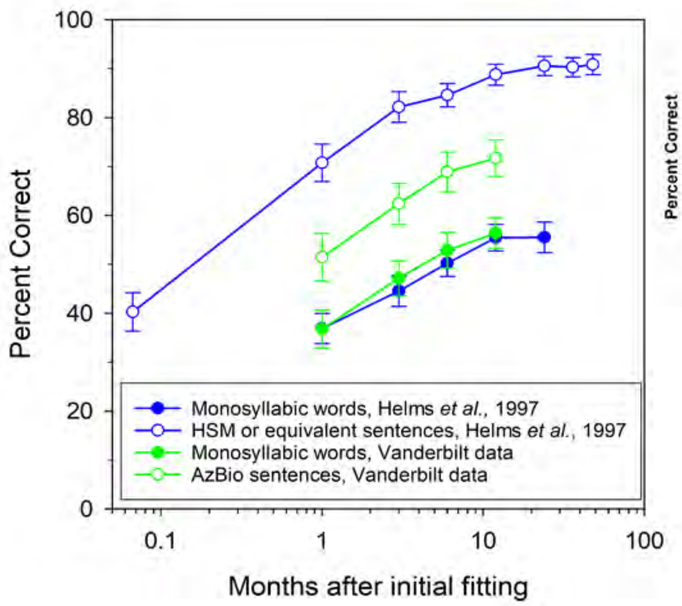

***Figure 3**. Means and SEMs for recognition of monosyllabic words (**solid circles**) and sentences (**open circles**) by implant subjects. The sentences included the AzBio sentences (**green circles and lines**) and the Hochmair-Schultz-Moser (HSM) sentences in German or their equivalents in other languages (**blue circles and lines**). See text for additional details about the tests and sources of data. From Wilson and Dorman (2018b), with permission.*

interval for the two monosyllabic word tests; and (5) lower scores for the word tests than for the sentence tests.

The improvements over time indicate a principal role of the brain in determining outcomes with CIs. In particular, the time course of the improvements is consistent with changes in brain function in adapting to a novel input (Moore and Shannon, 2009) but not consistent with changes at the periphery such as reductions in electrode impedances that occur during the first days, not months, of implant use. The brain makes sense of the input initially and makes progressively better sense of it over time, out to 3-12 months and perhaps even beyond 12 months. (Note that the acute comparisons in **Figure 2** did not capture the improvements over time that might have resulted with substitution of the new processing strategy on a long-term basis; also see Tyler et al., 1986.)

The results from the monosyllabic word tests also indicate that the performance of unilateral CIs has not changed much, if at all, since the early 1990s, when the new processing strategies became available for clinical use (also see Wilson, 2015, for additional data in this regard). These tests are particularly good fiducial markers because the scores for the individual subjects do not encounter ceiling or floor effects for any of the modern CIs and processing strategies tested to date.

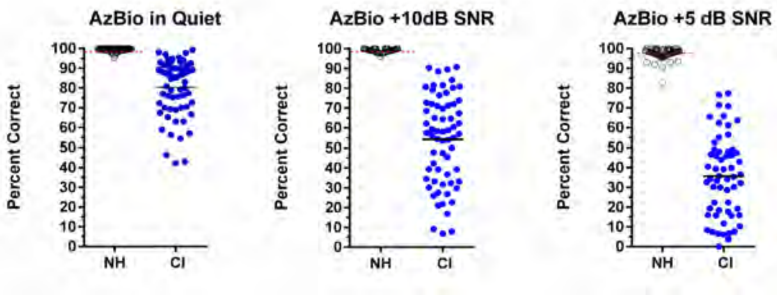

***Figure 4**. Recognition by subjects with normal hearing (NH; **black circles**) and CI (**blue circles**) subjects of AzBio sentences presented in an otherwise quiet condition (**left**) or in competition with environmental noise at the speech-to-noise ratios (SNRs) of +10 dB (**center**) and +5 dB (**right**).Horizontal lines, means of the scores for each test and set of subjects. From Wilson and Dorman (2018b), with permission; data courtesy of Dr. René Gifford.*

An additional aspect of performance with the present-day unilateral CIs is seen in **Figure 4**, which shows the effects of noise interference on performance. These data also are from VUMC and again kindly provided by Dr. Gifford. The subjects include 82 adults with normal hearing (NH) and 60 adult users of unilateral CIs from the same corpus mentioned previously or implanted later at the VUMC. The AzBio sentences were used and were presented in an otherwise quiet condition (**Figure 4**, ***left***) or in competition with environmental noise at the speech-to-noise ratios (SNRs) of +10 (**Figure 4, *center***) and +5 dB (**Figure 4**, ***right***). Scores for the individual subjects are shown along with the mean scores indicated by the horizontal lines.

