HiRes Fidelity 120® Sound Processing

Implementing Active Current Steering for Increased Spectral Resolution in Harmony® HiResolution® Bionic Ear Users

Spectral Resolution

Why is it important?

In general, cochlear implants have not been able to reproduce the fine spectral analyses performed by the normal cochlea. Nonetheless, today's cochlear implant users typically can understand speech remarkably well in quiet. Because the speech signal is redundant, only limited spectral resolution is necessary (see Shannon et al 2004). On the other hand, when the listening environment becomes more challenging, increased spectral resolution is required to separate speech from noise or to distinguish multiple talkers.

While speech can be understood in the presence of severe degradation of spectral and temporal cues, music recognition and appreciation are compromised by even mild degradation (Shannon 2005). Smith and colleagues (2002) have shown in normal-hearing listeners that increased spectral resolution is required to perceive harmonic pitch and to identify melodies and instruments. As many as 100 bands of spectral resolution are required for music perception in normal-hearing subjects. A study by Oxenham et al (2004) demonstrated that fine temporal resolution and place-specific frequency resolution together are required to produce the harmonic pitch percepts necessary for listening to complex acoustic signals.

Accordingly, cochlear implant systems must reproduce both fine temporal cues (such as with first generation HiRes) and spectral cues in high resolution to facilitate music perception and appreciation for implant recipients. Not surprisingly, many cochlear implant users do not enjoy music given the limited spectral resolution delivered by current devices. The challenge for today's cochlear implant systems is to maximize representation of frequency information with a limited number of fixed electrodes.

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A report from Advanced Bionics

Increasing Spectral Resolution in Cochlear Implants

Research Findings

For normal-hearing people, spectral resolution derives from a complex interaction of an acoustic signal's fundamental frequency, spectral shape, temporal waveform, and intensity. It is not understood completely how pitch is encoded, but it is known that two mechanisms underlie the representation of frequency in the auditory periphery. One mechanism—the place code—derives from the place of maximum stimulation along the basilar membrane, which is dependent upon the spectrum of the acoustic stimulus. The other—the periodicity code—derives from the temporal patterns of neural firing in auditory nerve fibers. These two mechanisms interact in complex ways to allow normal listeners to resolve differences in pitch.

The mechanisms for conveying spectral information in a cochlear implant are different than in a normal cochlea. With electrical stimulation, the delivery of frequency information can be separated into (1) place of stimulation and (2) the rate of stimulation. However, unlike normal hearing, the place of stimulation is not determined by the acoustic spectrum, but rather it can be manipulated independently by encoding which electrode is stimulated. Most implant recipients report an upward change in pitch as stimulation is moved in an apical-to-basal direction along the implanted electrode array. Evaluating the pitch percepts of cochlear implant users for different electrodes thus provides information about the success of using place to convey spectral information. Furthermore, the ability of implant users to distinguish the pitches evoked by stimulating different electrodes provides a measure of the independence of the electrodes and of each individual's spectral resolution capability.

Historically, the number of electrodes in a system has defined the number of spectral bands of stimulation. Therefore, the number of spectral bands of resolution was limited to the maximum number of electrodes. Given the established value of spectral resolution, researchers investigated mechanisms to enhance spectral resolution without adding additional electrodes.

Townshend and colleagues (1987) first reported that for three subjects with the UCSF device (precursor to the Harmony), additional pitch percepts could be created by stimulating two electrodes at the same time. The study showed that the perception of pitch could be varied systematically by adjusting the proportion of current delivered simultaneously to two electrodes. The additional pitches were heard as one pitch rather than two separate pitch components and were intermediate to the pitches heard when either electrode was stimulated alone. A similar experiment by Wilson et al (1994) in an Ineraid user showed the same results. Wilson suggested that this simultaneous stimulation technique, also referred to as current steering, could be used to introduce additional spectral resolution to implant users.

However, for cochlear implants with only one current source, the ability to actively steer current (with simultaneous stimulation) is not possible. Researchers have explored the viability of another mechanism that uses non-simultaneous stimulation for evoking pitches that are intermediate to those evoked by the corresponding electrodes when stimulated alone (McDermott and McKay 1994). This non-simultaneous mechanism is the one implemented by high-rate sound processing strategies. For example, when a frequency of a single tone is changed continuously, the intermediate pitch percept may vary continuously because the "skirts" of the analysis filters may cause stimulation on adjacent electrodes to overlap in time. There are at least three potential disadvantages to this non-simultaneous scheme for representing spectral information.

