Analyzing the maps of the children using bilateral cochlear implants

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Abstract:

For more than a decade, bilateral cochlear implants (BICIs) have been considered as a standard treatment for children with significant hearing loss, with the aim of providing access to bilateral hearing advantages. During this time, a large number of studies have worked on different aspects such as spatial hearing, speech perception or the central auditory system development after receiving BICIs. One area which has had relatively minimal attention is the mapping-related outcomes among this group. The mapping of the cochlear implant (CI) is an important aspect of the post-operation management. With regard to BICIs, it is necessary to increase knowledge regarding the relationship of the mapping parameters [T- and C-levels, and dynamic ranges (DRs)] between the two implants. It is also important to know how this relationship changes over time due to the experience of hearing with two implants. This study will focus on the mapping-related outcomes of two implants for two groups of children with sequential and with simultaneous BICIs. This data will provide evidence-based information regarding the outcomes of current approaches for the mapping of BICIs among children. The main objective is to compare the difference between the mapping parameters of the two ears in the first 10 weeks, and at 2 years and 5 years after the bilateral operation in different electrode array regions and in two situations of different and similar device type at each ear. A secondary objective is to examine that how the degree of the difference between implants is related to the demographic factors of age at bilateral implantation and time between implants.

This retrospective study involved 64 children with sequential BICIs and 29 children with simultaneous BICIs. All participants were bilaterally fitted with relatively recent versions of the Nucleus CI system [CI24M, CI24R, CI24RE (Freedom) or CI512]. T- and C-levels were extracted from maps obtained using the Custom Sound software in the first 10 weeks, and at 2 years and 5 years after bilateral implantation. More specifically, the T-and C-levels were extracted for three electrodes in each of three different electrode array regions: apical (electrodes 22, 20, 18), medial (electrodes 15, 13, 11) and basal (electrodes 3, 5, 7). The average of the three electrodes was used as the representative of each region. To represent the difference between the two implants, the T-ratio and C-ratio and DR-ratio were calculated by dividing the mean T-
levels, C-levels and DRs of each electrode array region of the second implant (CI2) by those of the first implant (CI1) for the sequential group. For the simultaneous group, the left implant was considered as CI2 and the right implant was considered as CI1. A ratio of 1 would indicate that the levels being compared were the same for each implant. According to the statistical analyses, for the sequential group, the mean T-ratio of the two implants was found to be close to 1 at all three time points and three electrode array regions and two situations of different and similar device type at each ear. That is, the T-levels of the two implants were very similar over time and along the electrode array, even with different device type at each ear. By contrast, the mean C-ratio and DR-ratio of the two implants were found to be less than 1 at all three time points and three electrode array regions and two situations of different and similar device type at each ear. In other words, the C-levels and DRs for CI2 were lower than those for CI1 over time and, along the electrode array, even with similar device type at each ear. However, the degree of difference in the C-levels and DRs between the two implants significantly decreased from the initial to the 2-year post-operation time point. For the simultaneous group, the mean T-ratio, C-ratio and DR-ratio of the two implants were found to be close to 1 at all three time points and three electrode array regions. In other words, the mapping parameters of the two implants were very similar over time, and along the electrode array. For the sequential group, time between implants was a factor that affected the degree of difference in the C-levels and DRs between the two implants, with longer time between implants associated with a greater difference. For both the sequential and the simultaneous group, no significant relationship was found between age at bilateral implantation and the degree of difference in the mapping parameters between the two implants.

It can be concluded that children with sequential BICIs differs from those with simultaneous BICIs, in terms of the pattern for difference in the mapping parameters between the two implants. Moreover, generally, the pattern does not change over time, although, the degree of difference in the mapping parameters between the two implants decreases following experience of hearing with BICIs for children with sequential BICIs. In the cases that clinicians find a different outcomes in clinical practice, they should try to find possible issues. The issue can be related to the lack of child’s attention to the task or to the lack of using the two implants.
together. The issue can also be related to some problems in the external and internal parts of CI system.