The scores for the NH subjects are at or near 100% correct for the quiet and +10 dB conditions and above 80% correct for the +5 dB condition. In contrast, scores for the CI subjects are much lower for all conditions and do not overlap the NH scores for the +10 and +5 dB conditions. Thus, the present-day unilateral CIs do not provide NH, especially in adverse acoustic conditions such as the ones shown and such as in typically noisy restaurants or workplaces. However, the CIs do provide highly useful hearing in relatively quiet (and reverberation-free) conditions, as shown by the data in **Figure 4**, ***left***, and by the sentence scores in **Figure 3**.

Adjunctive Stimulation

Although the performance of unilateral CIs has been relatively constant for the past 2+ decades, another way has been found to increase performance and that is to present stimuli in addition to the stimuli presented by a unilateral CI. As noted in **A Snapshot of the History**, this additional (or adjunctive) stimulation can be provided with a second CI on the

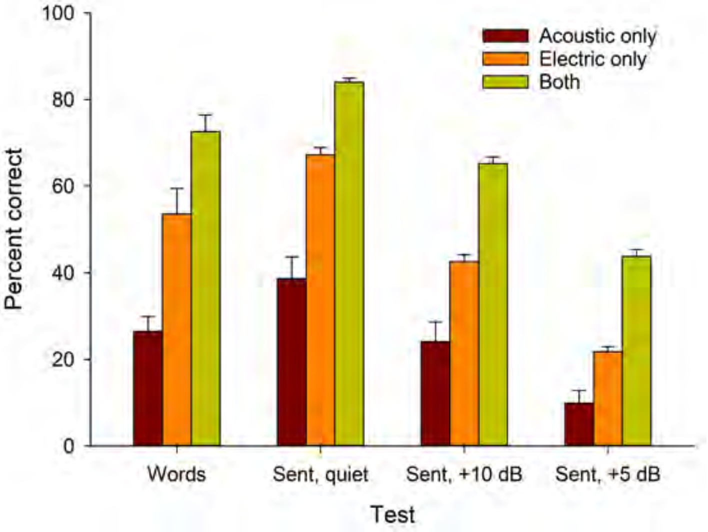

***Figure 5**. Means and SEMs of scores for the recognition of monosyllabic words (Words), AzBio sentences presented in an otherwise quiet condition (Sent, quiet), and the sentences presented in competition with speech-babble noise at the SNRs of +10 dB (Sent, +10 dB) and +5 dB (Sent, +5 dB). Measures were made with acoustical stimulation of the ear with residual hearing for each of the 15 subjects; electrical stimulation with the CI on the opposite side; and combined electric and acoustic stimulation. Data from Dorman et al. (2008).*

opposite side or with acoustic stimulation, the latter for persons with useful residual hearing on either side or both sides.

The effects of the additional stimulation can be large, as seen in **Figure 5**, which shows the effects of combined electric and acoustic stimulation (combined EAS; also called "hybrid" or "bimodal" stimulation). The data are from Dorman et al. (2008). They tested 15 subjects who had a full insertion of a CI on one side; residual hearing at low frequencies on the opposite side; and 5 months to 7 years of experience with the CI and 5 or more years of experience with a hearing aid. The tests included recognition of monosyllabic words and the AzBio sentences with acoustic stimulation of the one ear only with the hearing aid, electric stimulation of the opposite ear only with the CI, and combined EAS. As in **Figure 4**, the sentences were presented in an otherwise quiet condition and in competition with noise (4-talker babble noise) at the SNRs of +10 and +5 dB.

