Hearing with Two Ears: Technical Advances for Bilateral Cochlear Implantation

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The benefits of cochlear implantation have increased progressively with improvements in technology and in clinical practice over the last two decades. Most of the 60,000 people who have received cochlear implants worldwide have received substantial communication benefit from implantation in only one ear. However, advancements in technology now have the potential to add significant benefit through implantation of both ears.

In people with normal hearing, having two ears provides two major benefits:

1. The BILATERAL BENEFIT is the ability to listen with the ear that has a better signal-to-noise ratio. The bilateral benefit comes into play when speech and noise come from different directions, and is primarily a result of the head shadow effect.
2. The BINAURAL ADVANTAGE is the ability to combine sounds from the two ears and to hear better than with one ear alone. The binaural advantage enables sound localization (directional hearing) and helps people to hear more clearly in background noise.

Bilateral implantation can improve the quality of hearing in many everyday listening situations and can provide significant advantages over unilateral implantation. However, while conventional cochlear implants can provide *bilateral benefit* in recipients of two implants, they lack several key features that are necessary to enable listeners to experience a *binaural advantage*. Therefore, the benefit of implanting both ears has only been partially realized with conventional cochlear implant technology. Furthermore, the cost-benefit ratio of providing people with two implants over one implant has not yet been clearly established. Thus, in most cases to date, health insurance carriers have covered the cost of only one implant.

In young children, there may be other compelling reasons for considering bilateral implantation. First, a young child's auditory system is more plastic than that of an adult. Providing sound input to both ears in a young deaf child assures that sound is processed through both sides of the brain. Thus, the right and left auditory cortices can develop in a more normal sequence. On the other hand, if a child is implanted on only one side, the parts of the brain that would have been stimulated by the non-implanted ear will not develop, and eventually plasticity will be greatly diminished. The long-term consequence may be that the pathways that would have been stimulated by the non-stimulated ear will be permanently unresponsive to sound and not available for potential future restoration of hearing through advances in microbiology or genetic engineering. Second, a child who is deafened by meningitis and receives only one implant runs the risk of ossification of the unimplanted cochlea, thereby compromising the ability to benefit from future implantation in that ear.

For the first time, the technology used in the HiResolution™ Bionic Ear has the potential to deliver the critical sound information that can provide improved *bilateral benefit* and, more importantly, can facilitate a measurable *binaural advantage*. Adults may experience improved directional hearing and better hearing in background noise. In addition to those benefits, young children have access to sound in both ears that may enable the brain to mature and to learn to process all bilateral and binaural cues during a period where maximum plasticity occurs.

THE BINAURAL ADVANTAGE

The principal benefits derived from the *binaural advantage* are the ability to identify where sound is coming from, and to enable better hearing in background noise. The binaural advantage results from three effects, (1) interaural time differences, (2) interaural intensity differences, and (3) spectral cue enhancement.

Interaural Time Differences

The simplest way to understand how we determine where sound is coming from is to look at the acoustic information that arrives at the two ears when a listener is sitting without moving his or her head. When sound comes from directly in front of the listener, the path of the sound to the left and right ears is the same. However, if the sound source moves to the side of the listener's head, the path to one ear is closer than the path to the other ear. In that case, the sound arrives at the farther ear later than it arrives at the nearer ear. Thus, an interaural time difference exists and can be recognized by the brain.

If a sound originates in the horizontal plane, that is, the plane defined by the tip of the nose and the two ears, we can estimate the time difference between sounds arriving at each ear. The largest time difference occurs when one ear is pointing directly toward the sound source. In other words, if a sound source in front of the head is defined as 0º azimuth, then the largest time difference occurs when the sound source is at 90º azimuth.

If we compute the time difference for a sound coming from a source that is at 90º azimuth, it takes about two-thirds of a millisecond more for sound to reach the farther ear than it takes to reach the closer ear. That time difference introduces a phase shift between the two ears that is equal to the period of a tone of about 1500 Hz. For frequencies above 1500 Hz, the phase shift becomes ambiguous and the time-of-arrival cue becomes less useful for localizing sound. This is because smaller interaural phase differences can originate from a number of different locations for frequencies above 1500 Hz. Therefore, interaural time difference is most useful for sound frequencies of less than 1500 Hz.

Because of this frequency dependency, and because cochlear implant users typically have poor perception of timing differences even at low frequencies, interaural time difference is of limited importance for bilaterally implanted cochlear implant users.

