Chapter 1
Advances in Auditory Prostheses

Fan-Gang Zeng

1 Introduction

Advances in auditory prostheses were accompanied by competing ideas and bold experiments in the 1960s and 1970s, an interesting and exciting time that was reminiscent of the Era of Warring States in ancient China (for a detailed review see Zeng et al. 2008). The most contested technological issue was between a single-electrode (House 1974) and a multi-electrode (Clark et al. 1977) cochlear implant, with the former winning the battle as the first commercially available auditory prosthesis in 1984, but the latter winning the war because it has become the most successful neural prosthesis: it has restored partial hearing to more than 200,000 deaf people worldwide today. For cochlear implants to achieve this remarkable level of success, not only did they have to compete against other devices such as tactile aids and hearing aids, but they also had to overcome doubt from both the mainstream and deaf communities (for a detailed review see Levitt 2008). Many technological advances, particularly innovative signal processing, were made in the 1980s and 1990s to contribute to the progress in cochlear implant performance (Loizou 2006; Wilson and Dorman 2007).

Figure 1.1 shows sentence recognition scores with different generations of the cochlear implant from three major manufacturers. At present, all contemporary cochlear implants use similar signal processing that extracts temporal envelope information from a limited number of spectral bands and delivers these band-limited temporal envelopes non-simultaneously to 12 to 22 electrodes implanted in the cochlea. As a result, these implants produced similarly good speech performance (70–80% sentence recognition in quiet), which allows an average cochlear implant user to carry on a conversation over the telephone.

F.-G. Zeng (✉)
Departments of Otolaryngology–Head and Neck Surgery,
Anatomy and Neurobiology Biomedical Engineering, and Cognitive Science,
University of California–Irvine, 110 Med Sci E, Irvine, CA 92697, USA
e-mail: fzeng@uci.edu

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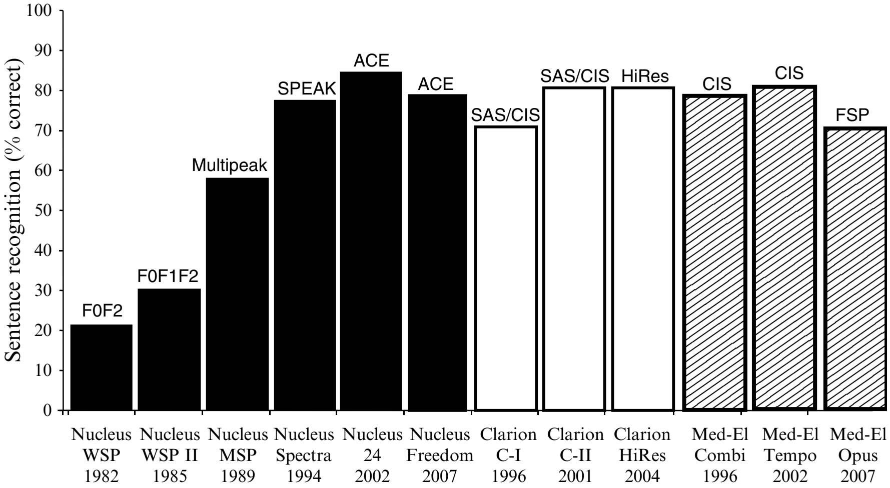

Fig. 1.1 Progressive sentence recognition with different generations of cochlear implants from the three major manufacturers, including the Nucleus device from Cochlear Corporation, the Clarion device from Advanced Bionics Corporation, and the devices from Med El (Adapted from Fig. 3 in Zeng et al. 2008)

Despite the good performance in quiet, there are still significant gaps in performance between normal-hearing and cochlear-implant listeners (Fig. 1.2). For example, the implant performance is extremely poor in noise, producing a 15-dB loss in functional signal-to-noise ratio with a steady-state noise background, and an even greater 30-dB loss with a competing voice (Zeng et al. 2005). Music perception is also extremely limited in implant users who can access some rhythmic information but little melody and timbre information (McDermott 2004). Finally, both tone perception and production are severely compromised in implant users who speak tonal languages such as Mandarin, Thai, and Vietnamese (Peng et al. 2008).

To close the performance gap between implant and normal listeners, new ideas and tools are needed and indeed have been developed intensely in recent years. Compared with the first 5 years of the new millennium, the number of publications related to cochlear implants has increased from 1196 to 1792 in the past 5 years (Fig. 1.3).

