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The history of Cochlear™ Nucleus® sound processor upgrades: 30 years and counting

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Abstract

Objective: To review developments in sound processors over the past 30 years that have resulted in significant improvements in outcomes for Nucleus® recipients.

Keywords: Cochlear implant; Sound processor; SmartSound; SCAN; Wireless accessories

1. Introduction

More than 30 years have passed since the first commercial use of a multi-channel cochlear implant took place, one historic day in Australia. Since then, we have witnessed ever-improving and truly remarkable cochlear implant outcomes in adults and children, and the number of Nucleus® implant recipients has grown to more than 400,000 worldwide. Cochlear Limited, the company that first brought multi-channel implants to the market, began with the visionary work of Professor Graeme Clark and his pioneering team of multi-disciplinary specialists. For more than three decades, their spirit of innovation has remained central to Cochlear's success. One example where this shows is in the development of smaller, more advanced and easier to use sound processors – from Cochlear's earliest body-worn processors to the world's first ear-level processors – and all the way through to the current Nucleus® 6 processor. Cochlear's ninth generation sound processor, Nucleus 6, is the smallest and most advanced on the market. It brings several breakthroughs in hearing performance, connectivity and lifestyle.

At the most elementary level, all sound processors are designed to analyze acoustic signals from a microphone(s) according to specific instructions and algorithms, encode this information in a form that can be reliably transmitted across the skin via a radio frequency (RF) carrier to the to the receiver-stimulator encased in the cochlear implant. The receiver-stimulator converts transmitted data into bi-phasic electrical pulses that are sent to the electrodes within the cochlea. Cochlear's processors use transcutaneous coupling, therefore, power for the receiver-stimulator as well as encoded data are transferred via the RF link.

The earliest processors contained mainly analog with a few digital circuits and could not process large amounts of data. Thus, processors such as the Wearable Speech Processor (WSP) and the Mini Speech Processor (MSP) coded and delivered basic acoustic parameters such as signal amplitudes, estimates of the fundamental frequency, first, second formats and, with the MSP, some higher frequency energy (Clark et al., 1990; Clark, 2003). Today's processors contain low power, custom digital signal processing (DSP) chips capable of quickly executing sophisticated mathematical computations. These processors implement sophisticated sound processing

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strategies, such as the Spectral Peak (SPEAK), Continuous Interleaved Sampling (CIS), and Advanced Combination Encoder (ACE) strategies. These encoders present information at high rates and to more electrodes (channels) within the cochlea (Clark, 2003; Patrick et al., 2006). Engineers have invented new DSP algorithms that combine outputs from multiple microphones to improve listening in difficult listening environments. Some algorithms specifically remove noisy elements of the acoustic signal. Improvements in signal processing have resulted in enhanced outcomes for recipients and are discussed below (Dawson et al., 2011; Hersbach et al., 2012; Mauger et al., 2014).

2. Peformance improvements

The advancement of performance outcomes is linked to both technology improvements and changes in candidacy for implantable hearing solutions. Because of favorable performance outcomes, candidacy has broadened, and because of broadened candidacy, performance outcomes have further improved – and the cycle continues. Today many additional treatment options are available because indications expanded. These include: middle ear and bone conduction implants, electro-acoustic implants and direct acoustic cochlear implants (Fig. 1). Sound processor technologies must also advance to address these changing candidacy and hearing needs. As an example, bilateral implantations are more prevalent because of superior results. There are almost 33,000 bilateral Nucleus recipients globally and approximately 60% are children and teens. It is well documented that two ears are better than one for localization, hearing in noise, sound quality, and ease of listening (Dunn et al., 2008; Litovsky et al., 2009; Dunn et al., 2010a,b; Litovsky, 2011; Ramsden et al., 2012; Galvin et al., 2013; Hughes and Galvin, 2013; Potts and Litovsky, 2014).