Interaural Intensity Differences

Because of the limitations of using time difference for localizing higher frequency sounds, other binaural effects must account for the ability to localize sound sources. The most important of the binaural effects arises from the *intensity differences* between the two ears. The head casts a sound shadow over the farther ear for high-frequency signals whose wavelengths are shorter than the head diameter. Typically, these are sounds with frequencies above 1500 Hz. The head also reflects sound back into the sound field in front of the closer ear. The result is a small increase in sound pressure in front of the closer ear and consequently, an intensity difference between the two ears. Ear canal measurements indicate that the intensity difference can be as much as 20 dB at 4 kHz and as much as 35 dB at 10 kHz for pure tones presented at a 90º azimuth.

Spectral Cue Enhancement

While interaural intensity and interaural time differences are most useful for localizing sound in the horizontal plane, they are ambiguous for localizing sounds in the vertical (up/down) and in the front vs. back directions. In other words, there are multiple locations for which the interaural intensity and time cues can be identical. Therefore, additional cues must be available for localizing sound in the vertical and front vs. back directions. Those cues are in the spectral domain. Spectral cues are not limited to binaural listening, but can also be useful in monaural hearing.

The external ear plays an important role in localizing sound because it produces changes in the spectrum of sound that enters the ear canal. Put differently, the external ear alters the relative intensities of the many sound frequencies that enter the ear canal. The external ear and its many convolutions act to cast many small shadows on the path of the sound that approaches the ear canal. The direct path to the ear canal and the delayed path caused by reflection of sound around the pinna and off the concha add together to produce a filtered spectrum that contains a characteristic pattern of peaks and valleys across frequencies. The amplitude spectrum of such a complex sound signal in the ear canal depends on the source of the sound relative to the body.

Direct measurements of ear canal sound pressure show that specific spectral features vary systematically with sound source location. Therefore, spectral cues are available for localizing complex sounds, particularly in the vertical direction, or when listening with only one ear. Those spectral cues enhance the effect of interaural intensity and time differences in bilateral listening.

NEW COCHLEAR IMPLANT TECHNOLOGY WITH ADVANTAGES FOR BILATERAL HEARING

Bilateral implantation with conventional cochlear implant technology offers two principal benefits: (1) the bilateral benefit that enables the user to use the ear with the better signal-to-noise ratio, and (2) the assurance that the better ear has been implanted. However, bilateral implantation with conventional cochlear implant technology does not provide the cues required for the binaural advantage, which is the primary mechanism that allows normal-hearing listeners to localize sound and to hear better in background noise. Those cues are not represented because of:

- The disadvantageous location of the microphones
- Limitations in input signal processing
- Detailed information in the sound signal is not preserved and is not delivered to the ear.

These shortcomings are addressed in the newest generation cochlear implant system through the following new features.

Microphone Location

All conventional cochlear implant systems have used microphones that are worn behind or above the ear or on the head, usually integrated into a hearing aid shell. These microphone locations do not allow the listener to take advantage of the spectral cues that are provided by the external ear. Thus, implant users have not been able to use that information to localize sound or to extract speech from noise.

In order to take advantage of external ear filtering, the HiRes™ Auria Sound Processor has the option for the T-Mic, a microphone that is located in the middle of the pinna directly in front of the ear canal. The T-Mic is made possible because the HiResolution™ Bionic Ear System has a separate power supply at the attachment of the ear hook to the hearing aid shell. Clinical experience with the T-Mic in monaural cochlear implant users shows a trend for improved sound and hearing quality, most likely due to the preservation of spectral cues that are provided by the structures of the outer ear. Furthermore, the T-Mic allows direct and convenient access to the telephone or headphones without the need for interface cables or telecoils that introduce noise to the signal. The binaural benefits of using the T-Mic in bilateral cochlear implant users are being assessed as part of a larger clinical study of bilateral HiResolution™ Bionic Ear users at one U.S. research center.

Input Signal Processing

Potential benefits of bilateral cochlear implantation include the ability to listen with the ear that has the better signal-to-noise ratio, and to detect interaural intensity differences. Both of these benefits depend in part on the quality of the input signal processing. Most conventional cochlear implant sound processors capture a relatively small input loudness (dynamic) range of less than 50 dB, and employ analog-to-digital converters with a resolution of less than 10 bits. These sound processors require the user to manually adjust the *Sensitivity* setting (input amplification) for different listening environments, and/or to switch between different input processing modes (e.g., "whisper" setting vs. normal setting).

