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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

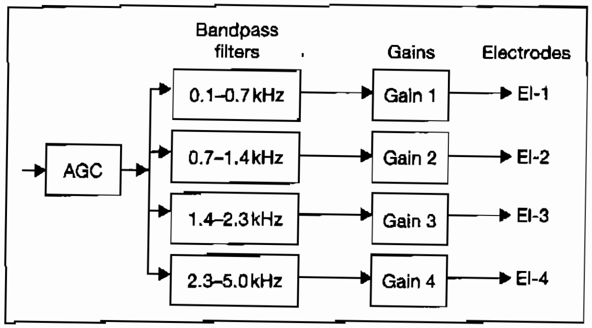

Fig. 1. Four-channel cochlear implant processor using the compressed analog principles. The signal is first compressed using an AGC, and then filtered into four contiguous frequency bands, with center frequencies at 0.5, 1, 2, and 3.4 kHz. The filtered waveforms go through adjustable gain controls and 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

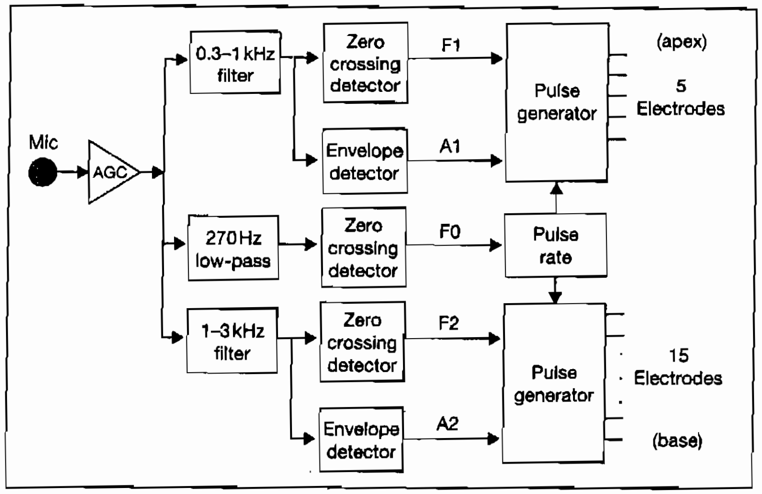

Fig. 2. Block diagram of the F0/F1/F2 processor. Two electrodes are used for pulsatile stimulation, one corresponding to the F1 frequency and the other corresponding to the frequency of F2. The rate of the impulses is that of F0 for voiced sounds, and a quasi-random rate (average of 100 pps) for unvoiced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

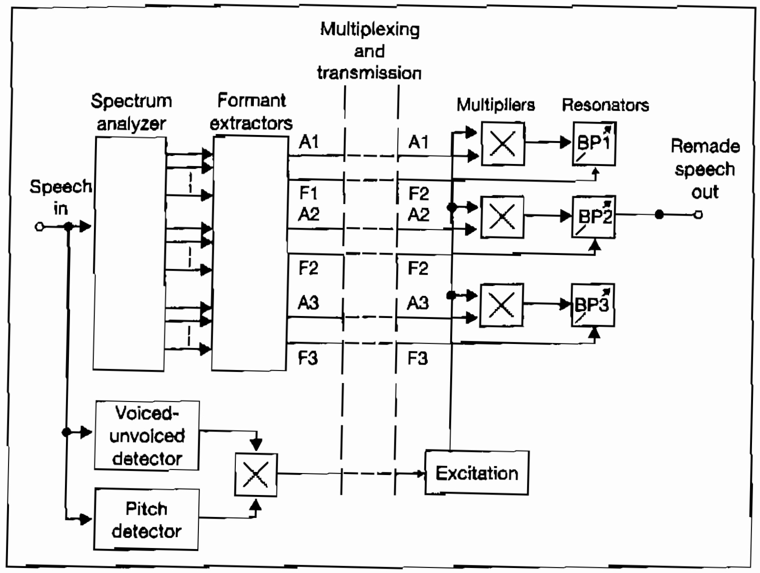

Fig. 3. Schematic diagram of a vocoder that was developed in the early 1960s. From Schroeder [10].

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.

