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Editorial

Recognizing the journey and celebrating the achievement of cochlear implants

1. Tribute to the Lasker Award recipients

More than half a century has passed since Georg von Békésy received the 1961 Nobel Prize in Physiology or Medicine for his discoveries of "the physical mechanism of stimulation within the cochlea." Around the same time several physicians began the pioneering work to restore hearing to deaf people by bypassing the malfunctioned cochlear mechanism to stimulate electrically the residual auditory nerve. Like a fairytale, the cochlear implant was ridiculed as an ugly duck in the beginning but has since grown into a beautiful swan, which not only has helped restore functional hearing to well over 400,000 persons but more recently finally received recognition from the mainstream scientific community. Dubbed America's Nobel, the 2013 Lasker ~ DeBakey Clinical Medical Research Award went to Graeme M. Clark, Ingeborg J. Hochmair and Blake S. Wilson for "the development of the modern cochlear implant — a device that bestows hearing to individuals with profound deafness." The Lasker Award is a huge recognition for a relatively small field like hearing research.

The first and foremost aim of the present special issue is to honor the three Lasker Award recipients, Graeme Clark, Ingeborg Hochmair and Blake Wilson by inviting them to present their work that has not only benefitted so many but also achieved the recognition that makes all hearing researchers proud. In the first paper of the special issue, Clark, 2015 demonstrates his unwavering vision for a multi-channel cochlear implant that takes advantage of both temporal and place coding to support functional speech recognition and language development for implant users. The relentless and excellent work by him and his colleagues since 1967, first at the University of Sydney and later at the University of Melbourne, has led to the most successful commercial product to date, the Cochlear Ltd device, which was the first FDA-approved multi-channel implant for adults in 1985 and for children in 1990, with approximately 250,000 users to date.

Beginning with their first eight-channel, puslatile-stimulation cochlear implant device being implanted in 1977, Ingeborg Hochmair, 2015 document their journey from a single-channel analog device with amplitude compression to a successful commercial device, the multi-channel Med El GmbH implant with monopolar, pulsatile stimulation. The Hochmair paper also presents important ongoing research using innovative technological development such as atraumatic deep insertion of electrodes into the apical region of the cochlea and signal processing such as fine structure encoding of sounds to improve the present device performance in speech understanding in noise and sound quality, especially in music appreciation.

By comparing early cochlear implant devices and their performance, Wilson, 2015 presents the historical context and describes the rationale for developing the Continuous Interleaved Sampling (CIS) sound coding strategy. The CIS strategy represents a clear paradigm shift from either analog processing or explicit feature extraction to envelope-based vocoding. The strategy also crystallizes the concept, and justifies the use of signal processing parameters that constitute the *de facto* standard of modern cochlear implant processors, from front-end processing, e.g., spectral weighting, filtering, and envelope extraction, to back-end processing, e.g., amplitude compression, mapping, and constant high-rate, interleaved, puslatile stimulation. The unique combination of new and prior elements in the CIS strategy allows accurate and minimally interfering representation and delivery of band-limited envelope cues to the auditory nerve, and additionally, easy and uniform engineering implementation and device fitting, that are responsible for producing reliable, robust and consistent open-set speech understanding for the great majority of modern cochlear implant users.

2. Early contributions to cochlear implants

At the closing time of editing the special issue, we were thrilled to learn that the three Lasker Award recipients, together with two additional researchers, Erwin S. Hochmair and Michael M. Merzenich, received the 2015 Fritz J. and Dolores H. Russ Prize. Awarded biennially by the United States' National Academy of Engineering and Ohio University, the Russ prize recognizes a bioengineering achievement in widespread use that improves the human condition. We are honored that all Russ Prize recipients contributed to the present special issue. Not surprisingly, Erwin Hochmair co-authored the aforementioned paper with Ingeborg Hochmair, as a reliable, productive and successful husband-wife team since day one.

Merzenich, 2015 recounts the UCSF contributions to the development of modern cochlear implants from sound coding, electrode design, and stimulation control to the realization that "cochlear implants were more a 'miracle' of brain plasticity than of our device engineering." As an intellectual leader in the early days of cochlear implants, Merzenich also gives a first person account of major events and issues, including intellectual and political interactions with not only other UCSF researchers but also relevant industrial and academic luminaries. Possibly having witnessed the difficulty in translating university research into commercial success, for example, the UCSF-Storz, Stanford-Biostim, and Utah-Ineraid

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devices, Merzenich observes that "the great achievement of cochlear implant research has been the production of devices, now in three successfully commercialized forms, that have the power to establish hearing in the congenitally deaf child, or to restore useful hearing in an individual who is socially isolated by a severe, acquired deafness."

