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History of Cochlear Implants and Auditory Brainstem Implants

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Abstract

Cochlear implants have evolved during the past 30 years from the single-electrode device introduced by Dr. William House, to the multi-electrode devices with complex digital signal processing that are in use now. This paper describes the history of the development of cochlear implants and auditory brainstem implants (ABIs). The designs of modern cochlear and auditory brainstem implants are described, and the different strategies of signal processing that are in use in these devices are discussed. The primary purpose of cochlear implants was to provide sound awareness in deaf individuals. Modern cochlear implants provide much more, including good speech comprehension, and even allow conversing on the telephone. ABIs that stimulate the cochlear nucleus were originally used only in patients with neurofibromatosis type 2 who had lost hearing due to removal of bilateral vestibular schwannoma. In such patients, ABIs provided sound awareness and some discrimination of speech. Recently, similar degrees of speech discrimination as achieved with cochlear implants have been obtained when ABIs were used in patients who had lost function of their auditory nerve on both sides for other reasons such as trauma and atresia of the internal auditory meatus.

Cochlear Implants

When Dr. William House [1] first introduced the cochlear implant it was met with great skepticism. Pioneering work by Michaelson regarding stimulation of the cochlea preceded the first clinical application of this technique [2]. While the success of modern multichannel cochlear implants is a result of technological developments, this success would not have been achieved, at least not as rapidly, if brave individuals such as Dr. House had not taken the bold step to try to provide some form of hearing sensations for individuals who were deaf because of injuries to cochlear hair cells.

Published studies of electrical stimulation of the auditory nerve date back half a century when Djourno and Eyries [3] described how electrical current passed through the auditory nerve in an individual with a deaf ear could cause sound sensation although only noise of cricket-like sounds. Later, Simmons et al. [4] showed that electrical stimulation of the intracranial portion of the auditory nerve using a bipolar stimulating electrode could produce a sensation of sound and some discrimination of the pitch of the stimulus impulses below 1,000 pulses per second (pps) with a difference limen of 5 pps. Above 1,000 pps, the discrimination of pitch was absent but the participant in the test could distinguish between rising and falling pulse rates.

The earliest cochlear implants used a single electrode placed inside the cochlea [1]. Introduction of cochlear implants that use multiple implanted electrodes and better processing of the signals from the microphone provided major improvements in speech discrimination. Using more than one electrode made it possible to stimulate different parts of the cochlea and thereby different populations of auditory nerve fibers with electrical signals derived from different frequency bands of sounds. Now, all contemporary cochlear implants separate the sound spectrum using bandpass filters so that the different electrodes are activated by different parts of the sound spectrum [5]. When such more sophisticated processing of sound was added the results were clearly astonishing, and modern cochlear implants can provide speech discrimination under normal environmental conditions [6]. Even those individuals who had great expectations were surprised by these accomplishments.

Sound Processing in Cochlear Implants

All modern cochlear implant devices process sounds and these processors have contributed greatly to the success of cochlear implants and auditory brainstem implants (ABIs). The advent of fast microprocessors, similar to what is found in personal computers, has made it possible to perform sophisticated signal processing of the sounds that are picked up by a microphone. Processors of modern cochlear and brainstem implants operate on the sounds picked up by the wearer's microphone. Refining the way the processors work and especially the algorithms used that has occurred during past one or two decades has contributed considerably to the success of cochlear implants. These processors have undergone many stages in their evolution since Dr. House introduced the first cochlear implants.

The processors of the first cochlear implants converted sound into a high-frequency signal that was applied to a single electrode in the cochlea. Contemporary cochlear implants have an array of several electrodes implanted

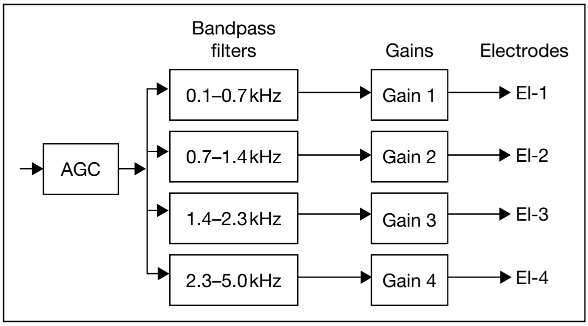

Fig. 1. Four-channel cochlear implant processor using the compressed analog principles. The signal is first compressed using an AGC, and then filtered into four contiguous frequency bands, with center frequencies at 0.5, 1, 2, and 3.4 kHz. The filtered waveforms go through adjustable gain controls and are then sent directly through a percutaneous connection to four intracochlear electrodes. Modified from Loizou [5].

in the cochlea so that the different electrodes stimulate auditory nerves along the basilar membrane, and processors that separate the sound spectrum using bandpass filters so that the different electrodes are activated by different parts of the sound spectrum. The dynamic range of electrical stimulation of auditory nerve fibers is much smaller than that of the normal activation through stimulation of cochlear hair cells; therefore, cochlear implant processors must compress the range of sound intensities (automatic gain control, AGC) before it is applied to the bank of bandpass filters. Also the output of the bandpass filters is often subjected to some form of gain control.