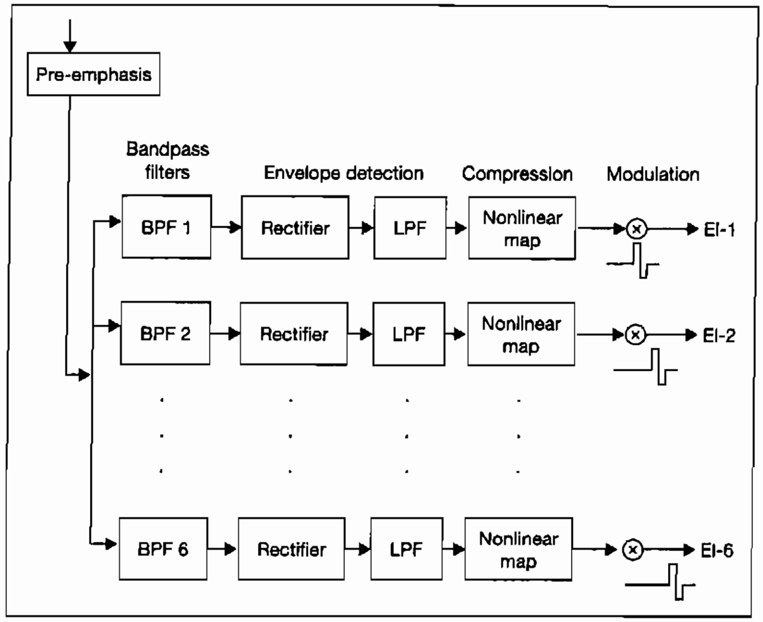

Fig. 4. Block diagram of a processor of the channel vocoder type that uses the CIS strategy in cochlear implants. The signal is first passed through a network that changes the spectrum (pre-emphasis) and then filtered in 6 bands. The envelope of the output of these six filters is full-wave rectified 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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Physiological Basis for Cochlear and Auditory Brainstem Implants

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Abstract

Cochlear implants bypass functions of the cochlea that have been regarded to be fundamental for discrimination of the frequency (or spectrum). Frequency discrimination is essential for discrimination of sounds, including speech sounds, and the normal auditory system is assumed to make use of both (power) spectral and temporal information for frequency discrimination. Spectral information is represented by the place on the basilar membrane that generates the largest amplitude of vibration on the basilar membrane. Evidence has been presented that the temporal representation of frequency is more robust than the place representation and thus regarded more important for speech discrimination. The fact that some cochlear implants provide good speech discrimination using only information about the energy in a few spectral bands seems to contradict these studies. In that way, frequency discrimination may be similar to trichromatic color vision, which is based on the energy in only three different spectral bands of light, accomplished by different color-sensitive pigments in the cones of the retina. Cochlear nucleus implants (ABIs) also bypass the auditory nerve, which does not perform any processing. Therefore, it may be expected that ABIs are equally efficient as cochlear implants. However, experience from the use of ABIs in patients with bilateral vestibular schwannoma has not been encouraging, but recent studies of the use of ABIs in patients with other causes of injuries to the auditory nerve have shown similar speech discrimination as achieved with modern cochlear implants. Cochlear implants and ABIs are successful in providing speech discrimination because of redundancy in the processing in the ear, redundancy of the speech signal and because the auditory nervous system has a high degree of plasticity. Expression of neural plasticity makes the auditory nervous system adapt to the change in demands of processing of the information provided by cochlear implants.

Cochlear implants bypass the normal function of the cochlea, and the processors in these devices are designed to replace functions of the cochlea that are regarded important for discrimination of sounds, foremost speech sounds. Modern cochlear implants provide useful hearing without replacing the function of the cochlea completely and without providing the same coding of sounds in the auditory nerve as that of the normal cochlea. The emphasis has been on providing information about both the temporal and spectral aspects of sounds, and more recently cochlear implant processors that only provide spectral information have become in common use [Loizou, this vol, pp 109–143]. Cochlear implants are mainly aimed at establishing adequate speech discrimination, and only recently has attention been directed to other kinds of sounds, such as music sounds.

When Dr. House first introduced the cochlear implant using a single electrode it was met with great skepticism because it seemed unlikely that such a simple device could in any way replace the intricate and complex function of the cochlea. Even the function of modern multichannel cochlear implants that provide some spectral and temporal information seems crude compared to that of the normal cochlea, and indeed, they replace only some functions of the cochlea, and incompletely.

There are three main reasons why cochlear implants are successful in providing speech intelligibility and identification of environmental sound despite the fact that they do not replace all the functions of the normal cochlea: (1) Much of the natural speech signals are redundant. (2) Much of the normal processing capabilities of the ear are redundant. (3) Much of the processing that normally occurs in the auditory nervous system is redundant. (4) The central nervous system has an enormous ability to adapt ('re-wire') to changing demands through expression of neural plasticity.

The fact that much of the speech signal is redundant explains why cochlear implants only need to transmit a small fraction of the information that is contained in speech sounds to achieve good speech intelligibility. This was recognized as early as 1928 when Dudley conceived the 'vocoder' for transmitting speech over telephone lines [1] and this observation has been confirmed in many later studies [Loizou, this vol, pp 109–143].

Vocoders (the name derived from VOice and CODER) were developed because bandwidth was expensive at the time when copper wires were used in long telephone cables such as transoceanic cables. Now, these principles have found use in cochlear and cochlear nucleus implants. Other schemes emerged for compression of speech with regard to the bandwidth [2] but none of these systems were ever realized because of the availability of satellites and later fiber optic cables which offered inexpensive and reliable bandwidth that became available before vocoder systems could be realized into practical telephone systems. Before cochlear implants became in use, vocoders were used for developing devices for speech communication using the tactile sense [3].

