# HiResolution® Bionic Ear System
# Research Summaries and Publications List

# Overview of Key Reference Summaries

**Briaire JJ, Frijns JH.** Unraveling the electrically evoked compound action potential. *Hearing Research*. 2005;205:143-156.

This paper illustrates how a high-quality 3D mathematical model of the human cochlea can facilitate interpretation of NRI recordings.

**Büchner A, Frohne-Büchner C, Stöver T, Gärtner L, Battmer RD, Lenarz T.** Comparison of a paired or sequential stimulation paradigm with Advanced Bionics high-resolution mode. *Otology and Neurotology*. 2005;26:941-947.

This study compared speech perception for paired versus sequential HiRes stimulation. Generally, sequential stimulation resulted in better outcomes and was preferred by subjects.

**Donaldson GS, Kreft H, Litvak L.** Place-pitch discrimination of single- versus dual-electrode stimuli by cochlear implant users. *Journal of the Acoustical Society of America*. 2005;118:623-626.

This study measured discrimination thresholds for single- versus dual-electrode stimuli as a means of estimating the number of place-pitch steps that could be achieved with simultaneous dual-electrode stimulation (using current steering). Six CII users showed a two to nine-fold increase in the number of place-pitch steps for simultaneous dual-electrode stimulation.

**Wright CG, Roland PS, Kuzma J.** Advanced Bionics Thin Lateral and Helix II electrodes: a temporal bone study. *Laryngoscope*. 2005;115:2041-2045.

Eight temporal bones were examined and analyzed following insertion of four Slim Lateral and four Helix II prototype electrode arrays. No insertion trauma was observed. The authors concluded that both of the arrays are appropriate for use when preservation of residual hearing is required.

**Bosco E, D'agosta L, Mancini P, Traisci G, D'Elia E, Filipo R.** Speech perception results in children implanted with Clarion® devices: Hi-Resolution™ and standard resolution modes. *Acta Otolaryngologica*. 2004;125:148-158.

A study of age-matched children using HiRes and standard resolution sound processing highlights the more rapid development of language acquisition in the HiRes group compared to the standard resolution group.

# Overview of Key Reference Summaries

**Cray JW, Allen RL, Stuart A, Hudson S, Layman E, Givens GD.** An investigation of telephone use among cochlear implant recipients. *American Journal of Audiology*. 2004;13:200-212.

Questionnaire results from 478 adult Advanced Bionics implant users showed that telephone use by implant recipients has increased significantly relative to earlier reports. Data indicated that 70% of respondents regularly used the telephone, and that telephone use averaged 5.4 hours per week.

**Koch DB, Osberger MJ, Segel P, Kessler D.** HiResolution and conventional sound processing in the HiResolution Bionic Ear: using appropriate outcome measures to assess speech recognition abilities. *Otology and Neurotology*. 2004;9:214-223.

Results of a North American multi-center study demonstrate the increased benefits offered by HiRes compared to conventional sound processing.

**Robbins AM, Koch DB, Osberger MJ, Zimmerman-Phillips S, Kishon-Rabin L.** Effect of age at
cochlear implantation on auditory skill development in infants and toddlers. *Archives of Otolaryngology-Head and Neck Surgery*. 2004;130:570-574.

This study examined the effect of age at implantation on auditory skill development. Children who were implanted at a younger age acquired auditory skills nearer to their normal-hearing peers at a younger age. However, the mean rate of acquisition of auditory skills was similar to normal-hearing infants and toddlers regardless of age at implantation.

**Spahr AJ, Dorman MS.** Performance of subjects fit with the Advanced Bionics CII and Nucleus 3G cochlear implant devices. *Archives of Otolaryngology-Head and Neck Surgery*. 2004;130:624-628.

This study compared performance between CII and Nucleus 3G users matched on monosyllabic word scores in quiet, and for age and duration of deafness. CII users had significantly higher scores for vowel identification, difficult sentences in noise (+5 and +10 dB SNR), and for a measure termed "robustness" which quantified performance in noise and at low levels to performance in quiet.

# Overview of Key Reference Summaries

**Donaldson GS, Allen SL.** Effects of presentation level on phoneme and sentence recognition in quiet by cochlear implant listeners. *Ear and Hearing*. 2003;457-460.