Given the broadened indications, more people with functional residual hearing receive cochlear implants; today there is an opportunity to use that acoustic hearing when it remains following surgery. Cochlear™ Hybrid™ Hearing uses acoustic amplification to improve low-frequency hearing, while the cochlear implant restores access to high-frequency hearing that is not available through conventional amplification (Figs. 2 and 3). It is well documented that acoustic hearing provides important additional information to what recipients receive electrically (Gantz et al., 2005; Dorman and Gifford, 2010; Dunn et al., 2010a,b; Gifford et al., 2013; Incerti et al., 2013; Lenarz et al., 2013; Gifford et al., 2014; Jurawitz et al., 2014; Roland et al., 2015). Every Nucleus 6 processor is Hybrid-ready.

As hearing performance improved through fundamental sound coding advancements, front-end input signal processing played a larger role in performance increases. Cochlear introduced SmartSound® processing in 2005 in the Freedom® sound processor. This processor combined a directional (front) microphone and an omni-directional (rear) microphone to create the beamformer. This change allowed for the industry's first adaptive beamformer to be commercially released (Patrick et al., 2006; Spriet et al., 2007). SmartSound evolved further with SmartSound 2; this facilitated different input processing approaches for a range of listening environments. There were four pre-defined programs – the Everyday, Noise, Focus and Music programs, but it required recipients to manually select and change programs (Wolfe et al., 2012). Now with the third generation of SmartSound processing in the Nucleus 6 processor, Cochlear introduces SmartSound®

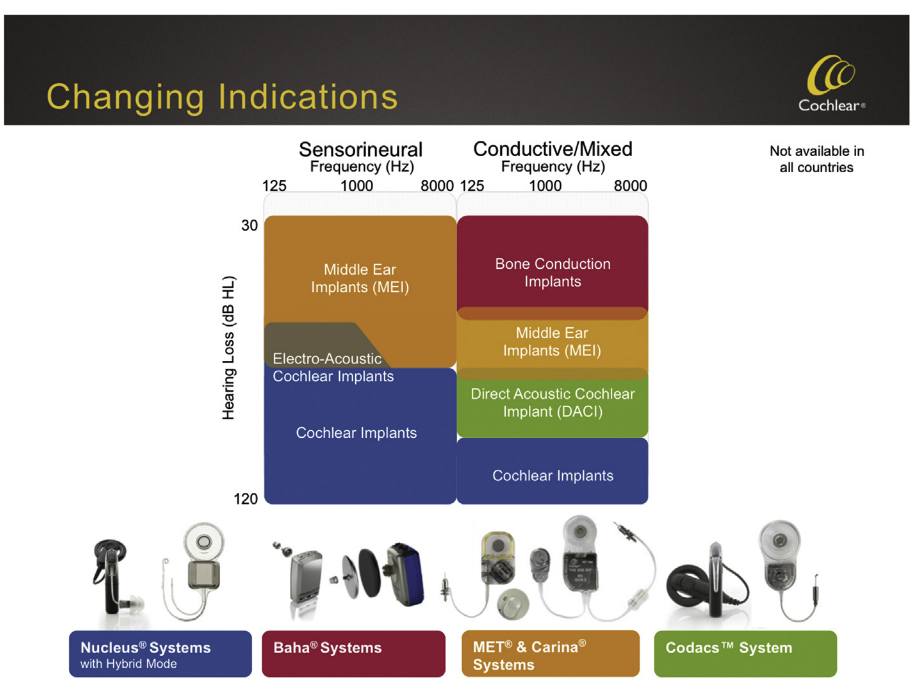

Fig. 1. Available treatment options related to degree of hearing loss as well as expanded indications.