It was earlier assumed that the complex function of the cochlea as a spectrum analyzer was the basis for the place hypothesis for frequency discrimination and that the neural coding of the temporal pattern of sounds was the basis for the temporal hypothesis of frequency discrimination. Both of these kinds of coding provided by the cochlea were assumed to be essential for discrimination of sounds such as speech sounds. The redundancy of these different kinds of analysis and coding of sounds in the ear were not fully appreciated before the results of studies of cochlear implants were available, although speech research had shown many years earlier that good speech discrimination could be achieved from spectral information only [1], thus based on the place hypothesis of frequency discrimination only. However, the experience from cochlear implants has confirmed these early results and brought new aspects on the functional importance of the analysis that occurs in the normal ear and the coding of sounds that occur in the auditory nerve. That the nervous system is plastic can explain why cochlear implants can provide adequate speech discrimination even though the coding of speech by cochlear implant processors is less sophisticated than that of the normal ear and why the use of different principles of coding can result in similar degree of speech discrimination.

The auditory nervous system is far more important for discrimination of sounds than generally recognized, and its capabilities to reorganize and the extent of redundancy in neural processing in the ascending auditory pathways, including the cerebral cortex, were likewise underestimated before experience of the performance of cochlear implants.

One aspect of the redundancy of the processing in the normal ear and auditory nervous system was demonstrated in psychoacoustic studies [1, 4, 5]. These studies showed that speech discrimination could be achieved on the basis of only spectral information or on the basis of only temporal information. That can explain why different processing schemes for cochlear implant processors can achieve similar speech discrimination abilities.

In this paper we will discuss the physiological basis for cochlear and cochlear nucleus implants. We will focus on frequency discrimination and discuss why cochlear and cochlear nucleus processors that are based on different principles can provide good speech discrimination. The similarity between auditory frequency discrimination using only power spectral cues and color vision will be discussed. Hypotheses about the differences in performance of auditory brainstem implants (ABIs) in NF2 patients and in patients with other causes of auditory nerve dysfunction are also discussed.

Auditory Frequency Discrimination: Place or Temporal Hypotheses?

Providing frequency discrimination is a prominent feature of the ear and the auditory nervous system and it is assumed to be important for speech discrimination, although changes in amplitude and duration of sounds and gaps between sounds are also important for discrimination of speech sounds. Much attention has therefore been devoted to find the anatomical and physiological bases for auditory frequency discrimination.

The ear provides two different codes of the frequency of sounds to the auditory nervous system, namely information about the (power) spectrum of sounds and about the waveform of sounds (temporal pattern) [for details about the anatomy and physiology of the cochlea, see 6]. Physically, the frequency (or spectrum) of sounds can be determined equally well from the result of spectral analysis such as that performed by the cochlea, as from analysis of the time pattern of sounds. This means that information about the frequency (or spectrum) of sounds can be derived from both of these two types of coding of sounds, which are the basis for the place hypothesis and the temporal hypothesis for frequency discrimination, respectively. Frequency analysis in the cochlea is the basis for the place hypothesis, and coding of the temporal pattern of sounds in the discharge pattern of auditory nerve fibers is the basis for the temporal hypothesis [6].

There is ample evidence from animal experiments that frequency is normally coded in the discharge pattern of single auditory nerve fibers, both as a temporal and a place code. Frequency tuning is a characteristic feature of nerve cells throughout the ascending classical auditory nervous system, and nerve cells in the ascending auditory pathways are organized anatomically according to the frequency to which they are tuned (tonotopical organization). There is less evidence, however, regarding which of these two ways of coding frequency is used as a basis for frequency discrimination in the normal auditory system. Still, psychoacoustic studies show that good speech discrimination can be achieved by either one of these two types of frequency coding [4, 5].

While the tonotopic organization in animals with normal hearing has been regarded to be the result of the tuning of the basilar membrane, recent studies showed that a rudimentary tonotopic organization exists in the nervous system in animals that are born deaf [7, 8]. Other studies have shown that organization can be refined through expression of neural plasticity elicited by sound stimulation [8, 9] and electrical stimulation of the cochlea can modify the cochleotropic organization that exists even in animals that never have had any auditory input [10–12]. It is assumed that the rudimentary tonotopic organization that exists at birth is normally refined by the sound that a child experiences through expression of neural plasticity.

Animal experiments have shown that tonotopic maps of the auditory cortex change after sound stimulation [13] as well as other properties of such neurons [14]. Neurons may be 'tagged' by the properties (frequency, etc.) of the sounds that activate the neurons. Expression of neural plasticity makes it possible for cochlear and cochlear nucleus implants to impose a new tonotopic organization of the auditory nervous system. The ability of the nervous system to change its function is greatest in a short period after birth [15], which explains why it is easier for young individuals to adapt to cochlear implants than adults [10, 15, 16].