Where did the growth in publications come from? Bilateral cochlear implants were one area of such growth, with the number of related publications almost doubling, while the combined hearing aids and cochlear implants were another area of publication growth, with publications increasing fourfold in the same period. New tools such as midbrain stimulation and optical cochlear implants have also emerged. In contrast with a previous *Springer Handbook of Auditory Research* volume on cochlear implants (Zeng et al. 2004), which focused on the basic science and technology of electric stimulation, the present volume goes beyond traditional cochlear implants and presents new technological approaches, from bilateral cochlear implantation to midbrain prostheses, as well as new evaluation tools from auditory training to cross-modality processing.

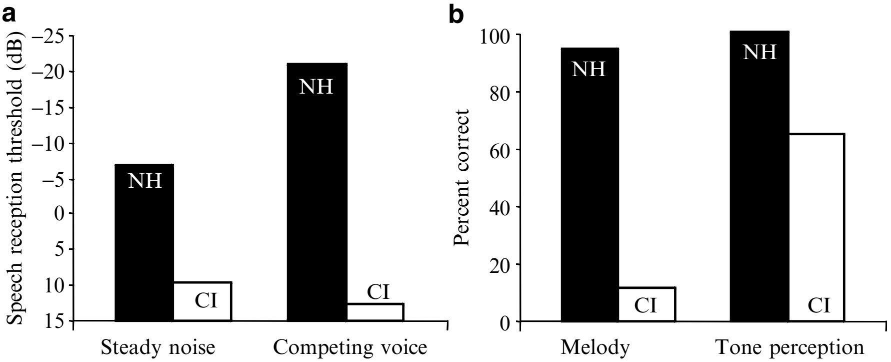

Fig. 1.2 Speech perception in noise (**a**) and music and tone perception (**b**) between normal-hearing (NH) and cochlear-implant (CI) listeners. Speech perception in noise is represented by signal-to-noise ratio in dB, at which 50% of speech is recognized. Music perception is percentage of melodies correctly recognized, while tone perception is percentage of Mandarin tones correctly recognized (Adapted from Fig. 21 in Zeng et al. 2008)

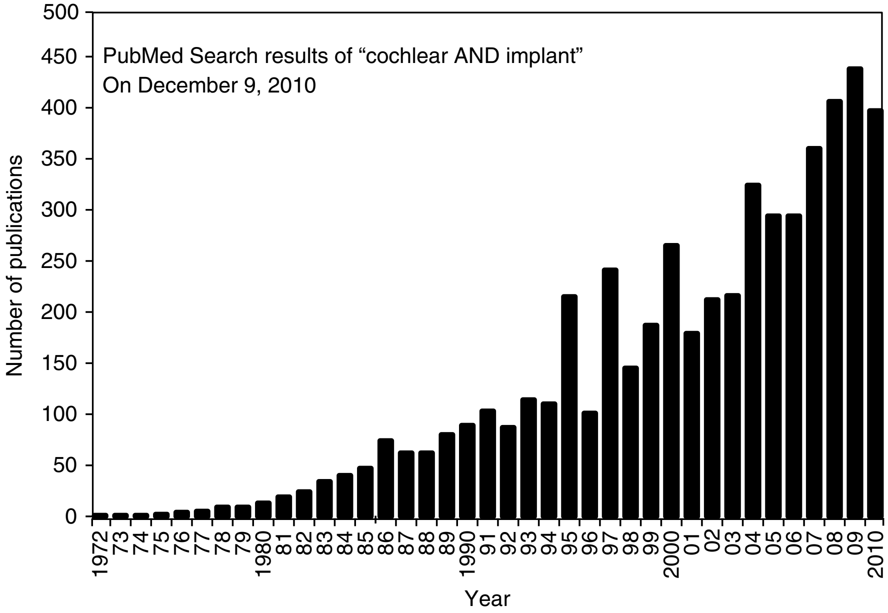

Fig. 1.3 Annual number of publications since 1972 on cochlear implants retrieved from PubMed (http://www.ncbi.nlm.nih.gov) on December 9, 2010

2 Advances in Technological Approaches

Cochlear implants have greatly expanded their function and utility through improvement in technology and application to a broad range of hearing related disorders. One aspect of the advances is the realization that auditory sensation can be induced by different physical energies (Fig. 1.4). In normal hearing, acoustic energies are converted into mechanical vibrations and then into electric potentials. In impaired hearing, different interventions are needed depending on the types and degrees of hearing impairment. For most listeners with cochlear loss, the mechanical amplification function is damaged and can be partially replaced by hearing aids, which take in sound and output its amplified acoustic version (first pathway in Fig. 1.4). To increase amplification and avoid acoustic feedback, sound can be converted into mechanical vibration to stimulate the middle ear (second pathway). In cases of profound deafness, sound has to be converted into electric pulses in a conventional cochlear implant, bypassing the damaged microphone function and directly stimulating the residual auditory nerve (third pathway). Recently, optic stimulation has also been found to be able to activate the nerve tissue directly (fourth pathway), providing potentially advantageous alternative to traditional electric stimulation.

