Pushing the Envelope of Auditory Research with Cochlear Implants

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The cochlear implant has advanced our understanding of hearing in novel ways, but still challenges our understanding in many regards.

The Function and Importance of Hearing, Either Acoustically or Electrically

Acoustic information is typically transferred to the brain by the collection of sound by the pinna (external ear), the amplification of frequencies important for speech understanding by the ear canal and middle ear bones, and the transduction of sound to the nervous system by the hair cells in the inner ear (**Figure 1A**). The inner ear, or cochlea, operates like a frequency analyzer, where hair cells near the base of the cochlea are tuned to and transmit high-frequency acoustic information (≈20,000 Hz) and where hair cells near the top of the cochlea are tuned to and transmit low-frequency acoustic information (≈20 Hz). The hair cells are an indispensable part of the transduction process because they start the electrochemical reactions that cause the spiral ganglia and auditory nerve to pass the acoustic information as electrical spikes that the brain interprets as sound. Hair cells are damaged or die because a person might have a genetic disposition, need to take an ototoxic medicine that saves their life but destroys their hearing, are exposed to

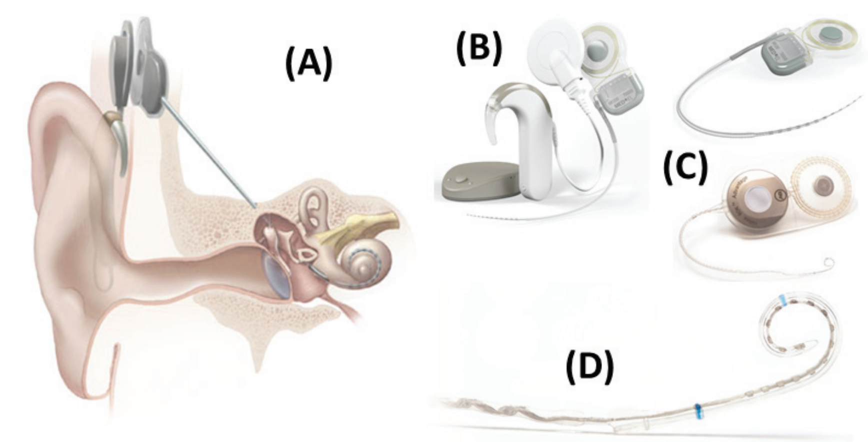

Figure 1. *A: diagram of the pinna, ear canal, middle ear, and inner ear (i.e., cochlea). A cochlear implant (CI) bypasses these structures with a behind-the-ear microphone attached to a speech processor, a frequency-modulated (FM) transmitter (outside the skin) and receiver (under the skin), and the CI, which is placed in the cochlea. A CI mimics the frequency organization of the cochlea by sending different frequency information to different places. B: a Med-El SYNCHRONY CI System, with the SONNET and RONDO speech processors. C: close-up view of the coil of wire that is the FM receiver and the electrode array, which is curved to follow the shape of the cochlea (a two-and-a-half-turn snail shell shape). Two types of CIs are shown: from Med-El SONNET (top) and from Advanced Bionics HiRes 90K Advantage (bottom). D: electrode contacts of the Advanced Bionics HiRes 90K Advantage CI. Images provided courtesy of Advanced Bionics and Med-El.*

high levels of sound too often, or simply ages. Hair cells in mammals do not regrow when they die, meaning that if we want to pass acoustic information to the brain in the absence of usable hair cells, we need a way to bypass the hair cell transduction process, such as with a cochlear implant (CI).

The modern-day CI is a biomedical device that includes a microphone on a speech processor placed behind the ear and an array of electrodes that are placed in the cochlea (**Figure 1**). Frequencies most important for speech understanding (typically about 200-8,000 Hz) are passed to the auditory system through the electrodes by their direct excitation of the spiral ganglia attached to the auditory nerve fibers, thereby bypassing the dead hair cells. Looked at another way, stimulation by the CI starts the electrochemical transduction process in the nerve with the electricity rather than the normal chemical transfer from the hair cells. Each electrode contact is assigned a frequency range, and the frequency-to-electrode allocation is such that the organization of frequencies follow that of the functional cochlea, high frequencies near the bottom and low frequencies near the top. Therefore, the CI mimics the frequency organization of the cochlea to maintain its ability to operate as a frequency analyzer.