In the simplest version of processors for multichannel cochlear implants, the spectrum of the signals from the microphone is divided into 4–8 frequency bands by a bank of bandpass filters. The output of these filters is applied to the respective electrodes after AGC (fig. 1). This type of processors (known as the compressed analog, CA principle) presents both spectral and temporal information to the implanted electrodes and thus both spectral and temporal information become coded in the discharge pattern of the stimulated nerve fibers. (The CA approach was originally used in the Ineraid device manufactured by Symbion, Inc., Utah, USA [7]. The CA approach was also used in a UCSF/Storz device, which is now discontinued.)

Electrical interaction (cross-talk) between the electrodes that are implanted in the cochlea reduced the actual channel separation in the cochlear implants that used the CA principle. To solve this problem, short electrical impulses were applied to the different electrodes of the cochlear implants instead of (analog) signals from the bandpass filters and the different electrodes were activated

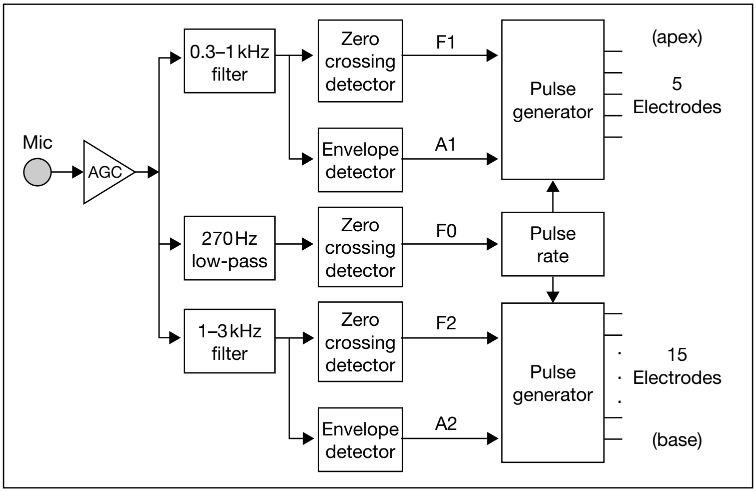

Fig. 2. Block diagram of the F0/F1/F2 processor. Two electrodes are used for pulsatile stimulation, one corresponding to the F1 frequency and the other corresponding to the frequency of F2. The rate of the impulses is that of F0 for voiced sounds, and a quasi-random rate (average of 100 pps) for unvoiced segments. From Loizou [5].

with small time intervals (continuous interleaved sampling, CIS) [5, 8; see also Loizou, this vol, pp 109–143]. The output of the bandpass filters controlled the amplitude of the impulses that were applied to the implanted electrodes. One manufacturer (Clarion) offers devices with processors that can be programmed with either the CA strategy or the CIS strategy. A modified CIS strategy, the enhanced CIS, is used in cochlear implants manufactured by the Philips Corporation under the name of LAURA [9].

With the progress in the sophistication of digital processing technology, the processors grew more and more complex and some of them analyze the sounds in detail and provide information about such features as formant frequencies of vowels and code that in the train of impulses that are applied to the implanted electrodes. The output of these processors was coded in electrical impulses that were applied to the electrodes in the implants. Introduction of these processors implied a fundamentally different approach from the CA or CIS principles of processing described above, although they used the CIS principle for applying the impulses to the stimulating electrodes. (Processors such as the Nucleus device that employ such feature extraction were introduced in the 1980s.)

Other processors especially designed for enhancing speech discrimination were developed for the Nucleus device in the early 1980s (fig. 2). These processors use a combination of temporal and spectral coding (known as the F0/F1/F2