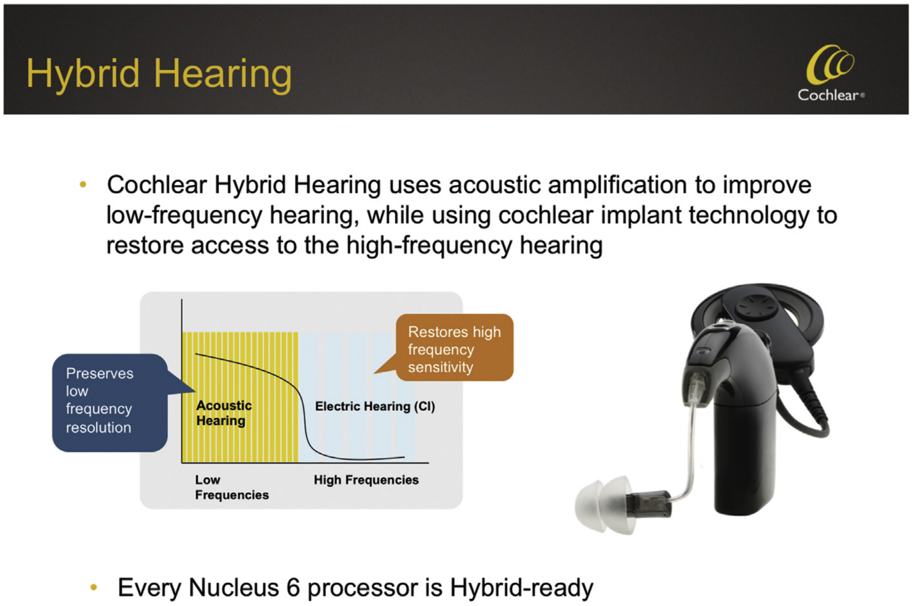

Fig. 2. Hybrid Hearing uses acoustic amplification to improve low-frequency hearing and electrical stimulation through the cochlear implant to restore high-frequency hearing.

iQ-making SmartSound completely automatic. Using a scene classifier (SCAN), the processor automatically and seamlessly selects the best input signal processing for a listening situation. SSiQ has two types of programs: first, the default SCAN program where the classifier analyses the recipient's sound environment, and automatically selects the appropriate input processing technologies and microphone directionality for optimum hearing performance and comfort. Second there are custom programs where specific technologies can be clinically specified based on the individual's hearing preferences and listening requirements (Mauger et al., 2014; Wolfe et al., 2015).

Mauger et al. (2014) demonstrated the benefit of SCAN's adaptive directionality in noise; these researchers measured an average 3.8 dB improvement on an adaptive speech reception threshold (SRT) test with SCAN compared to no input processing or SmartSound 2 (Left graph on Fig. 4). When both speech and noise came from the front – a very difficult listening situation – subjects on average performed 1.7–2.3 dB better with SCAN's noise reduction algorithm