Today's CIs are marvels of modern biomedical engineering and the most successful of all sensory prostheses. In the best cases, people with CIs achieve near-perfect speech understanding in quiet conditions and can speak on the phone, thereby understanding degraded speech signals without the help of visual cues. The pioneers of the modern-day multielectrode CI (Graeme M. Clark, Emeritus, University of Melbourne; Ingeborg Hochmair, MED-EL, Innsbruck; and Blake S. Wilson, Duke University) were recently recognized with the Lasker Award "for the development of the modern CI — a device that bestows hearing to individuals with profound deafness" (Pierce, 2013).

The National Institute on Deafness and Other Communication Disorders (NIDCD) of the National Institutes of Health (NIH) approximates that there are over 324,000 CI users worldwide (NIDCD, 2012). These users range over the full life span, with children being implanted at younger and younger ages (sometimes at six or nine months of age, which works because the cochlea is nearly full size when born and grows little as one ages) and adults at older and older ages (sometimes at 90+ years).

Why undergo the risk of major surgery for people with relatively fragile constitutions such as infants and seniors? People receive CIs when quality of life is an issue. Humans are social beings and without the ability to communicate with each other, many become reclusive and depressed. A majority of the world relies on hearing to communicate and socialize. In addition, many have established social circles, friends, and family for which communication stops with the loss of hearing, even in the presence of communication alternatives.

CI Speech-Processing Basics

Arguably, the last major advance in CI signal processing was over 20 years ago (Wilson et al., 1991) with the introduction of multichannel high carrier rate strategies (meaning that the stimulation rate on an individual electrode is closer to 1,000 pulses/s rather than the 100 pulses/s in the earliest CIs). Today's modern implants have between 12 and 22 intracochlear electrodes that serve as information channels to convey temporal envelope information (the slowly varying temporal information in a signal rather than the fast oscillations of the carrier or fine structure; see **Figure 2**). After all the filtering from microphone responses, preprocessing, and compression, all CIs operate using "vocoder-centric" signal processing (Loizou, 2006), which is based on a method of efficient information encoding originally designed by Dudley (1959). This partitions the spectrum into information channels, providing worse resolution than those with typical acoustic hearing (see **Figure 2**, Analysis Stage) but which, as discussed below, is sufficient for speech understanding. People with CIs receive on the order of 10 discrete spectral channels, whereas the typical auditory system can be best viewed as a continuum of auditory filters with orders of magnitude finer spectral resolution. Comparing typical hearing with CIs is like comparing modern-day graphing calculators with the old mechanical calculators. If all you knew were mechanical calculators, the modern-day graphing calculators that could compute your logarithms for you would seem grand and wonderful. However, no one who grew up on modern-day graphing calculators would tolerate a mechanical calculator and compute their logarithms with the help of a table unless they had to.

The next stage of CI processing is the extraction of the temporal envelope from each channel. The exact extraction method varies in practice, but the idea is the same in all cases. What matters is the slowly varying amplitude modu-