Declaration

This is to certify that

i. The thesis comprises only my original work towards the MPhil,

ii. Due acknowledgement has been made in the text,

iii. the thesis is less than 100,000 words in length
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Chapter 1: Introduction
Currently, CI is considered as an effective option for children with severe to profound hearing loss, helping them to achieve speech and language development (Dowell, Dettman et al. 2002, Svirsky, Teoh et al. 2004). However, with unilateral CI some listening situations are challenging and children cannot benefit enough. For example, unilateral CI users usually experience difficulties in noisy environments or those involving multiple talkers (Steffens, Lesinski-Schiedat et al. 2008, Lovett 2010, Sparreboom, Snik et al. 2011). One important reason for the difficulties is related to the lack of hearing through the two ears (bilateral hearing), allowing spatial hearing and separating noise from target sound. BICIs is an effort to provide bilateral hearing for children with severe to profound hearing loss in order to gain additional benefits in the challenging situations. Since the time that BICIs have been approved for children, many studies have examined the benefits of BICIs in different aspects (Johnston, Durieux-Smith et al. 2009, Redfern and McKinley 2011, Boons, Brokx et al. 2012, Litovsky, Goupell et al. 2012, Galvin, Holland et al. 2013). Generally, the result of the studies have shown that BICIs can bring more benefits for children in spatial hearing, speech perception in noise, language and quality of life. However, the magnitude of the benefits has been found to differ between children. There is an overall agreement indicating contribution of some factors to the magnitude of available benefits from BICIs. According to the results of the studies, the most affecting factors are age at bilateral implantation, time between implants, age at CI1, experience of hearing with two implants and previous hearing aid use (Peters, Litovsky et al. 2007, Scherf, Van Deun et al. 2009, Van Deun, van Wieringen et al. 2010, Vischer, Senn et al. 2011, Boons, Brokx et al. 2012, Strøm-Roum, Laurent et al. 2012). According to reports, there is a growing interest toward bilateral implantation worldwide and higher number of children are receiving BICIs (Balkany, Hoffman et al. 2008, Peters, Wyss et al. 2010). However, there is not sufficient research on post-operation managements that are likely to affect the outcomes with BICIs. Children with BICIs have additional needs which demand specific clinical management practices (Galvin, Leigh et al. 2009).

Mapping of CI is an important aspect of the post-operation management. CI map refers to a series of dynamic ranges (DRs) assigned for every available active electrode along the electrode array of CI system. To achieve this, the electrical signal creating the softest audible perception
(threshold level or T-level) and the comfortably loudest perception (comfortable level or C-level) are measured. As opposed to unilateral CI, mapping of BICIs requires some additional adjustments between two implants to maximize the advantages of bilateral hearing. To achieve this, some considerations should be taken into account to manage the binaural summation and to provide similar loudness at each implant (Wolfe and Schafer 2010, Shapiro and Bradham 2012). Mapping of CI per se is relatively difficult in children as they have limited or no previous hearing experience to accurately judge the loudness of the presented sound. In addition, younger children have limited spoken language to reflect their response. It becomes more difficult in children with BICIs as comparing the loudness between two implants is a difficult task for children, particularly for younger ones.

There is little research on BICIs mapping to date (Weberling, Firzt et al. 2011, Gordon, Chaikof et al. 2012, Domville-Lewis, Santa Maria et al. 2015). The difference in the mapping parameters between the two implants and factors affecting the degree of that have not examined enough yet. It is also not well known that how the degree of difference in the mapping parameters between two implants change over time. Additionally, there is not enough information about the changing trend of the mapping parameters of each implant over time for children with BICIs to see if it differs from what is occurring for children with unilateral CI. Therefore, there is a requirement for access to new information in these regards to assist clinicians to provide children with optimal BICIs map. Given the increasing trend toward the bilateral implantation, particularly for younger children, there is sufficient mapping data to analyse in detail. Acquiring such detailed knowledge will be helpful to access a potential pattern for a proper BICIs map for children. It may also help to recognize children with atypical BICIs map, who possibly need intense attention and management to achieve the advantage of bilateral hearing. Moreover, it provides evidence-based guidelines for clinicians that may describe how provide similar loudness at each implant or to what extent reduce signal intensity in order to remove the binaural summation. Finally, there will be available mapping data to be linked to the future performance data to investigate the relationship between them.