Proper training can improve the success of cochlear implants in adults. Recording of auditory evoked potentials (event-related potentials) [16] in individuals with cochlear implants has demonstrated that input from cochlear implants can change the function of the auditory nervous system.

Expression of neural plasticity is therefore important both for the normal organization of the auditory nervous system and for the ability of the nervous system to change its function such as is necessary for achieving the best possible function of cochlear and brainstem implants.

Relative Importance of Place and Temporal Coding of Speech Sounds

The place principle was earlier regarded by many investigators to be the basis of frequency discrimination, but more recent research has favored the temporal hypothesis for speech discrimination. It has been concluded that the place coding is not sufficiently robust to be the basis of normal frequency discrimination because it depends on the stimulus intensity [17–19]. Animal studies have indicated that place representation of formant frequencies is not sufficiently acute within physiologic sound levels (above 50 dB SPL) [20] but the temporal code is more robust than the place code for neural representation of vowels in the auditory nerve [21], thus supporting the temporal hypothesis for frequency discrimination.

Psychoacoustic studies have shown, however, that adequate frequency discrimination can be achieved on the basis of either the place principle or the temporal principle, and that individuals with normal hearing can understand speech solely on the basis of temporal information [4], as well as solely on the basis of spectral (place) information [1, 2]. That frequency discrimination can be achieved on the basis of either the place or the temporal hypothesis is an example of the extensive redundancy of the auditory system.

Another hypothesis regarding the role of spectral filtering in the cochlea suggests that the division of the spectrum facilitates temporal coding in the auditory nerve and its subsequent decoding in the ascending auditory pathways. That hypothesis assumes that the most important function of the normal cochlea is to divide the spectrum of sound into 'slices' of suitable size, each of which

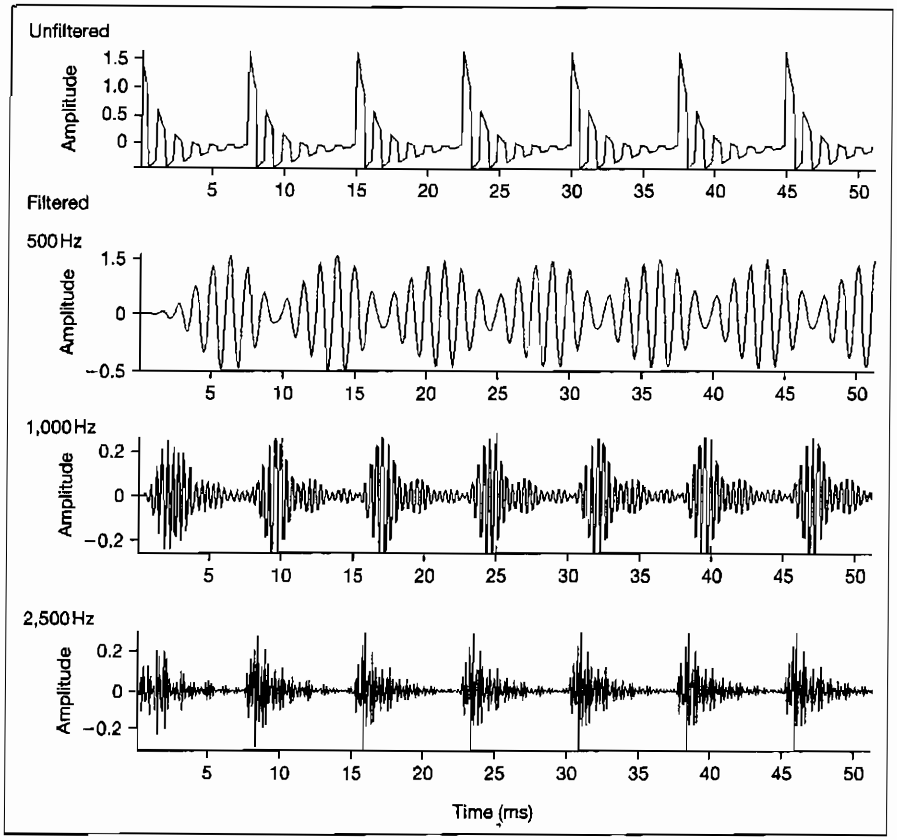

Fig. 1. Bandpass filtering of a synthetic vowel. The center frequencies of the filters were equal to the formant frequencies (500, 1,500, and 2,500 Hz). Courtesy of Peter Assmann and Ginger Stickly.

activates a specific population of cochlear hair cells which in turn excite specific populations of auditory nerve fibers. The waveform of such bandpass-filtered sounds that control the neural code in a population of auditory nerve fibers is much less complex than that of speech sounds that reach the ear (fig. 1).

This division of the sound spectrum is assumed to facilitate the temporal coding in single auditory nerve fibers, which become phase locked to a much less complex waveform than that of the sound wave that reaches the ear. It also reduces the demand on the encoding of the waveform of complex sounds, such as speech sounds. This is known as 'synchrony capture'.