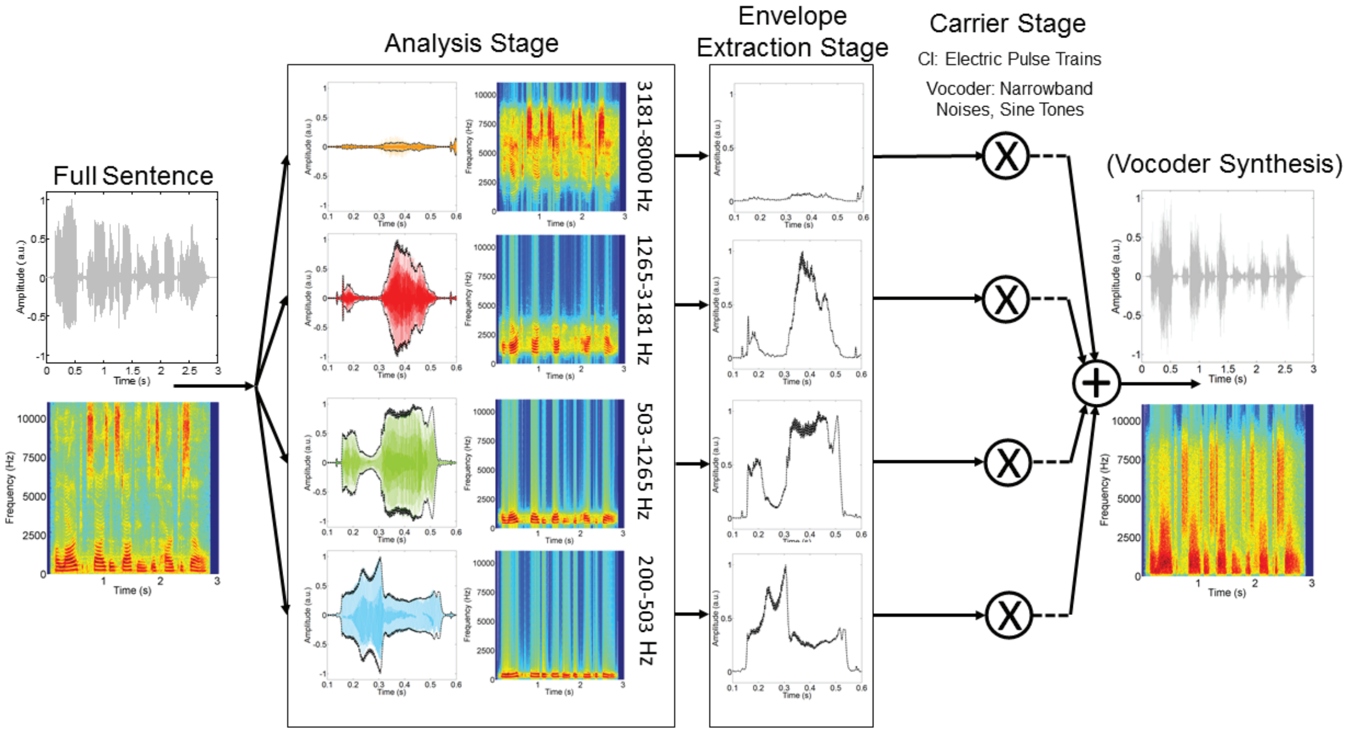

Figure 2. Basic speech processing performed by a CI. The Full Sentence stage shows the waveform and spectrogram of the sentence "A large size in stockings is hard to sell." The Analysis Stage bandpass filters the signal into contiguous bands. For this example, there are 4 channels that cover between 200 and 8,000 Hz. The corner frequencies are logarithmically spaced. For each channel, the waveform and spectrogram are shown. Surrounding each waveform is a black line, which represents the envelope information of that channel. The Envelope Extraction Stage was extracted by using the Hilbert transform and low-pass filtering at 160 Hz. After Envelope Extraction, the envelopes are used to modulate the amplitude of electrical pulse trains for CI users as shown in the Carrier Stage. Alternatively, sine tones or narrowband noises can be modulated by the envelopes and then summed into a single waveform that would be a vocoded version of the original waveform and considered a CI simulation as shown in the Vocoder Synthesis Stage.

lations rather than all the fast changes in the temporal fine structure. So the envelope is extracted for each channel (see **Figure 2**, Envelope Extraction Stage).

The last stage is the carrier stage. The envelope extracted from each channel is used to modulate the amplitude of a high-rate electrical carrier signal (see **Figure 2**, Carrier Stage). These modulated electrical pulse trains then bypass the dead hair cells in the cochlea to excite the spiral ganglia of the auditory nerve directly, which is interpreted as sound and speech. For this reason, people often say that CIs convey temporal but not spectral information. This is not quite correct, however, because providing only one channel of temporal envelope information is not very intelligible (which is why the field moved away from single-electrode implants long ago). Rather, CIs present temporal envelope information on a relatively limited number of spectral channels. The number of spectral channels that we use is enough to convey vowel information (Laback et al., 2004), but many finer spectral profile analysis tasks seem inaccessible to CI users (Goupell et al., 2008).

Clearly, the total amount of information has been massively reduced by this process compared with the information available in normal hearing. Fortunately, the primary purpose of a CI is to convey speech information. Speech is an incredibly robust signal with plenty of redundancy. It is this redundancy that allows cell phones to pass a very limited spectrum and total amount of information, which, in turn, avoids clogging the cell phone networks. Likewise, probably the only reason a CI works as well as it does is that we have an input signal that is so robust to degradation.