The other aspect of advances is stimulation at different places of the auditory system, which can be used to treat different types of hearing impairment. The eardrum

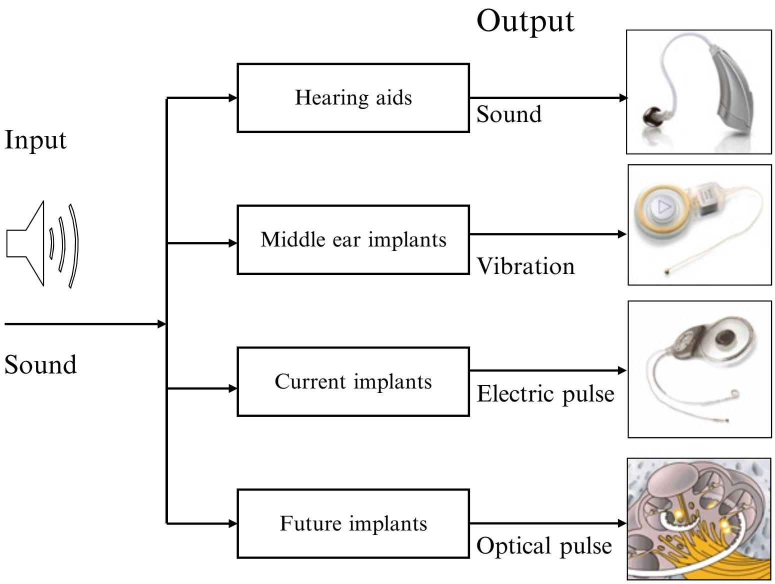

Fig. 1.4 Different approaches to stimulation of the auditory system. Hearing aid image is from www.starkey.com, middle ear implant image from www.medel.com, cochlear implant image from www.cochlear.com, and optical stimulation from www.optoiq.com

is stimulated acoustically in normal hearing and by amplified sound in a hearing aid to treat cochlear loss. The entire middle ear chain from incus to stapes can be stimulated mechanically to provide higher amplification and to treat persons with conductive loss related to collapsed ear canal and chronic ear diseases. The auditory nerve can be stimulated electrically, or optically, to provide functional hearing to persons with damaged inner hair cells. The entire central system from cochlear nucleus to cortex can also be stimulated to treat persons with acoustic tumors and other neurological diseases. Although not covered by the present volume, electric stimulation has been applied to treat auditory neuropathy, tinnitus, and multiple disabilities (Trimble et al. 2008; Van de Heyning et al. 2008; Teagle et al. 2010).

As the most natural extension to a single cochlear implant, bilateral cochlear implantation has experienced significant progress in terms of both clinical uptake and scientific understanding in the last decade. Van Hoesel (Chap. 2), who conducted the first study on bilateral cochlear implantation (van Hoesel et al. 1993), systematically reviews the rationale, progress, and remaining issues in this rapidly growing area. Compared with single cochlear implantation, bilateral implantation guarantees that the better ear is implanted. Although bilateral speech perception in noise and sound localization are improved by bilateral implants, the improvement is still modest and mostly comes from the acoustic head shadow effect that utilizes interaural level differences. There is little evidence that bilateral implant users take advantage of the interaural time difference to improve their functional binaural hearing, partially because of deprivation of binaural experience in typical users (Hancock et al. 2010) and partially because of the lack of encoding of low frequency fine structure information in current cochlear implants. One means of providing such low frequency fine structure information is to complement the cochlear implant with a contralateral hearing aid in subjects who have residual acoustic hearing.