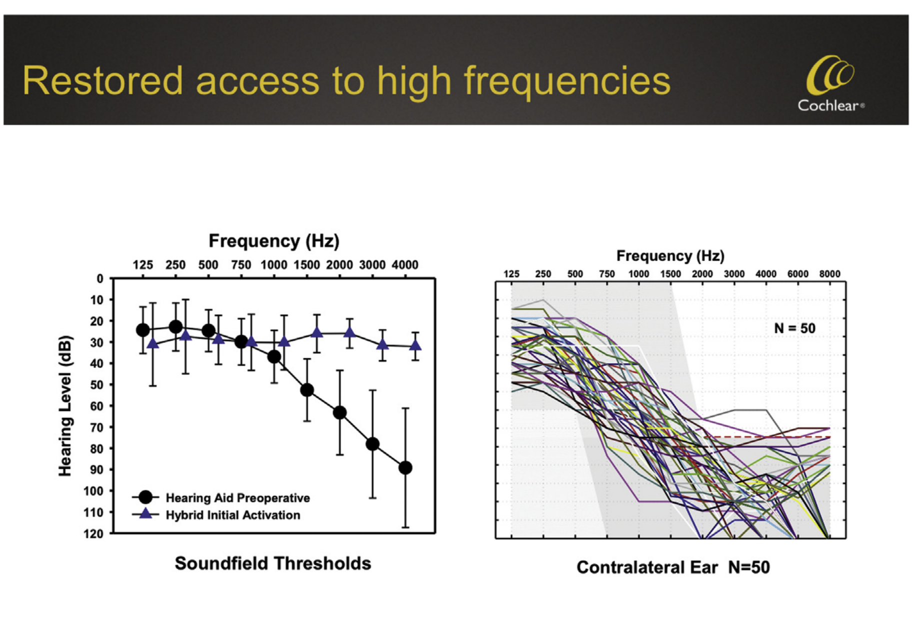

Fig. 3. The left panel illustrates mean pre-operative aided sound field thresholds and mean Hybrid sound field thresholds at initial activation for subjects in the Cochlear Nucleus Hybrid System FDA clinical trial. The right panel illustrates individual subject hearing thresholds in the contralateral ear.

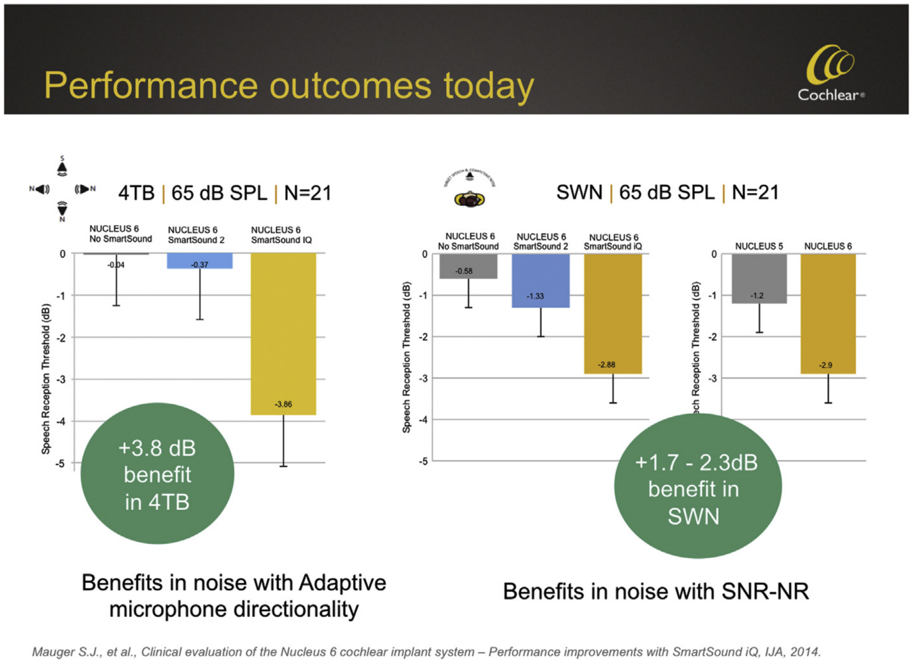

Fig. 4. The left panel illustrates the mean performance improvements with Nucleus 6 using SCAN (SmartSound iQ) in 4 talker babble noise when speech comes from the front and noise from the sides and behind compared to no SmartSound or SmartSound2. The right panel illustrates the mean performance improvements in speech weighted noise using the Nucleus 6 signal-to-noise reduction (SNR-NR) algorithm when speech and noise are co-located compared to no SmartSound or SmartSound2. Also illustrated is the mean performance improvement using Nucleus 6 with SNR-NR compared to performance with subjects' Nucleus 5 processor.

(SNR-NR) compared to listening with SmartSound2 processing or no input processing at all. Subjects performed on average 1.7 dB better with Nucleus 6 and SCAN with SNR-NR compared to their Nucleus 5 (Right graph on Fig. 4).

Recently, audiologists in Cochlear's design and development team began fitting Nucleus 6 to some of their first Nucleus 22 recipients. Fig. 5 provides preliminary results showing good improvements with SCAN, almost a 6 dB enhancement compared to their Freedom processor in speech weighted noise and a 5 dB improvement in 4 talker babble (Cochlear Limited, 2015a,b).