Means and SEMs of the scores are presented in **Figure 5** and demonstrate the large benefits of the combination for all tests. Compared with electric stimulation only, the combination produces a jump up in the recognition of monosyllabic words from 54 to 73% correct and a 2-fold increase in the recognition of the sentences in noise at the SNR of +5 dB. Thus, the barrier of ~55% correct for recognition of monosyllabic words by experienced users of unilateral CIs (**Figure 3**) can be broken, and recognition of speech in noise can be increased with combined EAS. Excellent results also have been obtained with bilateral electrical stimulation, as shown for example in Müller et al. (2002).

In broad terms, both combined EAS and bilateral CIs can improve speech reception substantially. Also, combined EAS can improve music reception and bilateral CIs can enable sound localization abilities. Furthermore, the brain can integrate the seemingly disparate inputs from electric and acoustic stimulation, or the inputs from the two sides from bilateral electrical stimulation, into unitary percepts that for speech are more intelligible, often far more intelligible, than either input alone. Step 5 was a major step forward.

Step 6?

In my view, the greatest opportunities for the next large step forward are

(1) increasing access worldwide to the marvelous technology that already has been developed and proven to be safe and highly beneficial;

(2) improving the performance of unilateral CIs, which is the only option for many patients and prospective patients and is the foundation of the adjunctive stimulation treatments; and

(3) broadening the eligibility and indications for CIs and the adjunctive treatments, perhaps to include the many millions of people worldwide who suffer from disabling hearing loss in their sixth decade and beyond (a condition called "presbycusis").

Any of these advances would be a worthy step 6.

Increasing Access

As mentioned in the **Introduction,** slightly more than half a million people worldwide have received a CI or bilateral CIs to date. In contrast, approximately 57 million people worldwide have a severe or worse hearing loss in the better hearing ear (Wilson et al., 2017). Most of these people could benefit from a CI. Additionally, manyfold more, with somewhat better hearing on the worse side or with substantially better hearing on the opposite side, could benefit greatly from combined EAS. A conservative estimate of the number of persons who could benefit from a CI or the adjunctive stimulation treatments is around 60 million and the actual number is probably very much higher. Taking the conservative estimate, approximately 1% of the people who could benefit from a CI has received one.

I think a population health perspective would be helpful in increasing the access; progress already has been made along these lines (Zeng, 2017). Access is limited by the cost of the device but also by the availability of trained medical personnel; the infrastructure for healthcare in a region or country; awareness of the benefits of the CI at the policy levels such as the Ministries of Finance and Ministries of Health; the cost of surgery and follow-up care; additional costs associated with the care for patients in remote regions far from tertiary-care hospitals; battery expenses; the cost for manufacturers in meeting regulatory requirements; the cost for manufacturers in supporting clinics; the cost of marketing where needed; and the cost of at least minimal profits to sustain manufacturing enterprises. Access might be increased by viewing it as a multifaceted problem that includes all of these factors and not just the cost of the device, although that is certainly important (Emmett et al., 2015).

Efforts are underway by Ingeborg J. Hochmair and me and by Fan-Gang Zeng and others to increase access. We know that even under the present conditions, CIs are cost effective or highly cost effective in high- and middle-income countries and are cost effective or approaching cost effectiveness in some of the lower income countries with improving economies (Emmett et al., 2015, 2016; Saunders et al., 2015). However, much more could be done to increase access—especially in the middle- and low-income countries—so that "All may hear," as Bill House put it years ago, and as was the motto for the House Ear Institute in Los Angeles (founded by Bill's half brother Howard) before its demise in 2013 (Shannon, 2015).

Improving Unilateral Cochlear Implants

As seen in **Figure 3** and as noted by Lim et al. (2017) and Zeng (2017), the performance of unilateral CIs has been relatively static since the mid-1990s despite many well-conceived efforts to improve them and despite (1) multiple relaxations in the candidacy criteria for cochlear implantation; (2) increases in the number of stimulus sites in the cochlea; and (3) the advent of multiple new devices and processing strategies. Presumably, today's recipients have healthier cochleas and certainly a higher number of good processing options than the recipients of the mid-1990s. In the mid-1990s, the candidacy criteria were akin to "can you hear a jet engine 3 meters away from you?" and, if not, you could be a candidate. Today, persons with substantial residual hearing, and even persons with a severe or worse loss in hearing one side but normal or nearly normal hearing on the other side, can be candidates for receiving a CI.

