# Overview and Challenges of Implantable Auditory Prostheses

Until the middle of 20th century it was believed that a full understanding of the anatomy and physiology of the ear and the neural system is required for achieving successful auditory prostheses devices that can substitute the clever and subtle functions of the middle and inner ears and the associated neural structures. Surprisingly however very quickly auditory implants happened to become successful enough to be an accepted clinical treatment for restoring hearing and communication abilities to individuals with profound and severe deafness and have been used by around 200,000 people worldwide to date. Auditory implants bypass the ear and stimulate the auditory system electrically via tiny electrodes inserted in close contact with or directly inside the auditory processing structures of the brain, from where neural activity transmits to cortical areas and produces auditory perception. The first demonstrations that electric stimulation, instead of sound, can induce auditory sensations likely started more than two centuries ago with an unpleasant sound when the Italian scientist Alessandro Volta (1745–1827) placed the two ends of a 50-volt battery to his ears. Electronic hearing was brought into clinical practice in 1960's and has considerably improved in both safety and performance since the early trials that electrically activated a wire simply inserted into the ear of the deaf volunteers.

## Cochlear Implants

Cochlear implants, mimicking the processing that takes place in a normal ear, transform acoustic energy to auditory nerve activity and thus bypass the malfunctioning or missing middle and inner ears in severe deafness. Figure 1 shows a typical modern cochlear implant system. The behind ear segment is a micro-computer that processes and converts into RF (Radio Frequency) the environmental sounds picked up by a microphone. The surgically placed internal part receives and decodes the RF signals and generates electrical current pulses. The electrical activity transmits to the auditory nerve fibers via contacts of a linear array of electrodes that the surgeon carefully inserts inside the cochlea through the round window in the inner ear. Auditory nerve, similar to the neural structures in the other stages of auditory processing is tonotopically organized. In other words the electrodes along the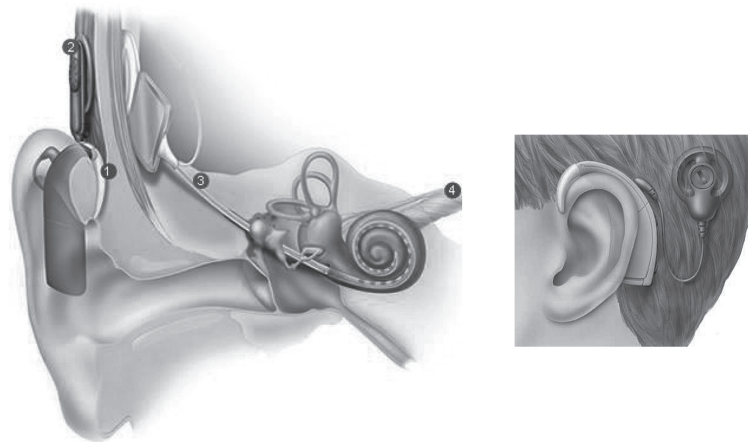 cochlea from cochlear base to apex are located in descending order of the frequency percept they produce when electrically activated. Cochlear implant processing takes advantage of this tonotopicity and encodes the energy of each narrow spectral band of the signal by the level of electrical activity on the implant electrode whose tonotopic location is estimated to be associated to the band's center frequency. Thus the electrical signal delivered to the auditory nerve is a coarse representation of the input sound's spectrogram obtained with a fixed number of frequency bins equal to the number of electrodes. However the auditory processing system of most cochlear implant users is not able to fully receive or optimally decode the information presented by the electrodes. The average speech perception performance of cochlear implant users is poorer than that of normal hearing listeners presented with a similarly spectrally degraded signal.

## Auditory Brainstem Implants

The design of auditory brainstem implants is similar to that of cochlear implants except that their matrix array of electrodes is located more centrally on the surface of Cochlear Nucleus, one of the first stages of the auditory brainstem. Auditory brainstem implants are now clinically used in the conditions that cannot be alleviated via cochlear implantation, i.e. where auditory nerve is absent or damaged (via congenital non-development, tumor damage, or surgical damage resulting from tumor removal) or where the cochlea has malformations that prevent viable electrode array insertion. The current brainstem implants use the same speech processors as cochlear implants. The stimulation site of brainstem implants is complex and contains different types of neurons with differing roles in auditory processing. This is perhaps the reason why performance of the users of these devices is usually poorer than the average users of cochlear implants.

## Challenges of electronic hearing

Despite not having access to much of the speech spectral and temporal details, most users of auditory implants are able to communicate well specially when using the device in conjunction with lip reading. However there is a huge individual variability in the outcome with the implant alone. To date there is no clear expla-

**Figure 1.** The external and the surgically implanted segments of a modern cochlear implant (www.cochlear.com).

nation why with the same device, some implant users have zero speech recognition in natural environments and some do perform much closer to normally hearing listeners. There is also no reliable method of predicting the outcome before prescribing the implant and performing the surgery. There are certainly inevitable differences among implant users in how the electrodes were inserted during the surgery and how the implant signal is coded by the neural system. The location of the electrode array within the stimulation site may introduce in some implantees a large mismatch between the tonotopic map of the electrodes and the center frequencies to which the electrodes are assigned in the signal processor. The spread of electrical current along the tonotopic axis, influenced by both the distance of electrodes from the neural fibers and the distribution of the functioning neurons, causes overlap in the neural fibers stimulated by different electrodes and thus may blur the spectral representations in some implant users. The ability of neural responses to follow and transmit to the higher processing stages the temporal variations of electrical stimulation might be another source of variability of implant users. Although using simple psychophysical and electrophysiological methods huge differences have been observed among implant users in their abilities to encode spectral and temporal information of the implant signal, none of these factors has been consistently known to play a considerable role in speech perception with an auditory implant.

Age and etiology of deafness play some role in the outcome with implants. In implanted adults there is a trend that those who were prelingually deafened or were not hearing for a long period before implantation are the poorer performers. However it is not known how the representation of speech information is affected by these factors. It has been speculated that the auditory system may lose some of its functioning neurons at different processing levels or be taken over by the other sensory modalities such as vision or touch if doesn't get stimulated for a long period.

## Future Directions

Respecting the individual differences, development of auditory implants requires a better understanding of how the brain of each individual implant user decodes the spectral and temporal information presented by implant electrodes. In addition to peripheral processing, implant studies should consider brain plasticity and the outstanding ability of the speech processing system to adapt to the novel situations and extract from the redundant complex signal the reliable information for communication. Central auditory processes may play an important role in compensating for or interacting with the limitations of cochlear implant stimulation and the misrepresentation of information at the peripheral neural system.

Implants that stimulate more central auditory system bypass more of the neural structures and can theoretically restore hearing to a wider range of deaf people affected by neuroplogical disorders. The future development of these implants should take into account the functional anatomy of the stimulation sites to devise new processing strategies.

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