3. Connectivity

Cochlear is the first implant manufacturer to introduce completely wireless accessories. Previously, the use of audio accessories with a sound processor required a wired connection. Although wired accessories work well, many recipients find them impractical and do not use them as much as they would like. The convenience of wireless accessories means more recipients now use audio accessories and enjoy their benefits. Fig. 6 illustrates the Mini-Microphone, the TV streamer and the Phone Clip. A recent Mini Microphone study demonstrated excellent improvement, with an average 8 dB improvement on recognition of sentences in noise compared to performance with Nucleus 6 alone (Fig. 7) (Cochlear Limited, 2015a,b).

Nucleus 6 is the industry's first processor with data logging that monitors and records sound processor and accessory usage. Clinicians use data logs to visualize device usage patterns, and gain clinical insights that may help in counseling the care giver or recipient to achieve a richer hearing journey/experience.

4. Lifestyle

Implant recipients have benefited from a significant reduction in sound processor size and improved processor design. With a 50% reduction in size compared to Freedom® processors, Nucleus 6 offers a more discreet appearance and greater comfort. It also carries the Water Resistance rating of IP57 and water-repellent nano-coating on the processor makes it more reliable around water than ever before. The Nucleus 6 is compatible with the Cochlear Aqua Accessory, making it waterproof (IP68), giving recipients the freedom to swim underwater in a pool, lake or ocean.

5. Future advancements

Cochlear implant technologies will advance with continued miniaturization of various components, allowing engineers to design smaller implants and sound processors that also require less power. Future implants may have different electrode arrays and receiver-stimulators that can be programmed to send current to the implanted electrodes in novel ways with the potential to focus electrical stimulation and potentially increase the number of independent channels, thus improving recipients' speech understanding (Bierer, 2010; Long et al, 2014). New electrode array designs will further minimize cochlear trauma and could deliver various therapeutic drugs to

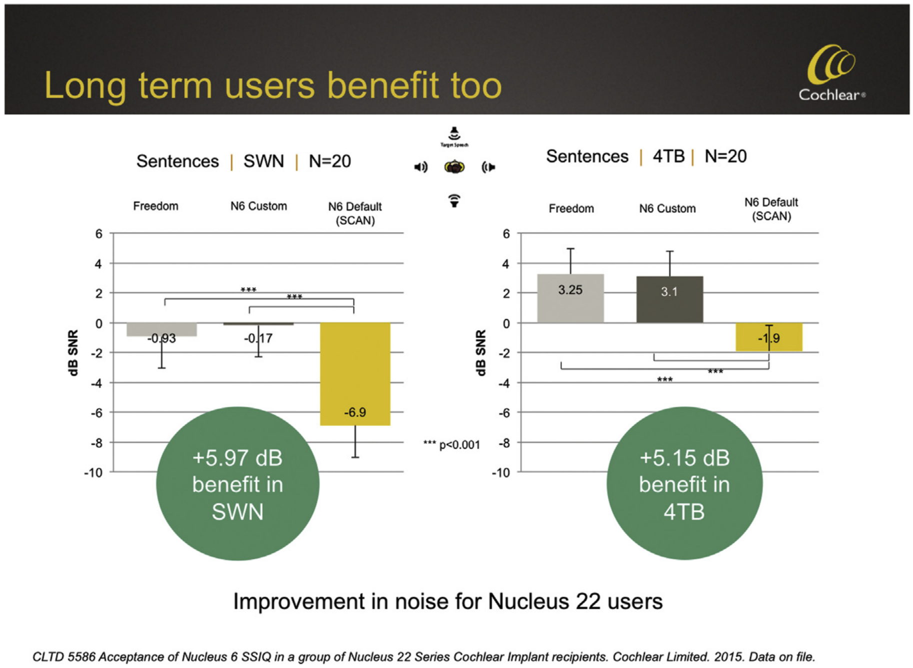

Fig. 5. The left panel illustrates mean performance improvements in speech weight noise for Nucleus 22 subjects using the default SCAN program compared to their Freedom processor and to Nucleus 6 using a program without SCAN. The right panel illustrates mean performance improvements in 4 talker babble noise for Nucleus 22 subjects using the default SCAN program compared to their Freedom processor and to Nucleus 6 using a program without SCAN.

enhance nerve growth and/or maintain residual hearing (Wilson and Dorman, 2008; Jolly et al., 2010; Shepherd, 2011; Astolfi et al., 2014).

