Cochlear implants (CIs) are a well-known and accepted treatment method for adults and children with severe to profound sensorineural hearing loss. Advances in technology, increased confidence in experience, and changes in candidacy criteria have led to CIs being made available to a broader population. Due to these technological advances, our expectations of CIs have also changed considerably. In general, users perform well in quiet and have some degree of phone use ability, but have difficulties in noise; more CI users are now able to enjoy music.

In general, the improvement in auditory perception following cochlear implantation varies widely from user to user and can range from speech perception to music enjoyment. Nearly all users have some perception of sound, most adults and children can expect open-set speech understanding including, for some, the ability to discriminate pitch and loudness, the use of the telephone and the enjoyment of music. Many recipients report that their lives are enriched following implant surgery. The ability to hear raises self-confidence and improves relationships with family, friends, and co-workers and offers increased job and social opportunities.

Benefits with a MED-EL Cochlear Implant may include the ability to:
- Hear conversation and environmental sounds at comfortable listening levels;
- Detect and identify sounds in the environment, such as the doorbell, car horns, and the telephone;
- Keep their voice loudness at an appropriate level;
- Understand others more accurately and with less effort;
- Understand speech by listening alone (without lip-reading);
- Use the telephone;
- Enjoy and appreciate music.

Improvements in benefit with the MED-EL MAESTRO™ system can also be related to the introduction of Fine Structure Processing in the OPUS audio processors. The FSP, FS4 and FS4p strategies aim at better frequency coding in the low to mid frequencies by allowing the neural structures in the inner ear to better phase-lock to the sound signal, as is the case in normal hearing in this frequency range.

This paper discusses numerous studies investigating the performance of MED-EL cochlear implants. Some studies demonstrate the advantages of specific features, while other studies compare the performance of MED-EL hearing implant systems to that of the competition.
Benefit for Infants and Toddlers

Performance of Children Receiving a CI at an Early Age

The increase in implantation of very young children has created the need for a tool to quickly and reliably assess the auditory behaviour of infants and toddlers. The LittlEARS Auditory Questionnaire is a parent questionnaire assessing the progress of the auditory development of hearing-impaired children implanted before the age of 24 months. 35 questions were developed which reflect the infant’s early auditory behaviour. Categories of auditory development consists of receptive, comprehensive and expressive auditory behaviour (Weichbold et al., 2005). The auditory questionnaire has been translated into and validated in a number of languages (Coninx et al., 2009).

In a longitudinal study (May-Mederake et al., 2010); the auditory development of children receiving a MED-EL cochlear implant was assessed over time. These results were compared to data from the normal hearing group. 63 children were enrolled in the study; all were implanted below the age of 24 months. As illustrated in the regression curve (Figure 1), the auditory behaviour in hearing impaired children follows the same developmental path as with their normal hearing peers. When implanted with the MED-EL MAESTRO CI System, within a shorter time span, hearing impaired, cochlear-implanted toddlers reach the same level as their normal hearing peers.

Auditory Performance in Infants Fit with FSP

20 children under the age of 36 months received a MED-EL cochlear implant and were fit with FSP available on the OPUS 2 processor. Results from the LittlEARS Auditory Questionnaire are shown for these infants over time, as seen in Figure 2 (Sonugler et al., 2009). Individual results show that auditory development matches that of their hearing peers – a significant benefit for small children using a MED-EL for future development of language. The one child who performs below the normative curve has been identified with additional cognitive factors.
Development of the First 100 Words

This study compares the development of first words in 63 normal hearing infants and toddlers and 76 young children using the MED-EL OPUS 2 processor. The children who received a CI demonstrated rapid development of receptive and expressive vocabulary skills – achieving 100 words within a shorter time frame than infants with normal hearing. Children implanted under the age of 18 months required a significantly shorter time to understand and express their first 100 words than those who received a CI after (Uruk et al., 2009). This again highlights the ability of the MED-EL cochlear implant system to support and promote the auditory development in early-implemented MED-EL users.

Language Development

Expressive and receptive language skills of 36 children who received a MED-EL CI under the age of 2 were evaluated on a number of tests (SETK, AWTS and TROG-R) (May-Mederake et al., 2009). These test results, represented in t-values, can be compared to the normative data of the tests (all normal hearing children). The children score, on average, within the normal range of the tests, in other words, they match the language skills of their normal hearing peers.