There is a wonderful visual analogy for how a CI works (Harmon and Julesz, 1973). Row A of **Figure 3** shows two pictures that have very low resolution that gradually increases in resolution. On the far left, you can discriminate the pictures but you may not be able to identify them. On the far right, are the full resolution pictures. But much like a CI, you do not need very high resolution before you have a good guess about what is in the pictures. And with some practice, most everyone can identify the low-resolution presidents in Row B.

Figure 3. *A, left to right: George Washington transitioning from low resolution to high resolution. B: low-resolution (20 pixels vertical) versions of George W. Bush, Bill Clinton, Barack Obama, and Ronald Reagan. Photos were taken from publically available official presidential portraits.*

The Two Big Problems in the Field

As mentioned above, CIs remove a massive amount of acoustic information before transferring signals to the auditory system. The field of CIs has many of areas in which it could improve but the two largest are probably (1) the issue of music, pitch, and noise; and (2) the issue of spatial hearing and noise.

Yes, "noise" was mentioned twice. But life is noisy and messy, and understanding speech with CIs does not work well in noise (e.g., Loizou et al., 2009). Because the major reason to get a CI is to provide/regain/restore the ability to understand speech and most of the time we are in noisy situations, then there is the need for CIs to work better in noise.

It is not uncommon to hear anecdotes about people who do not use their CIs because they cannot enjoy music any more. This is true; for most CI users, music is a bust (perhaps more so for those who enjoy classical music and symphonies that rely on good melodies and less so for those who like rap and dance music that rely on rhythm and beats). Because CIs only convey temporal envelope information and replace the carrier with a pulse train (**Figure 2**), much of the "temporal pitch" (i.e., the pitch that results from the periodicity of the waveform) is obliterated. Some of the "place pitch" (i.e., the pitch that results from the characteristic frequency of the neurons that are excited) remains. Not all temporal pitch is absent because some of it is conveyed in the temporal envelope (enough to provide the ability to discriminate genders, albeit at a relatively low level compared with acoustic hearing) (Fu et al., 2004). Because we want CI users to be out in the world socializing, perhaps at a noisy restaurant or cocktail party, the lack of fine structure or periodicity information severely hampers any fun in such situations. Fine structure or periodicity information is a major or perhaps "the" auditory grouping cue (i.e., grouping meaning how our brain organizes an auditory scene into single perceived objects), which is missing for a person with a CI. Without it, the envelopes mush together into a mostly unintelligible mess.

In the absence of temporal fine structure and periodicity grouping cues, grouping cues associated with spatial hearing (i.e., cues provided by having two ears that allow you to perceive sounds as coming from different locations) become incredibly important, which is the second major problem in the field. People have two ears because they help us locate sounds in space by calculating timing and level differences of the sound as it reaches the two ears.

In addition, two ears allow us to better understand speech in background noise. An increasing number people are receiving bilateral CIs with the hopes of gaining access to spatial hearing. In normal hearing, when other grouping cues like pitch fail, spatial cues allow for a good auditory scene organization (e.g., Brungart, 2001). Such cues allow listeners to pick out the person they are attending to at a loud and crowded party, even if they are surrounded by a number of people all of the same gender, who generally have the same voice pitch.

Thus, until we restore temporal fine structure and periodicity grouping cues (really, the "holy grail" of CI research; if we can fix periodicity and pitch, we can probably fix any aspect of hearing), CI users need to have some other cue to organize auditory scenes. The lowest hanging fruit may be spatial cues. Currently, bilateral CI users can locate sounds in space and better understand speech in noise than unilateral CI users. But the field is far from doing a great job of providing spatial cues.

How might we improve these percepts for CIs? There are limitations in several domains, including biological, surgical, and device related (Litovsky et al., 2012). More broadly though, the field has used an "engineer's approach" to this problem. The damaged ear is not functioning as designed. To fix the ear, we need to figure out what information to convey to the auditory system and then convey it.