Turner and Gantz (Chap. 3) focus on the improved performance of combined electro-acoustic stimulation (EAS) over electric stimulation alone. Compared with the typical 1 to 2 dB improvement in speech perception in noise with bilateral implants over unilateral implants, EAS can improve speech perception in noise by as much as 10 to 15 dB, depending on noise type and quality of residual hearing. The mechanisms underlying the improvement are also totally different between bilateral implantation and EAS, with the former relying on loudness summation, whereas the latter utilizes voice pitch to separate signals from noise or glimpsing signals at time intervals with favorable signal-to-noise ratios (Li and Loizou 2008). EAS, with its promising initial outcomes, improved surgical techniques, and signal processing, will likely continue to expand its candidacy criteria to include those who have significant residual hearing and possibly become the choice of treatment for presbycusis in the future.

In the near term, implantable middle ear devices have satisfactorily filled the gap between hearing aids and cochlear implants. Snik (Chap. 4) clearly delineates the complex technological and medical scenarios under which implantable middle ear devices can be used. Technologically, the middle ear implants avoid several pitfalls associated with the use of ear molds in most conventional hearing aids. These include the so-called occlusion effect where the hearing aid wearers' own voice sounds louder than normal, feedback squeal because of acoustic leakage between microphone and speaker, and undesirable blockage of residual hearing at low frequencies. Medically, for persons with conductive or mixed conductive and sensorineural loss, such as collapsed or lacking ear canals, chronic ear infection, and severe to profound hearing loss, hearing aids cannot be applied, and cochlear implants are not likely as effective as the implantable middle ear devices.

Dizziness and balance disorders are other major ear-related diseases that may also be treated by electric stimulation, but they have received little attention until recently. Golub, Phillips, and Rubinstein (Chap. 5) provide a thorough overview of the pathology and dysfunction of the vestibular system, as well as recent progress in the animal and engineering studies of vestibular implants. Especially interesting is their novel concept and design of a vestibular pacemaker that can be relatively easily fabricated and used to control dizziness. In October of 2010, the University of Washington group successfully implanted such a device in the first human volunteer. Compared with cochlear implantation, the enterprise of vestibular implantation is small but ready to take off, owing to the clinical need, encouraging animal studies, and the borrowing of similar cochlear implant technologies. Sophisticated sensor-based vestibular implants, a totally implantable device, and even vestibular brainstem implants, are likely to be developed and trialed by persons with severe balance disorders in the near future.

New technologies are also being developed to advance significant problems associated with current cochlear implants that use electrodes inserted in the scala tympani to stimulate the auditory nerve. With a bony wall separating the electrode and the nerve, the current implant not only requires high currents to activate the nerve, but also is severely limited by broad spatial selectivity and lack of access to apical neurons. Taking one approach, Richter and Matic (Chap. 6) advocate optical stimulation that should significantly improve spatial selectivity over the electric stimulation approach. The authors probe the mechanisms underlying optical stimulation and present promising preliminary animal data to demonstrate the feasibility of an optical cochlear implant. Middlebrooks and Snyder (Chap. 7) investigate an alternative approach that uses traditional electric stimulation but places the electrodes in direct contact with the neural tissue to achieve selective stimulation. In a cat model, this “intraneural stimulation” approach has produced not only low stimulation thresholds and sharp spatial selectivity, as expected, but more surprisingly and importantly, access to apical neurons that are more capable of transmitting temporal information than basal neurons. Both optical and intraneural stimulation approaches have the potential to improve current cochlear implant performance by quantum steps but are likely years away from human clinical trials: they have to overcome challenging technical issues such as size (for optical stimulation) and stability (for both).

In patients lacking a functional cochlea or auditory nerve, higher auditory structures have to be stimulated to restore hearing. Along with pioneers such as Robert Shannon, Derald Brackmann, and William Hitselberger, McCreery and Otto (Chap. 8) present a uniquely personal as well as masterfully professional account of research and development of cochlear nucleus auditory prostheses or auditory brainstem implants (ABI). ABIs have evolved from a simple single surface electrode device to sophisticated devices with multiple surface and penetrating electrodes. Their utilities have also been expanded from initial treatment of patients with bilateral acoustic tumors to current inclusion of non-tumor patients with ossified cochleae and damaged auditory nerves. The unexpected yet surprisingly good performance with the non-tumor patients is especially encouraging, because it not only allows many more suitable patients but also presents unique opportunities for improved understanding of the basic auditory structures and functions.