Frequency Discrimination through Cochlear and Cochlear Nucleus Implants

All processors in cochlear implants and ABIs have a bank of bandpass filters that cover the frequency range that is most important for speech discrimination. Some cochlear implant processors extract a combination of spectral and temporal features for stimulation of auditory nerve fibers in the cochlea (compressed analog type processors [22] and continuous interleaved sampling [23]), while other types of cochlear implants use only spectral features together with low-frequency envelope information (vocoder type) [Loizou, this vol, pp 109–143 and 24, 25].

The implant devices that only provide information about the energy in 6–8 frequency bands resemble those of channel vocoders that were developed for analysis-synthesis telephony systems created in the 1950s and 1960s for the purpose of achieving economic speech transmission over long lines [2; see also Loizou, this vol, pp 109–143]. Cochlear implants that provide the temporal pattern within each frequency band in addition to spectral information (place information) stimulate auditory nerve fibers in a way that is more similar to that which the normal ear provides. However, cochlear implants using the vocoder principle seem equally efficient in providing good speech discrimination as those that also provide temporal information [26].

Channel Vocoder Type Processors

The vocoder type processors have a similar bank of bandpass filters as the CA type of processors, but the auditory nerve fibers are stimulated by electrical impulses that are controlled by the rectified and low-pass filtered output of the bandpass filters [Loizou, this vol, pp 109–143]. This means that most of the temporal information is thrown away and essentially only (power) spectral information of vowels is provided together with some low-frequency temporal information about the envelope of the output of each filter.

The success of cochlear implants that function as channel vocoders and do not use the temporal pattern of sounds seems to contradict the hypothesis that temporal information is important for speech discrimination. The question is therefore: how can only information about the energy in a few broad frequency bands provide enough information to establish good speech discrimination?

Analogy between Channel Vocoder Type Cochlear Implants and Color Vision

Cochlear implants of the channel vocoder type have similarities with trichromatic color vision in humans. Trichromatic color discrimination is based

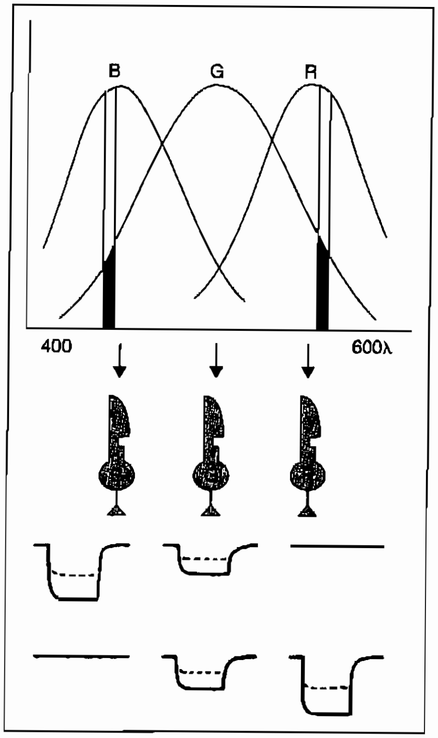

Fig. 2. Illustration of how a three-pigment system can distinguish colors (wavelength of light) independently of the intensity of the light, provided that the intensity is sufficient to elicit a response from at least two of the three kinds of receptors. Adapted from Shepherd [54].

on information about the light intensity in only three broad bands of the visual spectrum. Three kinds of photo pigment in the cones of the retina in the human eye act as spectral filters [27]. Trichromatic color vision using only the energy in three spectral bands provides the basis for discrimination of small nuances of color based on the fact that nuances of colors generate a unique combination of output in these three filters. This is similar to the channel vocoder type of cochlear implants that provide fine spectral discrimination of sounds that contain energy over a large frequency range based on the relationship between the output of a few spectral filters.

In the eye, the overall intensity of the light affects the activation of these three types of photo pigment equally and therefore does not affect the relationship between the output of the three receptors, and only the color (wavelength of light) will affect the relationship between the activation of the three types of photo pigments. The activation of the nerve fibers that innervate these three types of cones will thus be uniquely related to the spectrum of the light that reaches the eye (fig. 2).

This means that the relationship between the energy in these three bands of the visual spectrum provides sufficient information for discrimination between many nuances of colors and it is not necessary to have receptors that are sensitive to each wavelength of light that can be discriminated.

To illustrate how frequency discrimination in the auditory system can be achieved by using a few (3) filters, assume that the task is to determine the frequency of a pure tone, thus a single spectral component. When the bands of frequencies covered by each filter overlap as those of the eye (fig. 2), a tone with a frequency within the range covered by the filter bank, will cause output of more than one filter and the relationship between the output of the different filters will be unique for any frequency of the tone. It seems to be important that the different filters overlap so that a tone produces an output in more than one filter. It is probably also important that the filters have a rounded pass band rather than a flat top as is often preferred in man-made spectral filters.