- First, for complex stimuli, the filter "skirts" can create undesirable overlap between stimulus components, causing "spectral smearing." Consequently, subjects may not be able to distinguish between a tone presented at a frequency that is intermediate between two electrodes and two tones that are presented at frequencies matching both electrodes.

- Second, because non-simultaneous stimulation of adjacent electrodes requires substantial current to generate intermediate pitch percepts, the neural activation area is more diffuse compared to stimulating each electrode independently.

- Third, sequential stimulation in an implant with only a single current source may require a further reduction in the number of electrodes stimulated in each cycle (N of M versus n/2 of M) since each spectral band requires sequential stimulation of two adjacent electrodes.

Yet another mechanism proposed for steering current is to simply short adjacent electrodes together (Busby and Plant 2005). However, this mechanism is limited in that only one additional location between adjacent electrodes can be derived (n + [n-1] = total possible locations, where n = the number of electrodes). Moreover, the pitch of each intermediate location may vary because current will take the path of least resistance to the neural elements. Hence, sound quality cannot be assured because of uncontrollable fluctuations in electrode impedance.

Active Current Steering in the Harmony HiResolution Bionic Ear System

What is it? How is it implemented?

Now with the advent of the Harmony HiResolution Bionic Ear System, the technology exists to actively "steer" current between adjacent electrodes to deliver added spectral resolution as first proposed by Townshend et al (1987) and Wilson et al (1994).

Active current steering is made possible in the Harmony system because each electrode has its own separate power source—thereby allowing current to be delivered simultaneously to pairs of electrodes. Theoretically, with fine control over the proportion and amplitude of current delivered to each electrode of the pair, the locus of stimulation is "steered" between the two electrodes. Thus, many intermediate spectral bands may be delivered. As long as the total current delivered is constant, loudness perception remains essentially unaffected (Donaldson et al, 2005).

Hypothetically, if half the current is delivered to one electrode and half to a neighboring electrode, the stimulated neural population is approximately halfway between the two contacts (Figure 1A). As the weighting (proportion) of current is shifted toward one of the electrodes, the stimulated place is closer to that electrode (Figure 1B). As stimulation is shifted from one electrode to another, the individual implant user's pitch perception may shift accordingly.

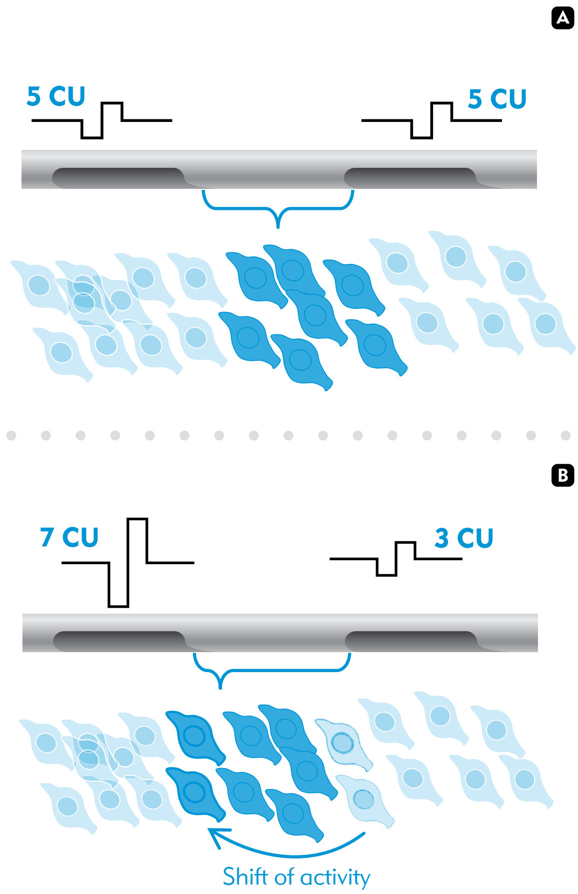

Figure 1. Diagram of active current steering whereby in the first example (A), half the current (CU—clinical units) is "steered" to each of two neighboring electrodes so that the locus of stimulation is approximately halfway between the two contacts. In the second example (B), as a greater proportion of current is steered toward one of the electrodes, the locus of stimulation is shifted closer to that electrode.

Enhancing Spectral Resolution with *Active* Current Steering

Experimental Evidence

A published study by Donaldson et al (2005) extended the work of Townshend et al (1987) and Wilson et al (1994) by investigating the use of active current steering to create additional discriminable pitches in between the electrodes in a small number of Harmony recipients. Their results showed that these listeners could hear multiple, unique pitches when current was steered between adjacent electrodes. For most subjects, the loudness perception for either of the adjacent electrodes stimulated alone was essentially equivalent to the loudness perception when the current delivered simultaneously to two electrodes was apportioned by linear interpolation.