This study assessed the effect of presentation level on speech perception in quiet in Clarion 1.2 CIS users and Nucleus SPEAK users. Clarion users showed significantly better consonant and sentence perception at low levels than Nucleus users, primarily attributable to the differences in input dynamic range between the two devices (Clarion: 60 dB IDR, Nucleus: 30 dB IDR).

**Frijns JHM, Klop MC, Bonnet RM, Briaire JJ.** Optimizing the number of electrodes with high-rate stimulation of the Clarion CII cochlear implant. *Acta Otolaryngologica*. 2003;123:138-142.

This study demonstrates the benefit of HiRes over standard resolution for listening in noise. HiRes programs were optimized for channel number and stimulation rate. All subjects preferred HiRes and benefited from the greater number of channels and higher rate of stimulation compared to conventional standard resolution programs.

**Moore BCJ.** Coding of sounds in the auditory system and its relevance to signal processing and coding in cochlear implants. *Otology and Neurotology*. 2003;24:243-254.

This excellent summary paper pulls together the important parameters of sound processing that may improve speech perception for cochlear implant users, including AGC, channel number, rate of stimulation, stochasticity, and reduced channel interaction.

# Unraveling the Electrically Evoked Compound Action Potential

**Briaire JJ, Frijns JHM**

The goal of achieving a thorough understanding of the processes underlying the electrical Compound Action Potential (eCAP) has been tackled by using a detailed two-part computer model of the cochlea: a 3-D volume conduction model and an active non-linear auditory nerve fiber model. The first guinea pig model was developed at Leiden University Medical Center and has been modified to better represent the human cochlea. Each modelled fiber represented 100 actual nerve fibers providing spatial resolution of 100 µm. A peri-modiolar electrode array based on the HiFocus design was used. The currents at each modelled node of Ranvier were composed of four elements: membrane capacitance, sodium and potassium ionic channels, and the leakage conductance. Each node's current was summed to determine a single fiber action potential (SFAP) and all SFAPs were summed to obtain the eCAP.

Anodic or cathodic leading pulses were delivered to either a myelinated (MCB) or an unmyelinated cell body (UCB) to yield four study conditions. Cathodic-leading biphasic pulses produced a response with a 70 µs shorter latency than anodic-leading pulses, thereby contradicting the hypothesis that a fiber's response always is initiated by the negative-leading phase of the stimulus. Large differences in SFAP characteristics were found between MCB and UMCB fiber morphologies, including latency, relative size of positive and negative peaks, and the presence of an early $P_o$ peak. Two APs were found to propagate in different directions, one moving toward the organ of Corti and one toward the central end of the axon.

The cell body current dominates the response in the UMCB condition, so that the AP trajectory resembled the plot for nerve fibers without peripheral processes. This model result could explain the absence of eCAP responses in subjects with neural degeneration who still have normal behavioral auditory responses and perform well with a cochlear implant. The model finding that at higher stimulation levels Po dominates and contributes less to the $N_1$-$P_2$ difference explains another clinical observation. That is, shallower-than-expected growth functions and saturation or even a decrease in eCAP amplitude often occur with increasing stimulation current.

The model appears to work well and to predict and explain some counter-intuitive clinical observations. Most importantly, the model indicates that the unitary response theory, in which every fiber contributes the same amount to the whole nerve response, does not predict the eCAPs measured with a cochlear implant.

# Comparison of a Paired or Sequential Stimulation Paradigm With Advanced Bionics' High-Resolution Mode

**Büchner A, Frohne-Büchner C, Stöver T, Gärtner L, Battmer RD, Lenarz T**

The aim of this study was to compare sequential and paired stimulation using HiRes sound processing. The paired stimulation paradigm stimulates two channels at the same time, therefore doubling the stimulation rate along with the update rate. Because of some overlap of the electric fields, the paired stimulation may cause more channel interaction. To investigate the interactions between stimulation rate and channel interaction, three conditions were compared: 1) 16-channel paired stimulation with 5000 pps per channel, 2) 16-channel sequential stimulation with 2500 pps per channel, and 3) eight-channel sequential stimulation with 5000 pps per channel. Programs 1 and 2 had the same number of channels, whereas programs 1 and 3 had the same stimulation rate. A crossover design was used in 13 subjects.

On average, both sequential stimulation programs (2 and 3) provided comparable speech results, whereas the program with paired stimulation generally resulted in poorer performance. Several subjects show a remarkable drop in performance when changing from sequential to paired mode, especially when listening in noise. A weak relationship was found between reductions in M levels and poorer speech performance when changing from sequential to paired stimulation.