Another exciting development is the research totally implantable cochlear implant (TIKI) developed by Cochlear Limited and the Co-operative Research Centre for Cochlear Implant and Hearing Aid Innovation (Briggs et al., 2008; Briggs, 2011). Three adults with severe to profound sensorineural hearing loss were implanted expressly for research purposes with the TIKI at the University of Melbourne Cochlear Implant Clinic, without any surgical or postoperative complications. These three subjects are able to use their TIKI in both “invisible hearing” mode or with their external ESPrit 3G sound processor. The major limitation of this research

Fig. 6. Cochlear's wireless accessories: Mini Microphone, TV Streamer and Phone Clip.

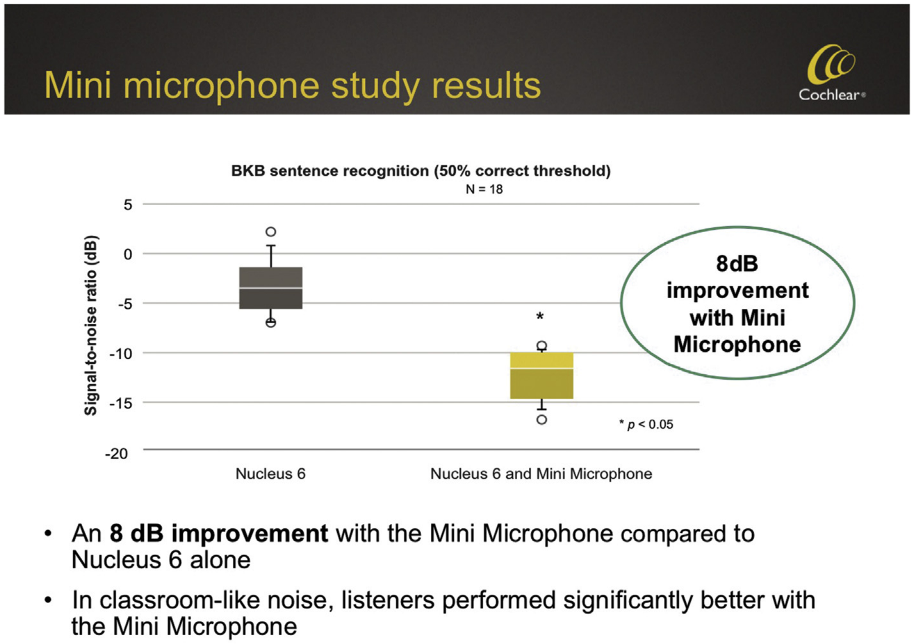

Fig. 7. Mean performance on the Bamford Kowal Bench speech reception threshold test (SRT) in noise using the Nucleus 6 alone and the Nucleus 6 with the Mini Microphone.

device is the internal microphone, which has limited sensitivity such that speech intelligibility is somewhat degraded with invisible hearing mode compared to outcomes with the ESPrit 3G processor. Additionally, body noise interference is bothersome and reduces the amount of time subjects use their invisible hearing. Research is ongoing to improve the subcutaneous microphone and signal processing.

6. Conclusion

Over the last 30 plus years, Cochlear has consistently produced many sound processor innovations. At the same time, speech perception outcomes have greatly improved leading to expanded indications, with more and more individuals accessing the range of our technologies. Lifestyle considerations and connectivity demands are becoming as important as hearing performance in propelling the design of sound processors. Cochlear remains firmly committed to backwards compatibility delivering on the promise of "Hear Now and Always" to our earliest cochlear implant recipients.

Declaration of interest

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