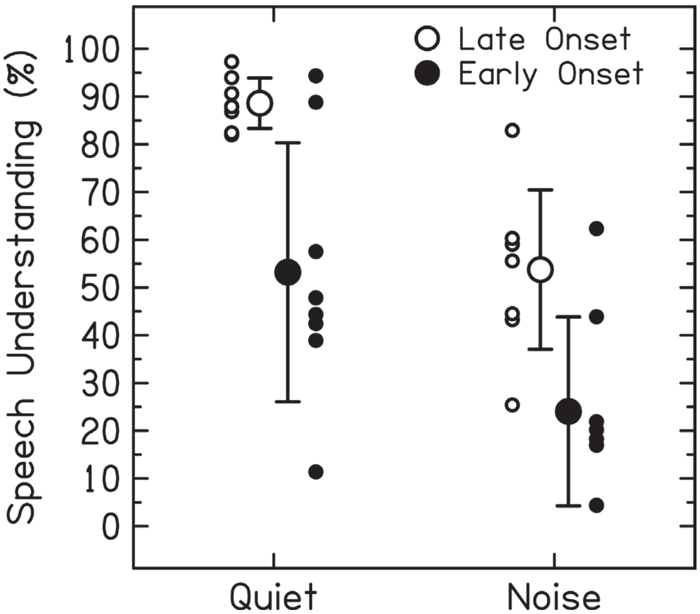

Figure 4. *Speech understanding for 8 late onset of deafness (typically short duration of hearing loss and deafness) and 8 early onset of deafness (typically long duration of hearing loss and deafness) adult CI listeners. All listeners received their CI as an adult. The 2 groups are matched in age, with an average age of 57 years. Speech understanding was measured using Az-Bio sentence in quiet or in a multitalker babble with +10-dB signal-to-noise ratio. Large circles are the average speech understanding ± 1 SD. Small circles show individual speech understanding scores. Data are from a subset of data collected in the Goupell Laboratory at the University of Maryland, College Park.*

In some ways, the engineer's approach is one that assumes that more information is always better, and so the real limitations rely in better technology. Perhaps for this reason, there is good reason why the last major breakthrough was two decades ago. (There have been many advances in the past 20 years such as increased battery life, smaller and more durable devices, and microphone beamforming to better accommodate background noise; however, there has not been another revolutionary increase in speech understanding to what occurred in the 1990s.) In contrast, one could take a different approach that attempts to present only the most important information because there is a limited amount of information that a CI can convey. Such an idea is relatively less prevalent but exists in some speech-processing strategies. Would it not then be prudent to rethink how we present the information to maximize the amount of "useful" input the auditory system receives? For example, even though some CI users have 22 contacts on their arrays, one would think this would create 22 information channels. Sadly, this does not happen. Because of a technological limitation of how the current travels through the cochlea (ultimately, where the ground electrode is located, which determines the path that the current takes), the electrical fields are quite broad, about 4-5 mm (Nelson et al., 2008). For a 35-mm cochlea, this means that each electrode excites about 1/8th of the cochlea. Therefore, it may not be surprising that CI users utilize only 7 or 8 independent information channels, even though they have 22 intracochlear electrodes (Friesen et al., 2001). Hopefully, someday soon we will provide more independent information channels through technological advances.

If CI users really only get information about eight channels, how do we present the information? As an alternative approach, one could simply avoid trying to pass the full signals to the auditory system. One way to achieve this would be to only activate eight channels at a time, the ones with the highest energy, because those channels have the most important information to convey (e.g., vowel formants). CIs that use peak-picking speech-processing strategies where only a subset of the possible electrodes fire are common. Such an idea is not dissimilar to removing information that might be masked in mp3 encoding. Also, along this line of thought of "less is more," many investigators have shown that removing electrodes that are "bad" for various reasons (e.g., bad modulation detection performance) can improve speech understanding (Garadat et al., 2012).

Yet another approach would be to do as much to the signal before it is passed to the auditory system. In other words, why not preprocess the signals and attempt to present relatively clean representations of the signals? Separating out noise before giving it to the auditory system has been an effective approach in hearing aids for years and is a simple and elegant solution to our problem. Of course, if this were an easy task, we would be finished with CI research as a whole. Separating out targets from noise without a priori information is a nontrivial task. Therefore, moving CI performance to even higher levels will likely need to involve not only basic research and basic understanding of how the auditory system encodes electrical stimulation but also ways of maximizing important information transfer (in contrast to forcing as much information into the auditory system as we can, we need to be judicious in our choice of information) and removing as much of the unwanted information like background noise as we can before presenting information to the auditory system.