The relationship between the outputs of a few filters can also provide information about the spectrum of broad sounds such as that of speech sounds; in the same way as the three spectral filters in the eye can provide information about the nuances of the color of light.

One of the strongest arguments against the place hypothesis for frequency discrimination has been its lack of robustness, consisting of a shift of the center frequency of cochlear filters and a widening of the filters that occur with increasing sound intensity [28, 29]. Since the bandpass filters in cochlear implant processors do not change with sound intensity, the vocoder-type cochlear implants may actually have an advantage over the cochlea as a frequency analyzer.

The Importance of Redundancy

The success of cochlear and cochlear nucleus implants depends on the redundancy in the processing in the cochlea and in the nervous system, and in natural sounds such as speech sounds. Only a small part of the speech wave is necessary for obtaining good intelligibility and this is why only spectral or only temporal information suffice to achieve good speech discrimination [2, 4].

Transmitting speech directly requires a bandwidth of approximately 3,000 Hz, but Dudley's channel vocoder could convert information about speech in a series control signal from which the speech could again be synthesized [Loizou, this vol, pp 109–143]. The bandwidth required for transmitting these signals was a small fraction of that required to transmit the speech signal, thus a sign of redundancy in the normal speech signal.

How Many Channels Are Necessary?

Development of the channel vocoder revealed that speech recognition does not require that fine spectral details are preserved [1, 2] and a total of 15 frequency bands was found to be sufficient for obtaining satisfactory speech intelligibly for telephone communication. The frequency analysis in the normal cochlea has been estimated to correspond to 28 independent filters [30], thus more than used in Dudley's channel vocoder and many more than the three filters that are the basis for trichromatic color vision. Speech intelligibility of cochlear implants that use the vocoder principle increases only slightly when the number of filters is increased above eight [31]. Studies in individuals with normal hearing where the vocoder principle has been simulated have shown that 4–5 channels are sufficient for a high degree of speech discrimination (90%), provided that a high degree of amplitude resolution is used [5, 32]. If the resolution of the coding of intensity is reduced, more channels are needed. Using 6 channels, the speech discrimination was reduced significantly when the intensity coding had only 8 steps and the number of channels had to be increased to 16 to obtain good speech discrimination (92%) with that resolution.

Coding of Sound Intensity

The function of cochlear implants that use the vocoder principle depends on proper coding of sound intensity in a wide range of sound intensities. Sound intensity is coded in auditory nerve fibers by the discharge rate, but only a few auditory nerve fibers seem to code sound intensity over the physiological range of sound intensities. The discharge rate of most nerve fibers reach saturation only 20–30 dB above hearing threshold [33]. Most nerve fibers, however, seem to code changes in sound intensity over a much larger range of sound intensities [34].

Cochlear implants code the intensity of sounds (the energy in respective frequency bands) by the amplitude of the electrical signals that are used to stimulate the auditory nerve. In the normal cochlea, increasing stimulus strength of a sound causes an increasing number of nerve fibers to become activated because of the widening of the segment of the basilar membrane that causes activation of nerve fibers [6]. In addition, the discharge rate at least of some nerve fibers increases with increasing stimulus intensity.

Functions Not Covered by Modern Cochlear Implants

Most modern cochlear implants generally do not convey information about the fine temporal pattern of sounds, and two-tone inhibition is not implemented in cochlear implants. The coding of the sounds in the discharge pattern of auditory nerve fibers is different from that provided by normal sound activation of hair cells; cochlear implants can activate many nerve fibers in a temporally coherent fashion.

Coding of the Temporal Pattern of Sounds

Modern cochlear implants of the vocoder type do not provide coding of the temporal pattern of sounds above 200 or 400 Hz [24, 25; see also Loizou, this vol, pp 109–143], thus fundamentally different from normal coding of sounds in the auditory nerve.

There are three different mechanisms for discrimination of pitch: place pitch, rate pitch and phase-locked pitch. Place pitch is based on the spectral filtering in the cochlea and rate pitch is based on coding of the temporal pattern of neural discharge in mostly a cycle-by-cycle manner and operates for low frequencies only. Phase-locked pitch is assumed to be based on temporal coding of the periodicity of sounds in a large range of frequencies. In the normal ear, all three forms of pitch perception may be utilized, but to a different degree for different sounds. It is evident that good speech discrimination can be achieved without preserving the temporal pattern of speech sounds such as vowels.

The performance of cochlear implants has mainly been judged on the basis of speech discrimination, but it has also been recognized that perception of music is inferior in cochlear implants [35–37]. While implant users perceive rhythm relatively well, melody recognition, perception of timbre and recognition of instruments are poor and implant users report that music is less pleasant than perceived by listeners with normal hearing [35]. The reason may be that music perception depends on coding of the fine temporal pattern of sounds such as what is assumed to be the basis for phase-locked pitch. The implant processors that use the continuous analog principle would be superior in that respect. New processing schemes that code periodicity have been shown to improve recognition of musical melody [38].