Benefit for Children

The EARS Study

The EARS study is an international study reviewing the auditory development of over 700 children who received a CI over a period of 5 years. Figure 5 shows how quickly children are able to access and use audition in their everyday listening environments (Esser-Leyding & Anderson, 2011). The Meaningful Auditory Integration Scale (MAIS) is a questionnaire completed by parents, who rate their children’s ability to perform a listening task as “never”, “sometimes” or “always”. There is significant improvement in parent-reported abilities, particularly in the first 6 months after first fitting with the audio processor. Access to sound, as evidenced in real-life situations and reported by the parents, provides significant benefit for all children. There is clear early benefit for all MED-EL recipients across all age groups.
Upgrade from the CIS+ Coding Strategy Used in the TEMPO+ (PULSARci100 or SONATAT100) to FSP Used in the OPUS Processors

Eleven children participated in an upgrade study over a period of 6 to 8 months. The study was cross-over in design. Results showed that those children who started out with FSP (as opposed to HDCIS) performed better in the long run (Ogut et al., 2009). When the cross-over data were collapsed between groups, FSP results were significantly better than scores for HDCIS measures (such as a monosyllable test – seen in Figure 6). It can be expected that this positive benefit with FSP will enhance listening in difficult everyday situations, as well as allow improved music appreciation.

Upgrade from the CIS+ Coding Strategy Used in the TEMPO+ (COMBI 40+) to FSP Used in the OPUS Processors

60 children who were long-term COMBI 40+ users (3.5 years or more), received OPUS 2 processors with who were fitted with the MAESTRO 3.0 software. Children rated listening to music and speech on a visual analogue scale. All children significantly preferred listening with FSP (Lorens et al., 2010), highlighting the benefits provided by FSP. This also highlights superior backwards compatibility, with FSP outperforming other CIS-based strategies, even though the COMBI 40+ does not have the I100 technology.
Benefit for Adults

**MED-EL Provides Unsurpassed Performance in Fluctuating Speech – 1**

Recent research results clearly indicate improved benefits with the MAESTRO CI System. Haumann et al. (2010) from the Cochlear Implant Centre in Hannover, Germany, presented data comparing speech perception in noise between the three major systems on the market (OPUS 2 from MED-EL, 3G and Freedom from Cochlear, Auria and Harmony from Advanced Bionics). The team used a modified HSM sentence test with roving level in an adaptive manner. This test measured a speech reception threshold, which is representative of speech perception in a loudness range between very soft and very loud. Results indicate a clear advantage for the MED-EL system (Figure 8). OPUS 2 users show a 2 dB advantage in SRT when compared to Harmony users, and a 6–7 dB advantage when compared to Freedom users. Furthermore, only the OPUS 2 users show a negative average SRT, i.e. on average, only OPUS 2 users can understand 50% of the speech correctly even when the noise is louder than the speech! Further details on this study are provided in “Focus On: Speech Perception in Everyday Life”.

**Figure 7a** shows preference for the FSP strategy for listening to speech and **7b** to music, when compared to CIS+ and HDCIS. Adapted from Lorens et al., 2010

**Figure 7b**

**Figure 8**: SNR measured in decibels (where the lower score gives a better outcome) for 5 different speech processors. Adapted from Haumann et al., 2010
MED-EL Provides Unsurpassed Performance in Fluctuating Speech – 2

Brough et al. (2010) from the CI centre in Manchester, England, assessed users of all brands and devices over a period of 21 months. 83 recipients wore the Esprit 3G, 40 used the Freedom, 37 used the TEMPO+, 7 used the OPUS 2, 8 used the Auria and 3 used the Harmony speech processor. Users were tested on sentences in quiet and noise. In general, OPUS 2 users outperformed the users of all other devices across all tests, and performance improved more quickly than in users of other systems. As an example, Figure 9 shows results for BKB sentences in noise. Further details on this study are provided in “Focus On: Speech Perception in Everyday Life”.

**Figure 9:** OPUS 2 users demonstrate significantly higher speech perception scores over 9 months when compared to users of other processors. Adapted from Brough et al., 2010

Uncompromised Performance in Difficult Listening Conditions

Seven adults were assessed in Würzburg, Germany, using a roving level method (Nopp et al., 2009). Users listened to fixed-level tests that were randomly interwoven in one listening run. There were no differences in these runs when compared to fixed-level tests alone. This shows that the MED-EL MAESTRO Cochlear Implant System provides uncompromised performance from soft to loud levels even when level varies between sentences in a conversation. More importantly, the user does not need to make any special program adjustments to manage loud speech or whisper. They can put on their processor and go! Further details on this study are provided in “Focus On: Speech Perception in Everyday Life”.