Probably the only reason a CI works as well as it does is that we have an input signal that is so robust to degradation.

Status of CI Research and the Field of Hearing Perception

Almost any issue of the *Journal of the Acoustical Society of America (JASA)* has a number of papers concerned with CIs or simulations of CI processing (i.e., vocoders; see below). Two things began to occur in the 1990s to produce this trend. First, CIs started providing high levels of speech understanding in a majority of the users. This increased the prevalence of CIs and the significance of understanding how they worked as well as how the brain was processing electrical stimulation. Second, there has been a slow shift away from understanding basic auditory phenomena to how these phenomena occur or do not occur in hearing-impaired individuals, either hearing aid or CI users. Although still in the realm of basic science, the translational aspects of hearing and how we can help people hear better seems to be the new direction of the field.

However, although we know a lot about hearing now, translating our findings to help people should be the end goal, CIs have opened up a Pandora's box of what we did not know about hearing. Take the field's obsession with envelope versus fine-structure encoding. Surely, CIs, the devices that primarily encode envelope information, provided a major impetus for all the attention paid to envelope versus fine-structure encoding. Every day, it seems that I stumble over questions that have not been asked for the typical acoustic hearing system alone but seem incredibly important when considering both typical hearing and CIs together.

The following is my opinion of how we are doing with understanding CIs and electrical stimulation of the auditory. Essentially these are some highlights from the field.

The Good

For the high-performing CI users (those who have typically had a short duration of profound hearing loss or deafness), speech-processing strategies do a wonderful job of providing access to hearing, particularly in quiet situations (see **Figure 4**). Although most of the temporal fine structure is removed from the signals, a small amount of temporal pitch information is conveyed by the temporal envelope, which can help CI users discriminate different gender speakers (Fu et al., 2004). As mentioned above, many people get bilateral CIs, which help improve the abilities to locate sounds in space and speech understanding in background noise. Most of the latter occurs through a monaural mechanism called the "better ear" effect, which is simply that one ear might have a better signal-to-noise ratio (Loizou et al., 2009).

CIs started as a treatment for adult postlingually deafened individuals. However, children who get implants often develop excellent language, speech production, and speech understanding (Svirsky et al., 2000). At the other end of the age spectrum, there was a worry that older people would not be good candidates for CIs because of possible medical complications or a lack of plasticity in the brain that would allow for speech understanding. What has become clear is that there appears to be no upper limit on age of implantation; CIs seem to be safe and effective and can improve the quality of life across the life span (Lin et al., 2012).

The Bad

Although we generally laud the successes of the high-performing CI users, there exists a wide variability in performance (see **Figure 4**). Even though many CI users achieve near-perfect speech understanding in quiet, many do not. The reasons are wide and varied, but factors such as etiology, duration of deafness, and age of implantation affect speech understanding with a CI. Sometimes it is easy to forget about the relatively poor-performing CI users, which may be a result of how researchers like me choose their participants. The adult CI literature is composed mostly of middle-aged high performers with short durations of deafness. But there are populations such as prelingually deafened individuals who have gone for decades of their life without auditory stimulation that fall into a population that would be typically poor CI users. In general, the field could pay more attention to the poor performers.

Coming back to the two big problems, pitch and spatial hearing, several investigators have attempted to develop novel stimulation strategies to reintroduce temporal fine structure by lowering the rate of the carrier on a subset of electrodes. In general, it is unclear if those strategies provide a benefit for pitch or spatial hearing, which is a major disappointment. However, the field seems to be moving in a good direction. Recently, Churchill et al. (2014) found a method to present both temporal fine structure and envelope information using a mixed rate stimulation strategy (where low rates are used to present envelope information and coherent temporal fine structure across several apical electrodes and high rates are used to present just envelope information at basal electrodes), which improves sound localization without degrading speech understanding in quiet.

The Weird

There are many things that we do not understand about the auditory system and electrical stimulation. For example, most typical hearing and CI listeners cannot detect changes in temporal information in acoustic or electrical pulses beyond 200-300 pulses/s, meaning that individuals cannot tell the difference between 400 and 600 pulses/s (van Hoesel, 2007; Kong et al., 2009). However, there is a small subset of CI listeners who can detect temporal information changes near 1,000 pulses/s (Kong and Carlyon, 2010; Noel and Eddington, 2013). These exceptional performers challenge our understanding of the temporal precision of the auditory nerve and neural encoding of electrical stimulation.