Bilateral cochlear implants currently employ two separate sound processors, each with its own microphone. When using two conventional cochlear implants, the ability to detect interaural intensity differences depends upon synchronous adjustments of sensitivity and volume between the two sound processors. Synchronous sensitivity and volume adjustments are not implemented or available on any current implant system.

The dynamic range limitations of conventional implants are addressed in the HiRes™ Auria Sound Processor through use of 12-bit analog-to-digital converter circuits that can be programmed to capture a dynamic range of up to 92 dB (80 dB programmable, and 12 dB fixed overhead). The wide input dynamic range assures that sound is captured in both very soft and very loud (or noisy) listening environments without requiring an adjustment of the sensitivity or volume controls on the sound processor. Most Auria users do not find it necessary to adjust sensitivity settings at all and prefer their processors to be programmed so that the sensitivity control is permanently disabled. In fact, in the bilateral HiResolution™ study, the audiologist is instructed to program the listeners' bilateral Auria processors with both the sensitivity and volume controls permanently disabled. By disabling both controls, synchrony between the two processors is assured.

Another important advantage of a wide input dynamic range is that children will have access to soft speech that is not spoken directly to them. In normal-hearing children, this incidental listening plays an important role in language acquisition. Thus, a wide input dynamic range, especially when combined with bilateral implantation, may facilitate language learning in very young children.

Preservation of Details of the Sound Signal

The HiResolution™ Bionic Ear System is the first cochlear implant system that has the *bandwidth* to (1) preserve the fine timing information in the sound signal, and (2) update all stimulation channels during each processing cycle at high speeds. All other systems to date have severe bandwidth limitations and can extract only speech envelope or feature information. Thus, any fine timing information above 1500 Hz, an important cue for detecting interaural intensity differences, is lost when using conventional cochlear implant processing strategies.

Because only a selected number of stimulation channels are updated during each processing cycle, bilateral users of some of the most commonly used conventional cochlear implant strategies (SPEAK and ACE) face a listening challenge. In noisy listening environments, the channels that are selected and updated by the two sound processors can be different depending on the location of the sound source and noise interference. Thus, the ability to correlate information across the two ears can be significantly impaired. This correlation of information between the two ears is required in order to experience a binaural advantage.

In contrast, the HiRes™ sound processing programmed by the SoundWave™ Professional Suite platform preserves fine timing structure up to 2800 Hz. The preservation of fine timing information is predicted to increase the ability of bilateral implant users to detect interaural intensity differences. Those abilities are being assessed in a U.S. bilateral HiRes™ clinical study by evaluating sound localization and speech perception in background noise.

Safety and Ease of Use

In addition to the potential bilateral listening benefits provided by the HiResolution™ Bionic Ear System, the new technology offers several improvements in safety and ease of use for bilateral implant users.

First, the HiResolution™ Bionic Ear has a safety feature (SmartLink™) that matches each sound processor to the correct implanted device and disables processor function in case of a mismatch. Because stimulation levels required to elicit comfortable hearing are often significantly different between the two ears, each cochlear implant sound processor can be programmed for one ear only. If a sound processor is accidentally used on the opposite ear, over-stimulation and discomfort may occur. This potential risk factor for bilaterally implanted children with older cochlear-implant technology is eliminated in the HiRes™ system.

SUMMARY

Bilateral implantation is becoming a desirable option for many cochlear-implant candidates, especially for young deaf children during the critical period for speech and language acquisition when the auditory system is most plastic. The HiResolution™ Bionic Ear System is able to process full broadband sound with the high level of detail required to deliver the cues necessary for improving bilateral effects and the binaural advantage. It has the input sound-processing capability to capture the wide range of intensities necessary to preserve the loudness relationships that are required to hear speech in noise. In addition, its high-rate sound sampling accurately represents the timing cues across all frequencies. Most importantly, the HiRes™ system is designed to faithfully reproduce with high resolution the fine time and intensity differences in the electrical signal delivered to the hearing nerve. In addition, the T-Mic, which is placed into the external ear, allows Auria users to take advantage of head-shadow and pinna effects for better speech perception in noise and improved localization. Compared to conventional cochlear implants, these technological advances are predicted to enhance the ability to hear with two implants.

Preliminary clinical results from patients who have been implanted with two Bionic Ears at one U.S. research center indicate that HiRes™ sound processing provides bilateral benefit that is superior to bilateral benefit from conventional sound processing. Future multicenter studies will explore further the extent of binaural benefit experienced by HiResolution™ Bionic Ear recipients.

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