All subjects preferred sequential stimulation and achieved excellent speech perception results using that mode. For these reasons, the authors recommended sequential stimulation as the default HiRes program setting.

# Place-Pitch Discrimination of Single- Versus Dual-Electrode Stimuli by Cochlear Implant Users

**Donaldson GS, Kreft H, Litvak L**

Donaldson and colleagues measured discrimination thresholds for single- versus dual-electrode stimuli as a means of estimating the number of place-pitch steps that could be achieved with simultaneous dual-electrode stimulation. Six postlingually deafened adult CII users served as subjects. Pairs of adjacent electrodes at each of three locations along the implanted array (basal, middle, and apical) were tested using stimuli that were balanced in loudness to a "medium loud" level. The middle electrode pair also was tested using stimuli balanced to a "medium soft" level. Stimuli were 200-ms pulse trains presented in monopolar mode.

Discrimination thresholds were obtained using a two-alternative forced choice (2AFC) procedure in which the subject heard a single-electrode stimulus (apical electrode stimulated alone) and a dual-electrode stimulus (apical and basal electrodes stimulated simultaneously) in random order on each trial. The subject's task was to choose the stimulus with the higher pitch. Thus, a correct response occurred when the dual-electrode stimulus was selected. The proportion of current ($\alpha$) directed to the more basal electrode of the dual-electrode pair was varied to determine the relative current weighting at discrimination threshold. Using this metric, a threshold value of $\alpha = 0.2$ would indicate that a pitch (or quality) change was detected when 20% of the current was directed to the more basal electrode of the pair. Similarly, a threshold of $\alpha = 0.9$ would indicate that a pitch change was not detected until 90% of the current was directed to the more basal electrode.

Thresholds varied considerably across subjects and, in some cases, across electrodes within subjects. For the medium-loud stimuli, one subject could not discriminate adjacent single electrodes in the apical cochlear location ($\alpha > 1$) and two other electrode pairs could not be tested. For the 15 remaining electrode pairs, discrimination thresholds ranged from $\alpha = 0.12$ to $\alpha = 0.64$, with an average value of $\alpha = 0.36$. A level effect was observed in three subjects and in the mean data, with medium-soft stimuli producing significantly larger mean thresholds than medium-loud stimuli.

The results suggest that dual-electrode stimulation could increase the number of place-pitch steps available to most users of the CII device. Five of six subjects in this study were able to perceive an intermediate pitch between the pitches of adjacent electrodes in all three cochlear locations. Four subjects had thresholds less than $\alpha = 0.3$ for at least one electrode pair, suggesting that three or more intermediate pitches may be possible in many cases. Furthermore, equal loudness could be achieved with simultaneous dual-electrode stimuli at net current levels that were similar or only slightly higher than those for single-electrode stimuli.

# Advanced Bionics Thin Lateral and Helix II Electrodes: A Temporal Bone Study

**Wright CG, Roland PS, Kuzma J**

Eight temporal bones were examined and analyzed following insertion of four Thin Lateral and four Helix II prototype electrode arrays, one in each specimen. All bones were freshly harvested and not frozen. Each specimen was fixed with 2.5% glutaraldehyde and had the stapes removed prior to electrode insertion. For both electrode array types, a 1.2-mm diameter cochleostomy was made 0.5 mm to 1.0 mm anterior to the round window. Surgilube was used during insertion, both at the cochleostomy and to coat the electrode arrays. The bones were decapped to view the electrode array through the basilar membrane from the scala vestibuli, and then decalcified to allow removal of additional bone without damage to cochlear structures.

No trauma was observed for any of the eight insertions. There were no elevations or penetrations of the basilar membrane, no fractures of the osseous spiral lamina, and no penetrations or disturbances of the spiral ligament. The Thin Lateral arrays typically were inserted one turn on average, or approximately 17 mm of linear insertion distance from the cochleostomy. The Thin Lateral arrays showed the intended lateral placement throughout their lengths with the exception of the basal region near the cochleostomy where the arrays were slightly more medial. The Helix II arrays showed a deeper mean insertion of 436 degrees, almost 90 degrees deeper than that of the Thin Lateral arrays. The Helix II arrays tended to lie near the modiolus at both the base and the apex, but were positioned more laterally in the middle of the array.