I described above how there is poor spectral resolution in CI users. A good engineering approach to solving this problem is to increase the spectral resolution with more electrodes and smaller electrical fields. Smaller electrical fields can be achieved by altering the placement of the ground electrode to other polarity configurations (i.e., change from monopolar to bipolar or tripolar stimulation). However, by doing this, even though we have increased spectral resolution and thus achieved our goal of presenting the CI user stimuli that are a little closer to typical acoustic hearing, these configurations produce mixed results at best and often poorer speech understanding in CI users (Pfingst et al., 2001). In other words, exquisite spectral resolution is a hallmark of typical hearing; however, better spectral resolution in a CI produces mostly no change or poorer speech understanding. This may be a result of us just not understanding enough about how hearing works. Or could it be a result of the necessity to excite something in the cochlea? Again, we have an impaired ear and we need to convey the information somehow. But better spectral resolution may increase the probability that the information is not conveyed well because of portions of the cochlea that are lacking in ganglia and neurons to transmit information (i.e., neural dead regions; Shannon et al., 2001). Therefore, the engineer's approach to the problem may be inappropriate. Having large current spreads and bandwidths will ensure that at least some neurons are transmitting the information, even if that is not how we think about how speech is encoding with typical hearing.

The Vocoder as a CI Simulation: To Model Electrical Stimulation and To Improve Our Understanding of It by Reducing Variability

Ever since Shannon et al. (1995), the vocoder has produced a cottage industry of auditory research. The appeal of the vocoder is that it essentially works like the vocoder-centric speech processing shown in **Figure 2**. The only difference in the processing is that instead of using modulated electrical pulse trains to encode envelopes, sine tones or narrowband noises are used. So the goal of many vocoder studies is to simulate some aspect of CI processing, and the major advantage of this technique is that normal-hearing listeners, for the most part, lack the variability of the real CI users. Using such an approach, the high-performing CI users tend to match the normal-hearing listeners presented the vocoded signals (Friesen et al., 2001).

CI simulations are not limited to speech signals. Some people have used band-limited pulse trains to simulated electrical pulse trains, also with success in mirroring effects between groups (Kan et al., 2013). However, one needs to take care. Acoustic signals can never replicate electrical stimulation because acoustical stimulation needs to follow certain physical laws and the electrical stimulation has a different set of rules. However, perfect replication is not the point of a vocoder. A good vocoder experiment targets a specific facet of CI processing or electrical stimulation to better understand the CI data. The simulation will never be perfect but has many merits and the error bars will be much more manageable in the normal-hearing listeners.

A great example is a paper by Oxenham and Kreft (2014) that modeled the current spread from electrodes to explain the masking of speech by different types of maskers. Their goal was to target a specific aspect of the CI with the simulation, which produced a congruence between the patterns of data across populations. On some levels, the debate about the worthiness of vocoder work as a CI simulation is one on the basic usefulness of models. Models are simplifications of real life, miniature versions of larger more complicated things. In many cases, the best models are those that are simple, which is why the vocoder does a wonderful job of cutting through all of confounding factors that increase variability in real CI data.

Summary and Future Directions

In conclusion, CIs are highly effective auditory prostheses that mimic how the inner ear encodes sound, but they are severely limited in their ability to transmit information. There are the major obstacles that CI researchers are trying to tackle, with areas of successes and areas where the field could improve. The CI has motivated exciting new research questions and has uncovered some new mysteries about the auditory system. The field continues to "push the envelope" to better understand how hearing works and how we can help those that lose or never had their hearing to regain or provide it.

Biosketch

Matthew Goupell is an assistant professor in the Department of Hearing and Speech Sciences at the University of Maryland. He received a BS in physics and mathematics at Hope College in Holland, MI (2001) and a PhD in physics at Michigan State University (2005). He spent three years as a post-doc at the Austrian Academy of Sciences in Vienna, Austria and two years as a post-doc at the University of Wisconsin – Madison researching auditory perception in bilateral cochlear-implant users. His research focuses on binaural hearing, aging, and cochlear implants.

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