**Figure 10:** Results of 7 users showing similar results for a fixed-roving level test in comparison to a randomly weaved run. Adapted from Nopp et al., 2009
Better listening performance with MED-EL

Cochlear Six subjects were included in a study comparing the MED-EL cochlear implant system on one ear and the COCHLEAR system on the other ear (Harris et al, 2011). One subject’s data were not analysed, as there was too big a difference between ears. One subject was recommended a MED-EL as she was blind, and the FineTuner was thought to be good for her. The others had done self-research and chose MED-EL because of potential music benefits. Each had a unilateral CI for between 1-6 years, with five being implanted in their worse ear first. On the Cochlear side: three used CI24R (2 with Freedom, one with ESPrit 3G) and three used CI24RE (All with Freedom). On the MED-EL side: all used SONATA and Opus 2, all with a minimum of two FSP channels. Speech in noise tests were: BKB sentences with a noise level where the subjects received 30-70% accuracy in the bilateral condition. They were then assessed on each side. Mu.S.I.C test subscales used were: rhythm, melody, chords, number of instruments, instrument detection and pitch. Subjective assessment included: Munich Music Questionnaire; Visual Analogue Scales for pleasant, distinct, tinny, reverberant, answer questions to quantify their subjective preferences for each device.

There were no objective differences in speech performance, but some subjective advantages. Listening to music with MED-EL appeared better for most subjects. Listening to music with the MED-EL device was more pleasant (4/5), more distinct (3/5), more natural (4/5), more tinny (4/5) and more reverberant (1/5). One subject rated all things equal. Subjects were asked what they would do if they needed to change their MED-EL device: 4/5 would choose a MED-EL, 1/5 was unsure. If they needed to change their Cochlear device, 2/5 would choose a Cochlear, 1/5 would switch to a MED-EL and 2/5 were unsure.

Quick Improvement in Quality of Life

Cochlear implantation can improve the overall psychological and social functioning of a hearing impaired person. In a multi-centre study, Baumgartner et al. (2007) assessed aspects concerning the quality of life of implantees. The Nijmegen Quality of Life Questionnaire (Hinderink et al., 2000) was used to subjectively evaluate an implantee’s perception of his/her changes in quality of life following cochlear implantation. Basic and advanced sound perception, speech production, a change in self esteem and ones’ social activities were addressed. **Overall users reached significantly improved levels within the first month of the device use** and an increase in all categories over the course of time could be seen (Figure 11). Patients’ self esteem increased along with their activities and social interactions. These data indicate **quick improvements in quality of life** with MED-EL MAESTRO Cochlear Implant Systems.

**Figure 11:** Scores showing changes on the Nijmegen Cochlear Implant Questionnaire demonstrating a significant increase in quality of life immediately following CI. Adapted from Hinderink et al., 2007
Superior Benefit for Older Adults
To assess recent technological advances, the subjective benefits for older adults using a MED-EL cochlear implant were evaluated (Anderson et al., 2006). Questions addressed the pre-implant history, post-implant device use, communication benefits, handling of the device and the quality of life. Technological advances (improved electrode design, new, faster speech-coding strategies and smaller, high-performance audio processors) that allow for more accurate listening were reflected well in the study. Over 80% of the respondents had no difficulty in differentiating between male and female voices, human voices and ambient noise, and understanding speech without lip-reading. A large proportion (91%) of the respondents agreed that the implant improved their quality of life and gave them greater confidence. The results suggest that implant use among the elderly is beneficial and successful treatment for improving speech recognition and quality of life for elderly, deaf patients.

Unique Benefits

Complete Cochlear Coverage: Speech Perception as a Function of Apical Stimulation
An important aspect of currently available cochlear implant systems is the ability to provide frequency information that accurately reflects the incoming signal. The design and the intra-cochlear position of an electrode array are factors that ultimately affect the performance of implant recipients.

The electrode insertion depth determines the position of the most apically stimulated electrode contact in the cochlea. Only MED-EL has electrode arrays that are able to provide insertions depths up to 31 mm. In the human cochlea, the highest density of neural innervation is located 18 to 24 mm from the base (Spöndlin et al., 1990). Between 24 and 31 mm, a high concentration of neural tissues is found in the form of dendrites. The insertion depth determines the amount of neural tissue that will be stimulated. An electrode array of only 20 mm stimulates a restricted frequency range. In contrast, the MED-EL Standard Electrode Array provides Complete Cochlear Coverage, and thus, stimulation of all neural tissues.