This project will focus on analysing of the maps of a high number of children with BICIs fitted with the Nucleus CI system on the both ears. The main objective is to compare the difference in
the mapping parameters (T- and C-levels, and DRs) between the two implants at first 10 weeks, 2 years and 5 years after bilateral implantation in different electrode array regions and in two situations of different and similar device type at each ear. A secondary objective is to examine that how the degree of the difference is related to the demographic factor of age at bilateral implantation and time between implants.
Chapter 2: Cochlear implant structure
Unlike hearing aids, that provide patients with amplified acoustic signals, the CI delivers direct electrical stimulation to the auditory neurons. This electrical stimulation induces action potentials that can be perceived as sound by the brain. There have been dramatic development in CI technology from the early time (1970s), when only single-channel devices were available, to the present time, when the multi-channel CIs with advanced sound processing strategies are available (Carlson, Driscoll et al. 2012). Performance with CIs has improved significantly as a result of these advances in device hardware and software and surgical technique. Early single-channel CIs helped patients in only lip-reading ability, whereas some of the present CI recipients show nearly 100% correct score on high-context sentences (open-set speech perception) (Wilson and Dorman 2007).

Since the participants of the present study were all implanted with Nucleus CI systems manufactured by Cochlear Limited Company, the features of Nucleus CI System is described in this chapter.

**Cochlear implant components**

The cochlear implant prosthesis is an electronic device that consists of external and internal components as showed in Figure 2-1.
The external components

The external components include the speech processor and the radio frequency transmitting coil.

Speech processor

Each speech processor consists of microphones, an electronic circuit for analyzing the sound, user controls and battery. Early speech processors were body-worn, but more recent processors are worn behind the ear (BTE). The BTE speech processor includes an ear hook to maintain it on the external ear. Speech processor is the main part of the CI system as the important features of the incoming acoustic sound including intensity, frequency and timing information are extracted in this part.

The speech processor has a microphone to capture the existing sounds including speech. The microphone can be either omnidirectional or directional. The former has the potential to capture the sounds from all directions, while the latter can capture sounds coming from the front. Some Cochlear products like Nucleus Freedom benefit from a dual microphone set up,
where they have both omnidirectional and directional microphones. The dual microphone system is more sensitive for the sounds coming from the front and the sounds arriving from the behind will be reduced.

From the microphone, the captured sound is transferred to the electronic circuit, where the signal is filtered and analysed by several band pass filters in order to simulate the frequency analyses of the normal ear. In the next step, the envelope of the output of each band pass filter is detected. A number of envelopes with the highest amplitudes are used to modulate a train of biphasic electrical pulses to be sent to their corresponding electrodes. The electrical stimulus delivered to the nerve has equal negative and positive phases in order to have no remaining net charge at the neuron level after stimulation. This form of stimulation is safe for the auditory neurons. Figure 2-2 shows the different steps of sound processing in the sound processor.

![Figure 2-2: Different steps of sound processing in the sound processor](image)

Speech processors have the following user controls: volume control and microphone sensitivity control. The volume control controls the maximum amount of stimulation. It allows CI users to change the perceived loudness of sound. The microphone sensitivity control determines the minimum intensity required for stimulation. At higher sensitivity settings, less acoustic intensity
is required to cause stimulation, while at lower sensitivity settings, greater intensity is needed to cause stimulation.

In Cochlear products, three kinds of batteries are available to power the CI system including: zinc-air, rechargeable lithium-ion and smaller compact rechargeable battery. To maximize battery life, the power level should be optimized. This is done automatically in the recent model speech processors through considering the amount of power consumption in the worst conditions.

**Radio-frequency transmitting coil**

The electrical signals coded in the speech processor are transmitted to the internal component of the CI system by a radio-frequency transmitting coil. There is an electromagnetic induction between the internal receiver stimulator and the external transmitting coil that is connected to the speech processor via a wire. Therefore, there is no physical connection between the transmitting coil and the internal receiver stimulator and the transmission of the electrical signals occurs via radio-frequency waves.

**The internal components of CI**

The internal components include the receiver stimulator and the electrode array.

**Receiver stimulator**

The receiver stimulator is implanted under skin behind the ear. It contains a magnet to which the external transmitting coil sticks and an electronic circuit to decode the received signals. The signal contains information that determines how much electrical current will be sent to the different electrodes. Since this part of CI system has physical contact with the body, it is required to be hermetically sealed in a biocompatible package.