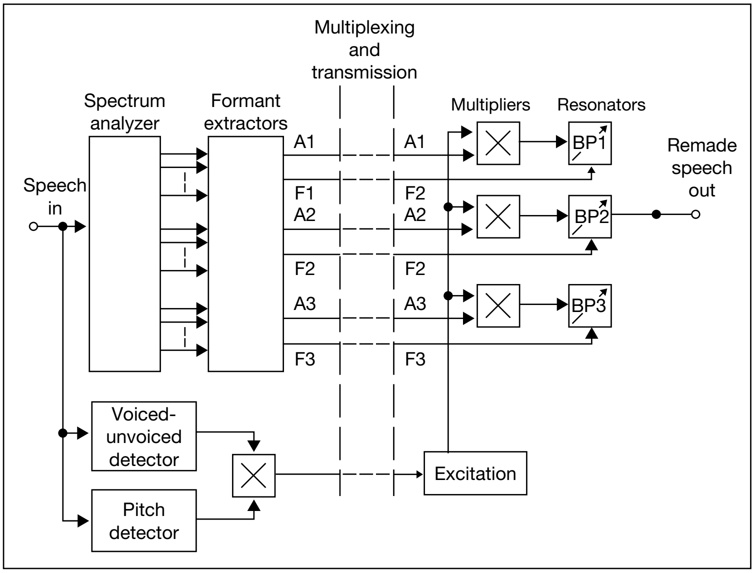

Fig. 3. Schematic diagram of a vocoder that was developed in the early 1960s. From Schroeder [10].

strategy). The fundamental (voice) frequency (F0) and the first and second formant (F1 and F2) were extracted from the speech signal using zero crossing detectors; F0 was extracted from the output of a 270-Hz low-pass filter, and F2 was extracted from the output of a 1,000- to 4,000-Hz bandpass filter (fig. 2). In a Nucleus device, the output of the processor controls the impulses that are applied to the implanted 22-electrode array. Another variant of this kind of processors, known as the MPEAK strategy, also extracts the fundamental frequency (F0) and the formant frequencies (F1 and F2) code the information in the pattern of the impulses that are applied to the implanted electrodes.

The algorithms used in these cochlear implant processors performed similar analysis as was developed half a century ago for use in analysis-synthesis telephony systems [10] (fig. 3). The goal was to provide continuous measures of features of speech sounds such as formant frequencies, the fundamental frequency of voiced sounds and information about fricative consonants, etc. to be sent to the receiver where it was used for synthesizing the speech. When used in cochlear implant processors, these complex systems did not live up to the expectations because they did work well in noisy environments [5], which often is present in connection with normal listening conditions. Background noise was not a concern for the development of telephony systems.

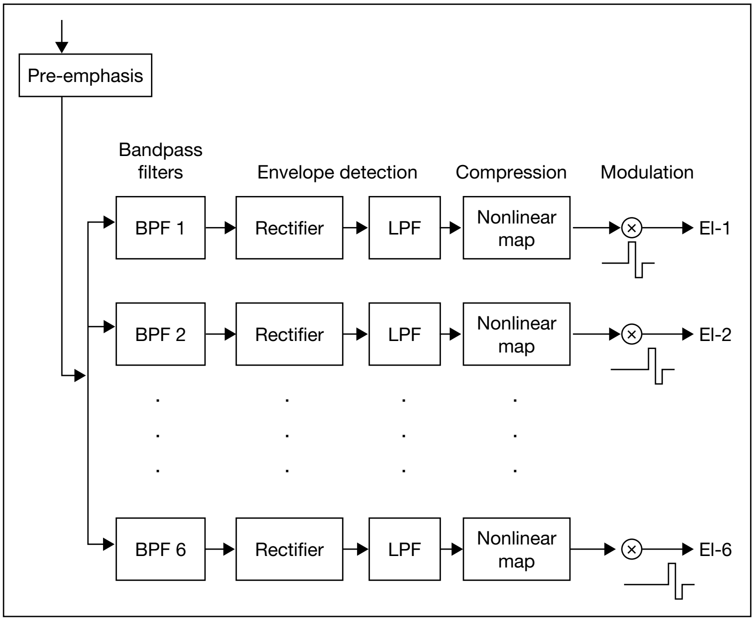

Fig. 4. Block diagram of a processor of the channel vocoder type that uses the CIS strategy in cochlear implants. The signal is first passed through a network that changes the spectrum (pre-emphasis) and then filtered in 6 bands. The envelope of the output of these six filters is full-wave rectified and low pass filtered. The low-pass filters are typically set at 200- or 400-Hz cut-off frequency. The amplitude of the envelope is compressed and then used to modulate the amplitude of biphasic impulses that are transmitted to the electrodes in an interleaved fashion. Modified from Loizou [5].

These kinds of processors were subsequently abandoned by most manufactures of cochlear implants because of the disappointing results in noisy environments and less complex systems were developed. These new strategies are based solely on information about the energy in a few frequency bands and the information about the temporal pattern is not used. Information about the energy in a few (6–10) frequency bands together with the smoothed temporal pattern of the envelope of the output of these bandpass filters is coded in the impulses that are applied to the implanted electrodes (fig. 4).