In a prospective, long-term study, the effects of electrical stimulation of the apical region of the cochlea on speech perception using different channel arrangements were evaluated. 14 newly implanted subjects with a MED-EL cochlear implant and a fully inserted (>30 mm) Standard Electrode Array participated in the study. Four different electrode configurations had been defined for the 12-electrode array: A) 8 most apical electrodes only, B) 8 most basal electrodes only, C) electrodes spread across the whole array, D) all 12 electrodes. The study followed an ABCABCD crossover design with one month of familiarisation with every condition prior to evaluation, after an initial 3-months period for the first condition. Starting conditions were randomised across patients. Conditions A, B, and C were repeated during the trial in order to compensate for learning effects. The final condition tested was all 12 electrodes (condition D).

Results are shown in Figure 12. Subjects in the lower left quadrant perform better without any apical stimulation, whereas subjects in the other three quadrants perform better with apical stimulation using either 8 or 12 channels. The results show that 12 out of the 14 subjects performed better with apical stimulation and only 2 subjects perform better without apical stimulation. These test results are supported by the fact that at the conclusion of the study, 11 subjects chose a setting using apical stimulation with 12 electrodes, and 3 subjects chose a setting using apical stimulation with 10 electrodes. Results indicate that all MED-EL users can benefit from at least some degree of apical stimulation and that Complete Cochlear Coverage as only provided by MED-EL therefore is an indispensable design feature of a modern cochlear implant system. Further details on Complete Cochlear Coverage are provided in “Focus On: Complete Cochlear Coverage”.
Bilateral Cochlear Implant Use

In binaural hearing, the auditory system relies on differences between sound signals from two sides for acoustic orientation, echo suppression and noise reduction. Together with clinicians around the world MED‑EL was at the forefront of research into the benefits of bilateral cochlear implants since 1997. Early studies on bilateral implantation with MED‑EL users (Schön et al., 1999; Müller et al., 2002) have already shown significant improvements in hearing and communication. This is evidenced by improved speech recognition abilities in quiet and in noise as well as better localisation abilities. Usefulness of bilateral MED‑EL cochlear implants is beyond any doubt today. Bilateral MED‑EL users commonly report that two implants have greatly enriched their total hearing experience. The addition of a second CI provides a greater amount of sound information, resulting in fuller sound quality. In addition, bilateral users report benefits in speech understanding, regardless of the position of the speakers (Müller et al., 2002; Schleich et al., 2004; Buss et al., 2008).

Bilateral MED‑EL cochlear implant users can qualitatively benefit from head shadow, squelch, and summation effects, effects which bilateral CI users benefit from and which are also known from normal hearing subjects. For sentences at a signal‑to‑noise ratio of 10 dB, Müller et al. (2002) found a head shadow effect of 20.4 percentage points (pp) and a squelch effect of 10.7 pp. For monosyllables in quiet, a summation effect of 18.7 pp was found. All effects were statistically significant. Using an adaptive sentence test, Schleich et al. (2004) demonstrated that bilateral CI users significantly benefit from a head shadow of 6.8 dB, a squelch effect of 0.9 dB, and a summation effect of 2.1 dB. Gains in speech perception with bilateral cochlear implants have also been demonstrated for tonal languages (Au et al., 2003; Kong et al., 2003). Improved speech comprehension was also demonstrated in more difficult, near real world scenarios where independent noise sources were placed around the subject (Rickets et al., 2006). More recent studies have also shown improvements of binaural listening abilities over time (Buss et al., 2008), i.e. the squelch effect was reliably observed after 12 months only.

Kühn-Inacker et al. (2004) showed that with MED‑EL bilateral cochlear implants, children’s communicative behaviour improved, particularly in complex listening conditions. This ability is of great benefit in a classroom situation. Localisation abilities in bilaterally implanted children and unilaterally implanted children using a contralateral hearing aid were measured by Litovsky et al. (2006). Over 2/3 of the bilaterally implanted children could discriminate sound sources separated by less than 20°. In contrast, unilaterally implanted children with a contralateral hearing aid could only sometimes perform the localisation test. The children showed significantly better speech reception in noise and localisation abilities when using both implants. In addition, the integration of the second implant and the use of binaural information were observed to be faster and easier with children with a short time lag between implantations. Further details on bilateral CI are provided in “Focus On: Bilateral Cochlear Implantation – A step closer to natural hearing”.
Telephone Use

Use of the telephone is considered to be an important aspect in everyday life by many users. The ability to use the phone promotes independent living, and is important for employment, socialisation, and self-esteem of cochlear implant users.