Because of its well defined laminated structure and easy access in humans, the inferior colliculus has also been targeted as a potential site of stimulation. As the inventors of the auditory midbrain implant (AMI) stimulating the inferior colliculus to restore hearing, Lim, M. Lenarz, and T. Lenarz (Chap. 9) discuss the scientific basis, engineering design, and preliminary human clinical trial data of the AMI. Although still in its infancy, AMI continues to push the technological and surgical envelope and to expand the horizon for wide acceptance and high efficiency of central auditory prostheses. For example, it may build a bridge between auditory prostheses and other well established neural prostheses, e.g., deep brain stimulation that have been used to treat a wide range of neurological disorders from Parkinson's disease to seizures. It is possible that future central prostheses will be integrated to treat not only one disability but also a host of disorders including hearing loss and its associated symptoms, such as tinnitus and depression.

3 Advances in Functional Rehabilitation and Assessment

While it is important to continue to develop innovative devices, it is equally important to evaluate their outcomes properly and to understand why and how they work. Rehabilitation and assessment of auditory prostheses can be challenging, due to the complexity and diversity at the input and output of the auditory system (Fig. 1.5). The input can be based solely in the hearing modality via either acoustic or electric stimulation or both; the auditory input can be combined with visual cues (e.g., lipreading) and tactile cues. The output can be measured by speech perception, music perception, language development, or cross-modality integration. The deprivation of auditory input and its restoration by various auditory prostheses provide opportunities to study the physiological processes underlying brain maturity, plasticity, and functionality. Functionally, research has taken advantage of brain plasticity to improve cochlear implant performance by perceptual learning and training. In recent years, significant advances have been made in understanding these input–output relationships, the feedback loop, and their underlying physiological processes. Quantitatively, the number of publications in the last 5 years has doubled that of the previous 5 years in essentially every category, including cochlear implant plasticity (37 vs. 67), training (102 vs. 223), language development (151 vs. 254), music (27 vs. 112), tonal language (137 vs. 264), and cross-modality (62 vs. 126) research. Chapters 10 through 15 qualitatively present advances in these areas.

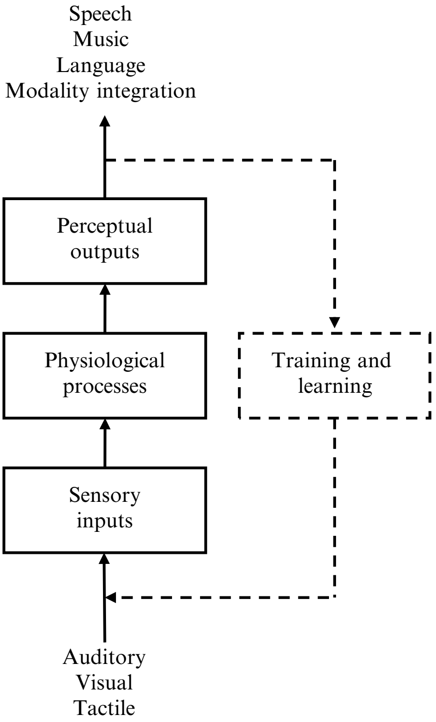

Fig. 1.5 A system approach to understanding of cochlear implant performance and function

Sharma and Dorman (Chap. 10) review both deprivation-induced and experience-dependent cortical plasticity as a result of deafness and restoration of hearing via cochlear implants. Coupled with language outcome measures and assisted by innovative non-invasive technologies from cortical potentials to brain imaging, central development research has identified a sensitive period up to 7 years, with an optimal time of the first 4 years of life, for good cochlear implant performance in prelingually deafened children. In postlingually deafened adults, central plasticity studies have identified non-specific cortical responses to electric stimulation due to cross-modal reorganization as one cause for poor cochlear implant performance. These central studies will continue to reveal neural mechanisms underlying cochlear implant performance, and more importantly, will guide development of effective rehabilitation for cochlear implant users.

Fu and Galvin (Chap. 11) document both the importance and effectiveness of auditory training for cochlear implant users. Because electric stimulation is significantly different from acoustic stimulation and usually provides limited and distorted sound information, auditory learning, sometimes referred to as adaptation, is needed to achieve a high level of cochlear implant performance. Compared with costly updates in hardware and software, structured auditory training can be much cheaper but equally effective if adequate information is provided. Auditory training will continue to grow in both basic and clinical areas, but research questions about the limit, optimization, and generalization of learning need to be answered.