These efforts and differences did not move the needle in the clockwise direction. New approaches are obviously needed, and some of the possibilities are presented by Wilson (2015, 2018), Zeng (2017), and Wilson and Dorman (2018b); one of those possibilities is to pay more attention to the "hearing brain" in designs and applications of CIs.

Better performance with unilateral CIs is important because not all patients or prospective patients have access to, or could benefit from, the adjunctive stimulation treatments. In particular, not all patients have enough residual hearing in either ear to benefit from combined EAS (Dorman et al., 2015), even with the relaxations in the candidacy criteria, and not all patients have access to bilateral CIs due to restrictions in insurance coverage or national health policies. Furthermore, the performance of the unilateral CI is the foundation of the adjunctive treatments and an increase in performance for unilateral CIs would be expected to boost the performance of the adjunctive treatments as well.

Broadening Eligibility and Indications

Even a slight further relaxation in the candidacy criteria, based on data, would increase substantially the number of persons who could benefit from a CI. Evidence for a broadening of eligibility is available today (Gifford et al., 2010; Wilson, 2012).

An immensely large population of persons who would be included as candidates with the slight relaxation are the sufferers of presbycusis, which is a socially isolating and otherwise debilitating condition. There are more than 10 million people in the United States alone who have this affliction, and the numbers in the United States and worldwide are growing exponentially with the ongoing increases in and aging of the world's populations. A hearing aid often is not effective for presbycusis sufferers because most of them have good or even normal hearing at low frequencies (below about 1.5 kHz) but poor or extremely poor hearing at the higher frequencies (Dubno et al., 2013). The amplification provided by a hearing aid is generally not needed at the low frequencies and is generally not effective (or only marginally effective) at the high frequencies because little remains that can be stimulated acoustically there. A better treatment is needed. Possibly, a shallowly and gently inserted CI could provide a "light tonotopic touch" at the basal (high-frequency) end of the cochlea to complement the low-frequency hearing that already exists for this stunningly large population of potential beneficiaries.

Coda

Although the present-day CIs are wonderful, considerable room remains for improvement and for greater access to the technology that has already been developed.

The modern CI is a shared triumph of engineering, medicine, and neuroscience, among other disciplines. Indeed, many members of our spectacular ASA have contributed mightily in making a seemingly impossible feat possible (see **Box**) and, in retrospect, the brave first steps and cooperation among the disciplines were essential in producing the devices we have today.

Contributions by Members of the Acoustical Society of America

Members of the ASA contributed mightily to the development of the modern CI. Two examples among many are that the citations for 14 Fellows of the ASA have been for contributions to the development and that 556 research articles and 95 letters that include the keywords "cochlear implant" have been published in *The Journal of the Acoustical Society of America* as of September 2018. Additionally, Fellows of the ASA have served as the Chair or Cochair or both for 14 of the 19 biennial "Conferences on Implantable Auditory Prostheses" conducted to date or scheduled for 2019. These conferences are the preeminent research conferences in the field; in all, 18 Fellows have participated or will participate as the Chair or Cochair. Interestingly, the citations for nine of these Fellows were not for the development and that speaks to the multidisciplinary nature of the effort.

In thinking back on the history of the CI, I am reminded of the development of aircraft. At the outset, many experts stated categorically that flight with a heavier-than-air machine was impossible. The pioneers proved that the naysayers were wrong. Later, much later, the DC-3 came along. It is a classic engineering design that remained in widespread use for decades and is still in use today. It transformed air travel and transportation, like the modern CI transformed otology and the lives of the great majority of its users. The DC-3 was surpassed, of course, with substantial investments of resources, high expertise, and unwavering confidence and diligence. I expect the same will happen for the CI.

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BioSketch

Blake Wilson is a fellow of the Acoustical Society of America (ASA) and a proud recipient of the ASA Helmholtz-Rayleigh Interdisciplinary Silver Medal in Psychological and Physiological Acoustics, Speech Communication, and Signal Processing in Acoustics, in his case "for contributions to the development and adoption of cochlear implants." He also is the recipient of other major awards including the 2013 Lasker Award (along with two others) and the 2015 Russ Prize (along with four others). He is a member of the National Academy of Engineering and of the faculties at Duke University, Durham, NC; The University of Texas at Dallas; and Warwick University, Coventry, UK.