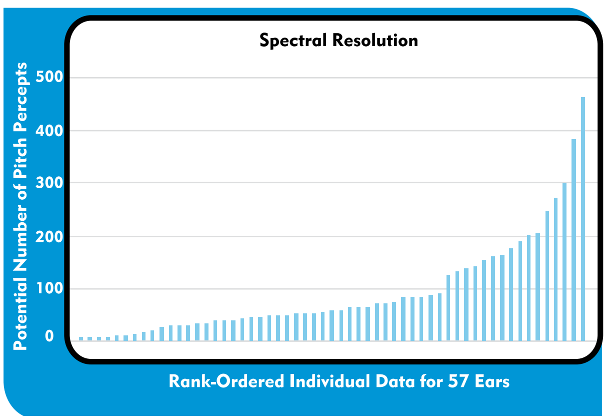

Figure 2. The estimated total number pitch percepts created, based on actual measures of current actively "steered" between basal, mid-array, and apical electrode pairs.

Donaldson et al's results suggest that the two disadvantages associated with non-simultaneous dual electrode stimulation (described in McDermott and McKay 1994) can be overcome in Harmony recipients. First, because a large number of spectral bands can be delivered using one electrode pair, the effects of spectral smearing can be reduced or eliminated. Second, because simultaneous stimulation requires much less current than non-simultaneous stimulation, a narrower cochlear region may be maximally stimulated, thereby potentially evoking more distinct pitch percepts.

A study of a larger group of Harmony users (Koch et al, 2007) supported Donaldson's initial results. In these experiments, subjects were first tasked to loudness-balance and pitch-rank three electrode pairs—a basal pair, a mid-array pair, and an apical pair. They then identified for each pair the electrode with the higher pitch while current was varied proportionally between electrodes in the pair. The smallest change in proportion yielding a discernible change in pitch was defined as the spectral resolution. Data from 57 ears indicated that the number of distinct pitch percepts averaged 5.4 for the basal pair, 8.7 for the mid-array pair, and 7.2 for the apical pair. Based on the assumption that the number of pitch percepts on these three electrode pairs was representative of the entire array, the total potential number of pitch percepts for these individual subjects was estimated to range from 8 to 466, with an average of 93 (see Figure 2).

Current steering was commercially pioneered by AB with Precision®—the first long-lasting rechargeable spinal cord stimulation (SCS) system for the treatment of back pain. The system is about half the size and offers greater comfort and convenience than other systems on the market. Moreover, Precision* can cover more than one pain area at the same time.

As a company that has been involved in multiple neurostimulation products, AB is able to leverage its research and development efforts in one product line to serve others. One example of such leveraging is the implementation of current steering in the Harmony HiResolution Bionic Ear System.

* *Precision is a registered trademark of Boston Scientific Neuromodulation Corporation, which has acquired rights to make and sell the SCS system first developed by Advanced Bionics.*

HiRes Fidelity 120

What is it? How is it implemented?

HiRes with Fidelity 120 (HiRes 120) is the first commercial implementation of active current steering in a cochlear implant system. Building on the fine temporal resolution of first generation HiRes, HiRes 120 was designed to enhance spectral resolution through the creation of additional spectral bands.

In first generation HiRes, incoming sound is filtered into 16 spectral bands. The energy of each band is extracted, and its envelope modulates a high-rate pulse train that is delivered to a single corresponding electrode.

In HiRes 120, the input signal is analyzed in greater spectral detail (than with conventional processing) to achieve a maximum of 120 spectral bands. Figure 3 diagrams the four basic stages of HiRes 120 sound processing: (1) capture, (2) compose, (3) detail, and (4) deliver. After capturing the incoming acoustic input (Stage 1), the signal is composed (Stage 2) for finer spectral resolution using fast Fourier transformation (FFT) algorithms. Next, in Stage 3, a detailed analysis of temporal and spectral information is processed in parallel. The temporal detail is extracted with Hilbert processing while a navigator locates the spectral maximum for each electrode pair across the 120 spectral bands (Figure 4). The estimated frequency of the spectral maximum is used to compute the rate of the pulse train and to continuously select the optimal location for delivering stimulation (Stage 4).

As described previously, in HiRes 120, spectral bands are delivered to locations along the electrode array by accurately varying the proportion of current delivered simultaneously to adjacent electrodes in each electrode pair. For each electrode pair, there are 8 spectral bands, as diagrammed in Figure 5. Therefore, when all 16 electrodes are enabled, 120 spectral bands may be delivered—that is 15 electrode pairs multiplied by 8 spectral bands = 120.