One example of human learning, language development, particularly spoken language development, seems to be so effortless for a normal-hearing child but so challenging, if not impossible, for a deaf child. Can normal language develop following pediatric cochlear implantation? This has been a classic question facing researchers in the auditory prosthesis field. By reviewing normal language development, its negative impact by hearing impairment, and remarkable progress made by cochlear implantation, Ambrose, Hammes-Ganguly, and Eisenberg (Chap. 12) convincingly answer this question: despite great individual differences, many pediatric implant users have developed language capabilities on par with their hearing peers. This is a remarkable triumph not only by cochlear implant researchers and educators, but more importantly, for half of the pediatric users of the total 200,000 cochlear implants worldwide. It is expected that language development performance will increase while individual variability will decrease as technology continues to advance and more children receive the cochlear implant in the first 3 to 4 years of life, the optimal time within the sensitive period (see Chap. 10).

However, music perception remains challenging to cochlear implant users. Except for rhythmic perception that is similar to normal hearing persons, cochlear implant users perform much poorer in melody and timbre perception. McDermott (Chap. 13) reviews extensive research and recent progress in this area and identifies both design and psychophysical deficiencies that contribute to poor implant music performance. The key to improving cochlear implant music perception seems to lie in the encoding of pitch and related temporal fine structure, which not only form the basis of melody and timbre perception but also are critical to separating multiple sound sources, including different musical instruments in an orchestra.

Similarly, tone production and perception are a challenge to cochlear implant users who speak a tonal language. Xu and Zhou (Chap. 14) summarize acoustic cues in normal tonal language processing and, not surprisingly, isolate the lack of temporal fine structure in current devices as the culprit for their users' poor tone production and perception. They also identify age of implantation and duration of device usage as two demographic factors that influence tone production and perception in pediatric cochlear implant users. It is important to note that poor tone representation in cochlear implants not only affects tonal language processing, as expected, but it also disrupts or delays other important tasks such as vocal singing and even generative language development in non-tonal languages (Nittrouer and Chapman 2009).

In a natural environment, communication is usually multi-modal, involving auditory, visual, and other senses. In fact, cochlear implants were used mostly as an aid to lip-read in early days. Recently, multisensory processing in cochlear implants has become a hot topic, providing a unique and interesting model to study brain plasticity and integration in humans. Barone and Deguine (Chap. 15) review the latest advances in this new direction of research and present a unifying compensation model to account for the observed greater than normal cross-modality activation before and after cochlear implantation. Despite rapid progress in neuroscience of multisensory processing in cochlear implants, cross-modal applications to rehabilitation are still lagging but have great potential to improve overall cochlear implant performance in the future.

4 Summary

After steady progress in cochlear implant performance, mostly because of improved signal processing with multi-electrode stimulation in the 1990s, auditory prostheses entered a new era in the first decade of the twenty-first century. Three distinctive features mark the new ear. The first feature is “multiple stimulation in different places.” The multiple stimulation includes bilateral electric stimulation, combined acoustic and electric stimulation, mechanical and optical stimulation, and visual and tactile stimulation. The different places include not only traditional acoustic and electric pathways, namely, the ear canal for hearing aids and scala tympani for cochlear implants, but also new stimulation sites from the auditory nerve to brain stem and midbrain structures that form direct contact with surface or penetrating electrodes. The second feature is the improvement of cochlear implant outcomes beyond speech perception, including language development, music perception, and tonal language processing. The means to improve cochlear implant performance has also been expanded to include identification of optimal cochlear implant time and candidacy as well as applications of auditory training and multisensory integration. The third feature is to apply the principles and successes of cochlear implants to the treatment of other neurological disorders such as auditory neuropathy, tinnitus, and dizziness.

The present volume is intended not only to capture these advances in auditory prostheses but also to extend the new horizon for future research and development. There is no question that current technological trends will continue, including fine timing control and sharp spatial selectivity in the device and the electronics-neuron interface, more and better use of residual low frequency acoustic hearing, structured learning and multisensory training, and biological means of preserving or even increasing nerve survival. There are also several new development efforts that will either significantly improve cochlear implant performance or change the face of auditory prostheses altogether. First, the rapid progress in bioengineering and regenerative medicine will produce more natural, highly efficient and effective electronics-neuron interfaces, including possibly a fifth pathway, chemical stimulation via reconstructed synapses, to evoke auditory sensation (Fig. 1.4). Second, auditory prostheses will be integrated with other peripheral and central prostheses (e.g., vestibular and deep brain implants) to treat not just one symptom but to address its whole spectrum (for example, hearing loss and its associated problems in tinnitus, dizziness, and depression). Finally, progress in neuroscience, particularly non-invasive brain monitoring will allow a full account of individual variability in cochlear implant performance, monitoring presurgical prediction of postsurgical performance, and more importantly, closed-loop fitting, operation and optimization of cochlear implants.

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