Technological developments in speech processing strategies and the trend to implant adults with more residual hearing have led to a steady improvement in the ability of CI users to discriminate speech without visual clues – telephone use is a perfect example of this. Anderson et al. (2006) conducted a survey of nearly 200 MED-EL cochlear implant users. With all subjects, a significant movement towards more frequent landline and mobile telephone use after cochlear implantation could be seen. The listening ability on the telephone was, in general, rated as “good”. 65% of respondents could understand “quite a lot” to “all”. With unfamiliar topics this number was reduced to 46%. With unfamiliar speakers, a conversation could still be held by 38% of landline users, and 25% of mobile phone users.

Results of this survey demonstrate a significant shift from pre-operative non-use of the telephone to use of a telephone post-operatively for users of MED-EL cochlear implants. Results suggest that with more recent and advanced cochlear implant technology provided by MED-EL, users are able to obtain more benefit using telephone. Most users make regular use of the phone in their everyday life. Talking to familiar speakers is the easiest listening condition on the phone. These results are further substantiated by Castro et al. (2006) who evaluated mobile phone listening performance in 22 MED-EL users. 75% use the telephone (landline and mobile) on a daily basis. Users scored over 88% on CID sentences when tested on a number of telephones (Landline, Nokia 6110, own mobile phone) demonstrating the significant benefit that a CI provides for users.

Music Listening and Appreciation

Music and Fine Structure Processing

As part of a larger MED-EL Fine Structure study (Müller et al., submitted), 46 experienced cochlear implant users reported positive changes in their music listening habits after 3 months of experience with FSP. All had previously used CIS+ as a coding strategy, for a minimum of 6 months prior to being upgraded to FSP with an OPUS audio processor. 82% reported listening to music every week, if not every day. 91% of the subjects reported that, in general, music sounds pleasant with their cochlear implant, 67% report that music sounded more natural and 64% reported that it sounded fuller or more resonant. 62% reported that they were better able to recognise familiar melodies; the same number reported improved ability to recognise individual instruments in a known piece of music. Finally, 65% reported improved enjoyment of familiar music and 59% report improved enjoyment of unfamiliar music. These results demonstrate an improvement in music appreciation and enjoyment for users of FSP among recipients of OPUS audio processors.

Musical Performance in Young CI Children

Perception of music is more difficult than language. Good language perception is routinely achieved by CI users; however music perception poses more of an auditory challenges (Limb 2006, McDermott 2004). New coding strategies, like MED-EL’s FSP, implemented in the OPUS 2 aim to improve music perception by attempting to more accurately encode fine structure cues of the signal.

A study evaluating the development of music listening skills in children fitted with MED-EL devices was conducted to determine the effectiveness of the training programme as well as to determine the ability of children to improve their music listening skills (Koşaner et al., 2009). 22 children using FSP and 3 using TEMPO+ participated in the study and skills were evaluated over 18 months. All children showed statistically significant improvement over time (Figure 13). This is important, as it shows that young MED-EL users are able to listen to music, despite being congenitally deafened and not having any music experience or music representation. These children are able to learn to sing and dance.
Conclusion

*MED-EL cochlear implants quickly provide significant gains in a variety of aspects of hearing for users of all ages. Moreover, MED-EL cochlear implants define the benchmark of performance for the whole industry.*

References


Haumann et al. (2009) Benefits of Electrical Stimulation Over Two Cochlear Turns in Postlingually Deafened CI Users – A Prospective Long-Term Study. Poster at Conference on Implantable Auditory Prosthesis, July 12–17, Lake Tahoe, USA.


May-Mederake et al. (2010) Evaluation of auditory development in infants and toddlers who received cochlear implants under the age of 24 months with the LitIEARS® Auditory Questionnaire, IJPORL, 74: 1149-5.


Müller et al. (submitted) Clinical trial results with the MED-EL Fine Structure processing coding strategy in experienced CI users.


Napp et al. (2009) Performance with the OPUS 2 speech processor in a roving-level speech test. Presented at 9th European Symposium on Paediatric CI, 14–17 May, Warsaw, Poland

Ogut et al. (2009) Comparison of pediatric CI user performance with CIS+, FSP and HDCIS coding strategies acutely and after trial in quiet and noise. Presented at 9th European Symposium on Paediatric CI, 14–17 May, Warsaw, Poland.


Uruk et al. (2009) First 100 words of Turkish hearing and hearing impaired children. Presented at 9th European Symposium on Paediatric CI, 14–17 May, Warsaw, Poland.