According to the scale devised by Balkany, all insertions would have been given a trauma rating of zero, indicating no trauma at all. The reasons given for the zero rating were the relatively small diameter of the arrays (Thin Lateral—0.25 x 0.5 mm at tip to 0.5 x 0.5 mm at base with 0.9 mm electrode spacing, Helix II—0.4 x 0.45 mm at tip to 0.6 x 0.7 mm at base with 0.85 mm spacing), the slightly curved shape of the Thin Lateral design, the absence of stylet penetration through any curved parts of cochlea, and the mechanical design that affords low stiffness for lateral bending yet higher stiffness for vertical bending (i.e., toward the basilar membrane).

Based upon the temporal bone results, the authors concluded that these arrays are suitable for clinical application where preservation of residual hearing is an issue. In particular, the Thin Lateral array was reported to limit electrical stimulation to the basal turn and could be inserted via the round window, making it particularly suitable for electro-acoustic stimulation.

# Speech Perception Results in Children Implanted with Clarion® Devices: HiResolution® and Standard Resolution Modes

**Bosco E, D'Agosta L, Mancini P, Traisci G, D'Elia C, Filipo R**

This study examined speech perception and language acquisition in two groups of children using different sound processing strategies (CIS, SAS, HiRes). Seventeen children had been implanted with the 1.2 device and used Standard Resolution processing (CIS or SAS). Twenty-three children had been implanted with the CII device and used HiRes. Children using HiRes were fitted with sequential 12-channel programs using a 21-µs pulse width and a stimulation rate of 2017 pps per channel.

Children were evaluated with an extensive test battery including a range of age-appropriate speech perception and language development tests and the MAIS and IT-MAIS questionnaires. For both groups, testing was conducted at one, three, six, nine, and 12 months post–switch-on and, for the standard resolution (CIS and SAS) group, testing continued at 18, 24, and 36 months. The mean age at implantation of the HiRes and Standard Res groups was 5.5 and 5.1 years, respectively. The average duration of acoustic deprivation for the HiRes and Standard Resolution groups was 18.9 and 15.7 months, respectively.

The mean score for the HiRes group on a word identification task was 72.3%. The mean score for the Standard Resolution group was 57.8%. In addition, the average score for two children bilaterally implanted and using HiRes was 83.3%. The difference between HiRes and Standard Resolution for a recognition task was 22.7% ($p = 0.002$). For language comprehension, the HiRes group performed better than the Standard Resolution group ($p = 0.01$). There was a significant difference in the MAIS results between the two groups of subjects ($p = 0.003$), with the HiRes group being superior to the Standard Resolution group.

In addition to the dramatic and encouraging speech perception and language acquisition scores, comments from parents, teachers, and speech therapists indicated that children using HiRes were better able to use the cues available to them in the surrounding environment. This incidental learning is an essential key to naturally acquiring language for pediatric cochlear implant users.

# An Investigation of Telephone Use Among Cochlear Implant Recipients

**Cray JW, Allen RL, Stuart A, Hudson S, Layman E, Givens GD**

A questionnaire assessing telephone use was sent to 803 adult Advanced Bionics cochlear implant users who were implanted between 1998 and 1999. All subjects had more than 12 months of implant listening experience. Usable questionnaires were returned by 478 subjects.

Seventy percent of the subjects were identified as active telephone users, while 30% were considered non-users. The group of telephone users was significantly younger (52 years versus 63 years) and reported significantly greater daily use of their implants (15 hours versus 11.8 hours) compared to the group of non-users. In the active telephone user group, more subjects used oral communication and could understand speech without lipreading. There was no significant difference between groups in terms of onset or duration of hearing impairment or in level of education. On average, the telephone users spent 5.4 hours per week on the phone. Sixty-five percent were able to make appointments by telephone, and 50% were able to ask for additional information, inquire about products, etc.

The authors concluded that the percentage of implant users who are able to use the telephone regularly has increased in recent years and can be attributed to advances both in cochlear implant and telephone technology.

# HiResolution® and Conventional Sound Processing in the HiResolution Bionic Ear: Using Appropriate Outcome Measures to Assess Speech Recognition Abilities

**Koch DB, Osberger MJ, Segel P, Kessler DK**

The aim of this study was to compare performance between HiRes and conventional sound-processing strategies (CIS, MPS, SAS). Fifty-one postlinguistically deafened adults participated in the study at 18 sites in the United States and Canada. After being implanted with the CII Bionic Ear System, subjects were fit initially with their preferred conventional strategy and assessed on a battery of speech perception tests after three months of use. Patients then were fit with HiRes and assessed again after three months of use.