Two-Tone Suppression

In the normal auditory system, the response areas of auditory nerve fibers are surrounded by inhibitory bands [39], known as two-tone suppression [6]. Two-tone suppression that is a prominent property of the normal auditory system is not included in cochlear implants. It is believed that two-tone suppression may enhance spectral contrast in a similar way as lateral inhibition, which has been studied extensively in the visual system where it enhances contrast [40]. It is possible that two-tone inhibition in the auditory system enhances responses to sounds with rapidly varying frequency [41, 42].

Coherent Activation of Auditory Nerve Fibers

Cochlear implants cause temporal and spatially coherent activation of many nerve fibers, which is different from the normal activation of the auditory nerve. The importance of this is unknown but some hypotheses suggest that temporal coherence of activity in the auditory nerve is important for detection of sounds and for discrimination of sound intensity (loudness) [6].

Incorrect Stimulation of Nerve Fibers

Since the electrodes in cochlear implants are placed in the basal portion of the cochlea they do not stimulate auditory nerve fibers according to the frequencies to which they are normally tuned. The tonotopic maps on the nuclei of the ascending auditory pathways including the cerebral cortex will therefore be different in cochlear implant users than it is in individuals with normal hearing. Since the functional importance of the anatomical organization in individuals with normal hearing is unknown, it is also unknown what consequence different maps in cochlear implant users may have. Expression of neural plasticity is likely to correct these maps at least to some extent.

In the normal ear, the waves on the basilar membrane travel relatively slowly from the basal portion towards the apical portion of the basilar membrane and low-frequency components will normally activate nerve fibers later than high-frequency components. Cochlear implants do not take that difference in the travel times for low and high frequencies into account.

Cause of Variability in Performance of Cochlear Implants

The variability in performance of cochlear implants is considerable even within groups of individuals with similar age and with seemingly similar experience of previous sound exposure [26] (fig. 3). This variability is unexplained. The deviation in performance from the average performance may have different causes in different individuals; it may have to do with the amount of reserves that a person has, the size of which does not become apparent until the loss of hearing occurs. Differences in intellectual resources are likely to contribute to differences in performance of cochlear implants.

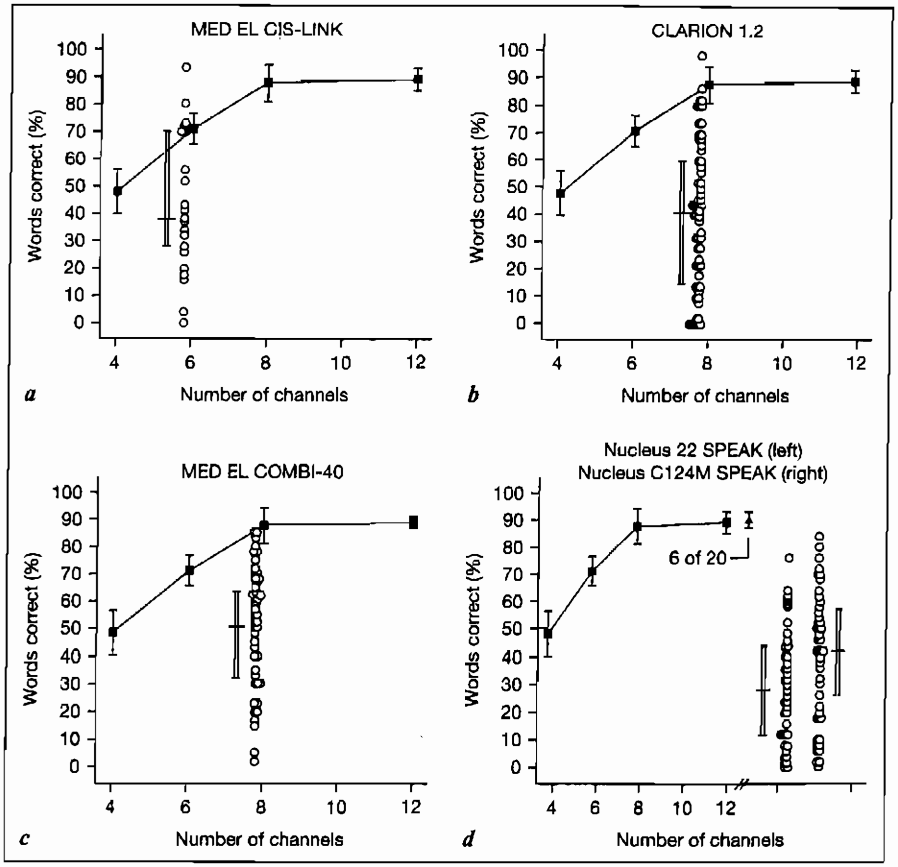

Fig. 3. Monosyllabic word recognition as a function of the number of channels in a signal processor for normal-hearing listeners (filled squares and solid lines). Performance of cochlear implant wearers is shown by open circles. The broad vertical lines indicate the interquartile range of performance. Horizontal bars indicate median scores. Reprinted from Møller [6] with permission from Elsevier. Data from Dorman [26].