** In the United States, an optional feature for adults only. See package insert for details.*

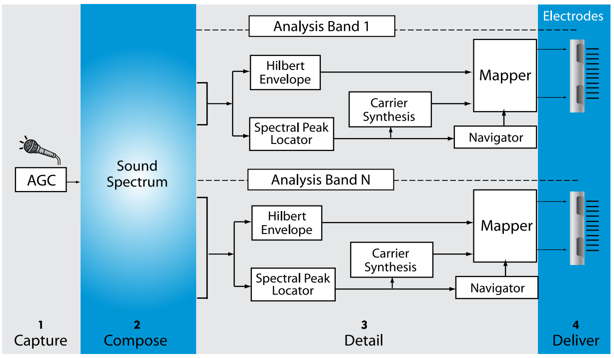

Figure 3. The four stages of HiRes 120 sound processing: Capture, Compose, Detail, and Deliver.

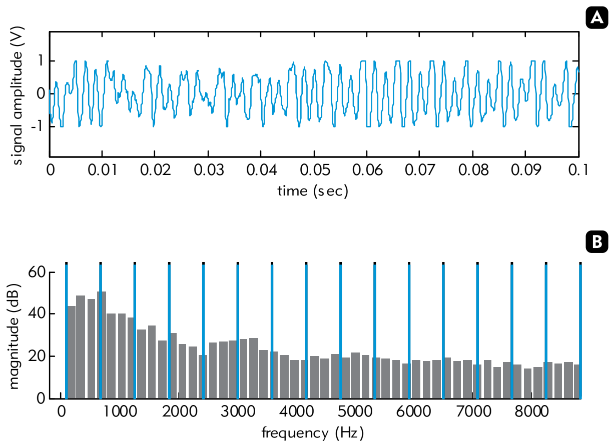

Figure 4. In Stage 3, temporal information is extracted with Hilbert processing (A) while a navigator locates the spectral maximum to determine the corresponding spectral band for stimulation (B).

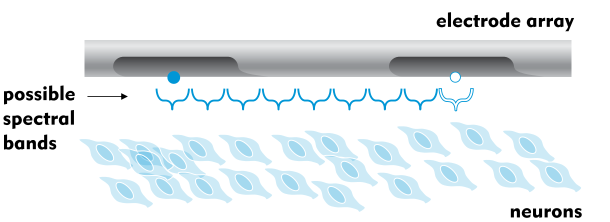

Figure 5. In Stage 4, by varying the proportion of current delivered simultaneously to adjacent electrodes, up to eight spectral bands may be delivered for each electrode pairing.

Music Appreciation and HiResolution Preference

Clinical Study Results

Music plays important psychological and social functions in life. Birthdays, graduations, weddings, and other important milestones in life are celebrated with music.

Despite its importance to quality of life, music listening has received far less attention than speech perception in the cochlear implant research literature. Moreover, while performance on standard speech perception tests has improved with advancements in sound processing, studies of music perception and appreciation have shown disappointingly poor results among implant recipients. For example, Mirza and colleagues (2003) reported on 35 adult respondents to a music appreciation questionnaire. Subjects (using MXM, Clarion, and Nucleus 22 or 24 devices) were asked to rate on a scale of 10 their enjoyment of music before becoming deaf and after implantation. The mean rating before deafness was 8.7 while after implantation the mean rating was 2.6. In fact, only 16 (46%) of the subjects reported that they listened to music in their daily lives after they received their implants.

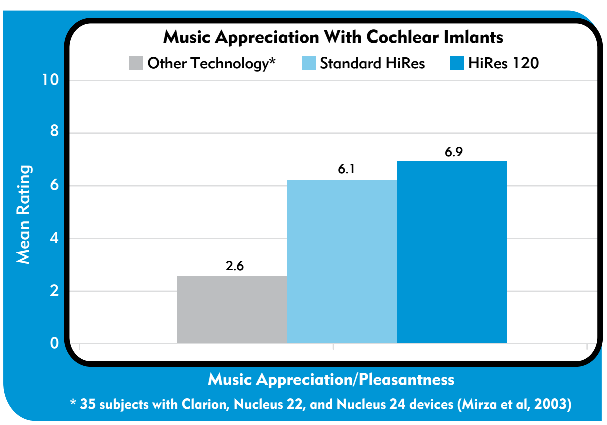

Figure 6. Mean ratings of music appreciation with at least 9 months of use with other cochlear implant technologies (from Mirza et al 2003) compared to at least 4 months of use with standard HiRes and at the 3-month test interval with HiRes 120 (from a multicenter study). See Table 1 for additional demographic information and study method descriptions.