The mean improvement from conventional to HiRes processing was significant for all speech recognition tests (monosyllabic words and sentences in quiet and in noise) ($p < .01$). Notably, subjects who were the lowest performers with conventional sound processing showed the greatest improvements with HiRes. At the end of the study, 96% of all subjects preferred HiRes, including those patients who achieved relatively high scores with conventional processing.

Results from previous clinical trials indicate that the largest learning effects typically occur during the first month of implant use, with limited improvements beyond three months of device experience. The data from this study suggest that the benefits experienced with HiRes are not simply a result of learning effects and that cochlear implant recipients have the potential to benefit from improvements in sound processing technology.

# Effect of Age at Cochlear Implantation on Auditory Skill Development in Infants and Toddlers

**Robbins AM, Koch DB, Osberger MJ, Zimmerman-Phillips S, Kishon-Rabin L**

This study evaluated auditory skill development as a function of age at implantation in children implanted under three years of age. Auditory skill development was assessed with the IT-MAIS before implantation and at 3, 6, and 12 months after implantation. IT-MAIS results from 107 children implanted with the Clarion CI device were compared to previously published IT-MAIS scores from 109 children with normal hearing within the same age range. The implanted children were divided into three groups—those implanted between 12 and 17 months of age, those implanted between 18 and 23 months of age, and those implanted between 24 and 36 months of age.

All children showed rapid acquisition of auditory skills during the first year after implantation. However, the younger children showed higher scores after 12 months. Children who were implanted at a younger age acquired auditory skills nearer to their normal-hearing peers at a younger age. The mean rate of acquisition of auditory skills was similar to normal-hearing infants and toddlers regardless of age at implantation. The authors concluded that implanting children with profound hearing loss at the youngest age possible allows the best opportunity for them to acquire communication skills that approximate those of their peers with normal hearing.

# Performance of Subjects Fit With the Advanced Bionics CII and Nucleus 3G Cochlear Implant Devices

**Spahr AJ, Dorman MF**

This study compared performance between 15 users of the CII device and 15 users of the Nucleus 3G device who were matched on monosyllabic word scores in quiet and for age and duration of deafness. Subjects were assessed with speech-based tests of spectral and temporal resolution, speech in noise, and speech at low presentation levels. The hypothesis was that testing in more difficult listening conditions might reveal differences in sound-processing algorithms.

In quiet situations with a high level of audibility, both devices gave equivalent levels of performance. However, significant group differences were seen for vowel identification, difficult sentences in noise (+5 and +10 dB SNR), and for a measure termed "robustness" that quantified performance in noise and at low levels relative to performance in quiet. On these measures, the subjects using the CII performed significantly better than the subjects using the 3G.

The authors suggest that the differences in performance may be attributed to differences in signal processing. Specifically, the CII system appears to deliver more information in difficult listening environments, which may contribute to increased implant benefit in everyday listening situations.

# Effects of Presentation Level on Phoneme and Sentence Recognition in Quiet by Cochlear Implant Listeners

**Donaldson GS, Allen SL**

The effect of presentation level on the perception of consonants, vowels, and sentences in quiet was evaluated in two groups of subjects: Nucleus 22 SPEAK users and Clarion 1.2 CIS users. The hypothesis was that speech perception ability would decrease as presentation levels dropped below 60 dB SPL and that differences in audibility and input dynamic range between the two devices would influence speech perception at lower levels.

Performance-intensity functions for vowels, consonants, and sentences were measured for each subject using levels of 70, 60, 50, 40, and 30 dBA. Presentation level primarily affected the perception of consonants and sentences with less effect on the perception of vowels. Both groups showed similar scores at 70 dB with significant decreases in the perception of consonants and sentences as levels fell below 50 dBA. For consonants, the scores for the CIS users were significantly better than the SPEAK users at 30 and 40 dBA. For sentences, the CIS users scored as much as 30% higher than the SPEAK users at 40 and 50 dBA. The audibility thresholds of CIS users were 15 dB better than the SPEAK users.

The authors concluded that audibility and a wider input dynamic range accounted for the better performance of the CIS users at lower presentation levels. A wide dynamic range allows a cochlear-implant listener to detect speech cues over a large intensity range and may improve listening in background noise, give better sound quality, and permit detection of a wider range of environmental sounds.