The special issue also presents important contributions and achievements from other researchers in cochlear implant research and development. Claude-Henri Chouard, 2015 describes one of the earliest efforts in multisite implants, beginning in 1973 in Paris. Chouard was a former student of Charles Eyriès, who along with André Djourno, demonstrated hearing sensation by electric stimulation in a deaf patient for the first time in 1957, also in Paris. The French team developed the "Chorimac" devices that contained some modern features such as a transcutaneous transmission link and multiple bandpass channels. The devices also used sequential stimulation, but not nonsimultaneous stimulation, as the compensating phases of the stimulus pulses overlapped across the electrodes. This and other limitations, such as the $\leq$300 Hz per channel stimulation rate, which was a result of a 3-ms sampling rate of the band-limited signal consisting of both envelope and fine-structure cues, to the use of pulse duration modulation and a voltage source for the pulses, might explain the relatively low levels of performance obtained with the Chorimac devices. Although the Chorimac and subsequent devices were commercialized, and certainly improved, initially by Bertin SA, later by MXM-Neurelec SA and currently by Oticon Medical AB, they have not been widely used outside of France.

Any special issue on cochlear implant development would be incomplete without acknowledging the trailblazing role played by "Dr. Bill," William F. House, M.D., D.D.S., the father of Neurotology, who passed away on December 7, 2012 at the age of 89. Eisenberg, 2015, who started her audiology career with House in 1976, discusses not only House's motivation, resolve and team approach in developing the first FDA-approved 3M-House single-channel device, but also his pioneering contributions to surgical innovations on acoustic tumor removal and the development of auditory brainstem implants. Although limited open-set speech recognition was achieved by some of its hundreds of users, with a few of them having a decade or longer experience, the 3M-House device did not achieve much commercial success, being purchased and subsequently phased out by the Cochlear Corporation in 1989. Two recent attempts to revive the 3M-House implant also failed: The Allhear Inc. founded by House went into bankruptcy in 2008 and the IES device, which presumably relied on technology transfer from House, was denied for approval by the Chinese FDA in 2013, officially signaling the end of an era.

3. Recent research and development

Shannon, 2015 recounts the 25 years of innovative research from 1989 to 2013 at the House Ear Institute on perceptual capabilities and signal processing for both cochlear implants and auditory brainstem implants. The "second stage of auditory implant research at House" under Shannon's leadership not only improved basic understanding of auditory implants and their users' performance, but also trained a large cohort of auditory implant researchers before the official closure of the House Research Institute in 2013.

As a specialty journal, the special issue can afford to delve into both breadth and depth by inviting leaders in the field to present their recent research and development in cochlear implants. Abbas and Brown, 2015 review measurements of responses to cochlear implant stimulation from the auditory nerve to the brain and uses of those measures. Pfingst et al., 2015 present human and animal studies on not only the importance of cochlear health for implant function but also tissue-engineering procedures for improving or even replacing the implant function. Other researchers present various approaches to further improve cochlear implant function and expand its utilities, including reducing or exploiting channel interaction (Kalkman et al., 2015; Schatzer et al., 2015); coordinated electro-acoustic stimulation (Dorman et al., 2015; Tillein et al., 2015); bilateral implantation (Kan and Litovsky, 2015; Laback et al., 2015); learning or training (Chatterjee et al., 2015; Svirsky et al., 2015; van Wieringen and Wouters, 2015); audio-visual integration and brain imaging (Strelnikova et al., 2015); and lowering the cost (Zeng et al., 2015).

4. Future research in cochlear implants

The success of cochlear implants has been extended beyond treating deafness to other indications and devices. Ling et al. (2015) review the conception and research of vestibular implants to treat balance-related disorders including disequilibrium, oscillopsia, or vertigo. Lim and Lenarz (2015) describe the development and translation of the auditory midbrain implant for patients without a functional auditory nerve or implantable cochlea. To overcome the intrinsic limitations related to broad electric stimulation, novel optogenetic stimulation has been proposed to demonstrate the proof of principle in developing an optical cochlear implant (Jeschke and Moser, 2015) and an optical auditory brainstem implant (Hight et al., 2015).

Thanks to the cochlear implant pioneers, including the three Lasker Award recipients, who overcame not only limited knowledge and resources but also suspicion or even hostility, today's environment is much improved. Judged by the active, dynamic and diverse studies presented in this special issue, the torch has been successfully passed. Present and future hearing researchers will take the cochlear implant to a new horizon, continuing to confer benefits on mankind.

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