These systems that are known as channel vocoder-type processors, are now the most common type of processors in cochlear implant devices. The paper by Loizou [this vol, pp 109–143] provides a detailed description of processors that use the principles of the channel vocoder principle including variations of that strategy. One of these schemes, known as the Spectral Maxima Sound Processor treats all sounds equally and determines spectral maxima on the basis of the output of 16 bandpass filters. The output of the 6 bandpass filters with the largest amplitudes modulates the amplitude of biphasic impulses with a constant rate of 250 pps. These impulses are applied to the electrodes in the cochlea. A similar analysis scheme, the spectral peak strategy uses 20 filters instead of 16. For details about these processing strategies, see Loizou [5]. Many other strategies have emerged during recent years not only to improve speech discrimination but also to improve perception of other kinds of sounds, especially music. Some of these developments are discussed in the paper by Loizou [this vol].

Selection of Patients for Cochlear Implants

The success of cochlear implants depends on the selection criteria and these have changed over years. When cochlear implants first became available, only individuals who were essentially deaf (profound sensorineural hearing loss) received cochlear implants, and it took a long time before young children were given implants. More recently, a broader indication is accepted [11, 12] because it has become evident that individuals with severe hearing loss can benefit from cochlear implants. Bilateral implantation is now accepted. It is now regarded to be essential to provide cochlear implants to children as young as possible [13, 14; see also Sharma and Dorman, this vol, pp 66–88, and Kral and Tillein, this vol, pp 89–108].

Understanding the cause of hearing loss is important for selection of candidates for cochlear implants. Cochlear implants should naturally not be considered for individuals who have hearing loss caused by auditory nerve pathologies, for example individuals who have had bilateral vestibular schwannoma removed. Cochlear implants should not be given to children with auditory nerve aplasia caused by a narrow internal auditory canal, or trauma causing interruption of the auditory nerve [15]. Such children should instead have ABIs [Shepherd and McCreery, this vol, pp 186–205]. Candidates for cochlear implants should have appropriate examination and tests to exclude auditory nerve disorders as a cause of their deafness including an MRI scan that shows the structure of the internal auditory canal and not only the anatomy of the middle and inner ear [16]. ABIs should also be considered for individuals with hearing loss from injuries caused by trauma or diseases affecting the auditory nerve (auditory neuropathy) [Shepherd and McCreery, this vol, pp 186–205].

Auditory Brainstem Implants

Early studies of electrical stimulation of the inferior colliculus in humans did not provide any sensation of sound [4]. However, Colletti et al. [17] recently implanted electrodes in the inferior colliculus in a patient with bilateral auditory nerve section from bilateral vestibular schwannoma removal, demonstrating that electrical stimulation of the inferior colliculus can indeed provide sound sensation and some comprehension of speech.

William House and his colleagues at the House Ear Institute in Los Angeles [18, 19] introduced the use of a prosthesis that stimulated the cochlear nucleus electrically through an array of electrodes placed on the surface of the cochlear nucleus. These devices became known as ABIs. Before introduction of the ABI, it was shown that electrical stimulation of the cochlear nucleus in humans could produce auditory sensations [20].

Placement of the Electrode Array

ABIs use an array of approximately 20 electrodes placed on a plastic sheet. The electrode array is placed in the lateral recess of the fourth ventricle through the foramen of Luschka [21] in a similar way as electrodes that have been used for recording evoked potentials from the cochlear nucleus in neurosurgical operations [21–23]. Placement of an electrode array on the surface of the cochlear nucleus [Fayad et al., this vol, pp 144–153] is technically more demanding than placements of electrodes in the cochlea. Not only is it more difficult to maintain a stable electrode placement of electrodes in the brain than in the cochlea, but also it is also more difficult to place the electrode array so that an optimal population of nerve cells is stimulated. The use of electrophysiological methods for guiding positioning of electrode arrays is now widely used [15, 24; see also Nevison, this vol, pp 154–166].

Processors

Processors used in connection with ABIs use similar strategy as those used in cochlear implants. However, as more information about stimulation of the cochlear nucleus is obtained it may be expected that specialized strategies for processing of sounds for ABIs will be developed.

Selection of Candidates for ABIs

When first introduced, ABIs were almost exclusively used in patients with neurofibromatosis type 2 who had bilateral vestibular schwannoma removed. More recently, ABIs have been used in patients with bilateral traumatic injuries to the auditory nerve [15, 25, 26] and in children with malfunction of the auditory nerve such as may occur from internal auditory meatus malformation (atresia) causing auditory nerve aplasia [26]. ABIs are also now used in patients with cochlea malformation preventing implantation of electrodes [Shepherd and McCreery, this vol, pp 186–205]. While the results of ABIs in patients with bilateral tumors were disappointing, the results obtained in patients with other causes of auditory nerve injuries are similar to those obtained in patients with cochlear implants.

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