# Optimizing the Number of Electrodes With High-Rate Stimulation of the Clarion® CII Cochlear Implant

**Frijns JHM, Klop MC, Bonnet RM, Briaire JJ**

The effects of high-rate stimulation and increased channel number were evaluated in nine adults and one child using tests of speech perception in quiet and in noise. Subjects were part of a multi-center European HiRes study and had at least three months experience (range three to 11 months) using conventional sound processing with standard resolution. All but one subject had been using CIS (833 pps/channel, monopolar, 75 µs/phase). The study used a blind crossover design with three HiRes strategies (eight, 12, and 16 channels) fitted using the BEPS software. The pulse rate per channel was fixed at 1400 pps, the pulse width was 21 µs, and the interpulse interval was varied (43, 21, or 0 µs) according to the number of channels to maintain a constant pulse rate per channel. In Leiden, the fitting approach used aims at avoiding cross-turn stimulation and maximizing the amount of high-frequency information conveyed. To ensure that the subjects did not know how many channels were being used, Ts and Ms always were measured for each electrode. Subjects were divided into three groups, using the three HiRes programs according to a modified Latin square design to avoid learning effects. For each strategy, after one month of use, speech performance was assessed using monosyllabic words presented at 65 dB SPL with SNR infinite, +10, +5, 0, and -5 dB.

To find the optimal program for each user after the trial, three programs were defined based on performance in noise:

- Program with highest performance at +5 dB SNR,
- Program with optimal weighted average of scores at +10 dB and +5 dB SNR,
- Program with optimal speech reception threshold (SRT): SNR at which 50% of the phonemes were understood.

In general, performance deteriorated with increasing noise level for all three HiRes strategies. No program was optimal for all users in all conditions. Nonetheless, performance with all HiRes strategies was better than with standard resolution. In the +5 dB SNR condition, word recognition with the 8- and 12-channel HiRes programs showed a significant improvement over word recognition with standard resolution ($p < .05$).

In summary, although all subjects had very good results with standard resolution before the study, they all experience improved benefit from HiRes, especially in noise. A ceiling effect was observed for tests in quiet but improvements could still be observed. The optimal number of channels was dependent on the individual user. It is important to note that even non-optimized HiRes programs provided improved benefit over standard resolution programs.

# Coding of Sounds in the Auditory System and its Relevance to Signal Processing and Coding in Cochlear Implants

**Moore BCJ**

This review paper describes how sounds are coded in the normal auditory system and examines the ways in which contemporary cochlear implants provide usable hearing. Suggestions are made as to how future cochlear implants might better replicate the normal coding mechanisms.

Specifically, the encoding of a wide dynamic range is partially a result of fast-acting compressive mechanisms within the cochlea. This mechanism is absent in profound hearing impairment. Thus, rapid magnitude increases occur because the basilar membrane's compressive effect and neurotransmitter release are absent, resulting in a reduced electrical dynamic range of 3 dB to 20 dB. This compression mechanism might be compensated for partially through a dual-action AGC circuit that maintains the information-bearing modulation depth of speech while avoiding co-modulation effects that occur with fast compression.

Frequency representation and resolution is significantly poorer in an implanted ear than a normal ear. Thus, spectral shape and periodicity are inadequately represented. Introducing more spectral channels and delivering those channels to precise locations using modiolar-hugging electrodes would provide more usable spectral information to implant users. Adding phase information to each channel might provide the coincidence detection required across channels for better representation of spectral shape, intensity, and pitch. Furthermore, the low pulse rates of older cochlear implant systems have not represented temporal detail, thereby limiting the phase-locking coding mechanism. Implant users rarely can discriminate pulse rates exceeding 300 Hz because of the mismatch between temporal and place information. For coding the pitch of complex tones, cochlear implants do not make effective use of resolved harmonics, periodicity being almost entirely based on a temporal code.

For localization, pinna cues are not available because the implant system's microphone typically is located behind the ear and spectral cues are not represented adequately. Better spectral representation and locating the microphone within the ear would improve that ability. Moreover, bilateral implantation, which might improve the ability to localize sounds and to hear speech in noise, may be limited by differences between electrode array positions and a lack of synchronization between the two implants.

Notably, many of the review's recommendations on how an implant system might provide improved hearing are implemented in the HiResolution® Bionic Ear. These features include the T-Mic®, CD-quality front-end audio sampling, dual-action AGC, increased temporal and spectral resolution, high stimulation rates, and focused electrical stimulation.

# HiResolution® Bionic Ear System
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