Addressing the call for more research in music perception and appreciation especially as sound processing technology advances, a multicenter study investigating the benefits of HiRes 120 included several measures of music listening and overall sound quality benefits (in addition to a standard battery of speech perception measures).

In this study, 50 recipients were asked to rate the *pleasantness* and *distinctness* of instrumental music passages on a scale of 0 (extremely unpleasant/ indistinct) to 10 (extremely pleasant/distinct). The music *pleasantness* mean ratings after one and three months with HiRes 120 were 7.0 and 6.9, respectively, compared to a 6.1 mean rating in the baseline condition (standard HiRes). Similarly, the music *distinctness* mean ratings for HiRes 120 were 5.7 at one month and 5.8 at three months. In summary, 16 of 26 subjects (62%) indicated higher *pleasantness* ratings, and 17 of 26 subjects (65%) indicated greater *distinctness* ratings with HiRes 120 compared to standard HiRes.

Figure 6 and Table 1 summarize demographic information and the mean ratings for music listening from the Mirza et al and the HiRes 120 multicenter studies. Subjects using either standard HiRes or HiRes 120 rated their music listening experience markedly higher than patients using other technologies.

In addition to music ratings, preference for processing strategy was assessed. A total of 43 out of 50 subjects (86%) reported a preference for the HiRes 120 over standard HiRes. Subjects also rated strength of preference for the two strategies on a scale from 1 (weak preference) to 10 (strong preference). The mean strength of preference for the 43 subjects who preferred HiRes 120 was 7.9 (range: 1–10). The strength of preference was rated as 8 or higher by 26 of the 43 subjects. Indeed, 16 of the 43 subjects rated their preference as 10 (strong preference). For the seven subjects who preferred standard HiRes, the mean strength of preference was 4.4 (range: 1–9).

To further assess strategy preference, subjects indicated those aspects of sound that were better with their preferred processing mode, using a five-point Likert scale (*strongly disagree, disagree, neutral, agree,* or *strongly agree*) in response to questionnaire items. Over three quarters of the subjects agreed or strongly agreed that HiRes 120 resulted in better overall sound quality and more natural sounding speech and that environmental sounds were easier to distinguish compared with standard HiRes.

Previously, based on study results such as Mirza et al, clinicians generally have counseled candiates to have low, if any, expectations for music enjoyment following implantation. However, the findings of the HiRes 120 multicenter study give clinicians and patients considerable room for optimism. Moreover, the unsurpassed temporal and spectral resolution of HiResolution Sound (HiRes or HiRes 120) offers present and future Harmony users increased potential for music appreciation and overall sound quality than has been previously possible.

Table 1: Subjective Ratings of Music Listening

	Mirza et al (2003)	HiRes Multicenter Study		
Strategy	Various	HiRes	HiRes 120	HiRes 120
n	35	50	50	50
Duration of Use (Range)	≥ 9 mos (.75 - 10 yrs)	≥ 4 mos (.33 - 4 yrs)	1 mo*	3 mos*
‡ Mean Ratings Music Enjoyment/ Pleasantness	2.6	6.1	7.0	6.9
‡ Mean Ratings Music Distinctness		5.1	5.7	5.8

* test interval
‡ scale of 1–10
Note: The Mirza et al study asked subjects to rate general music listening enjoyment, whereas the HiRes 120 study had subjects rate music pleasantness and distinctness after listening to specific musical passages.

Summary

The increased spectral resolution of HiRes 120, in combination with the fine temporal resolution already implemented in standard HiRes, has the potential to provide some patients with better speech perception (especially in noise), enhanced music appreciation, and improved sound quality overall.

HiRes 120 retains the time-efficient, simplified fitting approach of HiResolution Sound (HiRes) to facilitate upgrading patients from HiRes to HiRes 120.

The Harmony HiResolution Bionic Ear is a unique and technologically innovative cochlear implant system with built-in flexibility and upgradeability. Its flexibility arises from 16 independent circuits (channels) that allow each electrode to be powered and programmed separately with variable pulsatile waveforms, using simultaneous or non-simultaneous stimulation. Its upgradeability lies in the untapped capability of the Harmony's implanted electronics. Consequently, Harmony recipients have access to HiRes sound today and will have access to new sound-processing strategies in the future simply through software upgrades. HiRes Fidelity 120 represents the latest in such software upgrades now available* to Harmony users.

** In the United States, an optional feature for adults only. See package insert for details.*

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