Auditory Brainstem Implants

While ABIs in patients with NF2 provide assistance in lip-reading but no speech discrimination [43] recent experience shows that ABIs in patients with other causes of injuries to the auditory nerve can be equally efficient in providing speech comprehension as cochlear implants [44–47]. ABIs in children with malfunction of the auditory nerve such as may occur from internal auditory meatus malformation (atresia) causing auditory nerve aplasia also provide much better speech discrimination than those implanted in NF2 patients [Colletti, this vol, pp 167–185; 46].

Physiological Basis for ABIs

The main difference between cochlear implants and ABIs is that the latter also bypass the auditory nerve. The auditory nerve acts as a connection between the cochlea and the cochlear nucleus and does not perform any processing of information. Provided that proper placement of the stimulating electrode array on the surface of the cochlear nucleus can be arranged, ABIs can be expected to perform as well as cochlear implants. It is not known why ABIs do not provide useable speech discrimination in NF2 patients [43] but do much better in patients with other causes of auditory nerve malfunction [47]. Severance of the auditory nerve, often occurring in operations for large vestibular schwannoma, may affect the cells in the cochlear nucleus in a way that is different from what occurs in other forms of auditory nerve lesions. Animal experiments have shown that degeneration of nerve fibers that terminate on cells in the cochlear nucleus can result in changes in the cells in the cochlear nucleus [48, 49].

Anatomical Organization of the Cochlear Nucleus

The cochlear nucleus has three main divisions, the dorsal cochlear nucleus, the anterior ventral cochlear nucleus and the posterior ventral cochlear nucleus [6]. The surface of the ventral cochlear nucleus and that of the dorsal cochlear nucleus share the floor of the lateral recess of the fourth ventricle. The anterior ventral nucleus occupies the most rostral part of the cochlear nucleus [50, 51]. Each auditory nerve fiber bifurcates and one of the branches bifurcates again, and these three branches connect to cells in one of the three divisions of the cochlear nucleus. This means that cells in each of the three divisions receive input from the same auditory nerve fibers [6]. This is the beginning of parallel processing that is prominent in the ascending auditory pathways. Since ABIs activate only one of the three divisions of the cochlear nucleus, only one of the parallel pathways to higher nervous centers becomes activated. The implications of that are unknown.

The three divisions of the cochlear nucleus have different anatomical organization and the responses of cells are different. The cells in the cochlear nucleus are interconnected in complex networks and the cells have excitatory and inhibitory influence on each other. It may be preferable to place the stimulating electrodes on the surface of the ventral cochlear nucleus because the cells of that division receive only few auditory nerve fibers (primary-like nerve cells) and, therefore, electrical stimulation of these cells would be similar to stimulating auditory nerve fibers. However, electrical stimulation of the cochlear nucleus can stimulate different types of cells. Electrical stimulation from ABIs is less likely to activate nerve fibers within the cochlear nucleus [Shepherd and McCreery, this vol, pp 186–205].

The cochlear nucleus is tonotopically organized [6, 52], but it is not known if it is important to stimulate the cochlear nucleus cells according to this tonotopic organization. Since the orientation of the tonotopic maps of the cochlear nucleus in humans is insufficiently known, it is not possible to orient the electrode array so that frequency bands of the sound stimulate cells that are normally activated by the same spectrum of sounds.

While cochlear implants cannot stimulate auditory nerve fibers that normally respond to low-frequency sounds, ABIs can stimulate all neurons that normally respond to sounds within the entire audible hearing range, provided that the implanted electrode array is correctly placed. ABIs thereby have the potential of providing better hearing than cochlear implants.

Cause of Difference in Performance of ABIs in Patients with Different Cause of Auditory Nerve Injuries

The systematic difference in the performance of ABIs in NF2 patients and in patients with auditory nerve pathologies of other causes may have a specific cause, though yet unknown. Also, the performance of ABIs in NF2 patients varies and that may have causes similar to those discussed for cochlear implants (fig. 3).

The Role of Neural Plasticity

Since cochlear and cochlear nucleus implants do not accurately replace all the normal functions of the ear, the success of cochlear and cochlear nucleus implants implies that the nervous system must 'learn' a new code. Therefore, the success of cochlear implants and ABIs relies on functional adaptation of the processing of information in the auditory nervous system. Expression of neural plasticity enables the auditory nervous system to adapt to changing demands and it has been known for a long time that expression of neural plasticity helps to regain function after trauma or insults, such as from strokes [53]. Training is a powerful method for activating neural plasticity and a part of all cochlear and cochlear nucleus implant programs. These matters are discussed in papers by Sharma and Dorman [this vol, pp 66–88] and Kral and Tillein [this vol, pp 89–108].

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