**Electrode array**

Nucleus implants have 22 intra cochlear electrodes, numbered from E1 at the basal end to E22 at the apical end. In addition, the Nucleus 24 and Freedom implants have two extra-cochlear electrodes as the reference electrodes. The first is a ball electrode connected by a separate lead
wire to the receiver stimulator package. The second is a platinum plate mounted on the titanium package of the implant. Electrodes placed near the apical end of the cochlea stimulate the place along the cochlea which would normally correspond to low-frequency acoustic signals, whereas high-frequency information is conveyed by the electrodes placed near the basal end of the cochlea. The electrode arrays are available in different forms of contour, straight and double arrays as shown in the Figure 2-3.

The Contour electrode array is a precurved perimodiolar array with 22 electrode contacts. Since the positions of electrodes are in close distance to the modiolous, the amount of electrical current needed for stimulation is reduced, which in turn reduces the power consumption and cause longer battery life. Due to the position of electrodes, they provide the most precise and efficient stimulation for patients since it provides focused stimulation to the auditory neural elements. This form of the electrode array is used for people with normal cochlea.

The straight electrode array was introduced with the first generation of CI systems. This type of electrode array is not placed as close as countor electrode array to the modiolus. There is higher risk of damage to the ganglion cells by insertion of this type of electrode array. The

\[ \text{Figure 2-3: Different forms of electrode arrays; contour (a), straight (b) and double(C)} \]
reason laid on the fact that the insertion force is directly toward the cochlear inner wall during surgery. The straight electrode arrays are usually used in cases with common cavity of the Cochlea, fibrous tissue or those who might undergo revision surgery.

The double electrode array is a special type which is used in cases whose cochlea is surgically inaccessible. Some disease like meningitis causes considerable ossification in the cochlea, so that, the full insertion of a standard electrode array is not possible and only a few numbers of active electrodes can be inserted.

**Candidacy criteria for cochlear implant**

Cochlear implant is not proper for every individual with hearing loss. There are some criteria required to be met for implantation, although the criteria vary across clinics within countries and between countries.

The current candidacy criteria for cochlear implantation are different, in some aspects, from those at the early times. Actually, the criteria gradually changed over time, so that the candidacy requirements were relaxed. The changes were mainly related to the three areas of the severity of the hearing loss, the magnitude of the benefits with hearing aid and age at implantation.

Previously, only individuals who were totally deaf or had bilateral profound hearing loss (pure tone average $\geq 90$ dBHL beyond 1000 HZ), who had no benefit from hearing aid were considered as appropriate candidates for cochlear implantation. Nowadays, implantation is offered for cases having a higher amount of residual hearing (pure tone average $\geq 70$ dBHL beyond 1000 HZ), with limited pre-operation open-set speech perception by hearing aid (Fitzpatrick, Olds et al. 2009). According to the approval of cochlear corporation in 2009, limited benefit from appropriate binaural hearing aids for children younger than 2 years old defined as the lack of progress in development of simple auditory skills and participation in intensive aural rehabilitation over 3–6 months. To assess the benefit from binaural hearing aid for this group of children, Meaningful Auditory Integration Scale or Early Speech Perception Test is recommended to be used. For children older than 2 years old, limited benefit from appropriate
binaural hearing aids defined as scoring < 30% on open-set Multisyllabic Lexical Neighbourhood Test or Lexical Neighbourhood Test depending on the child’s cognitive and linguistic skills (Heman-Ackah, Roland Jr et al. 2012).

With regard to the age at implantation, for a long time, only children aged 2 years or older were preferred for the implantation. Over time, the trend changed toward the implantation at younger age in order to early access to hearing and to enable better language outcomes (Sampaio, Araujo et al. 2011). Actually, the administration of the newborn hearing screening program paved the way for earlier diagnosis of hearing loss in infants. Consequently, it provided a chance for early intervention so that, implantation was approved for children as young as 12 months by 2000. Currently, despite some controversies, successful operation and satisfying results have been reported in children implanted even as young as 4 months in some clinics (Colletti, Carner et al. 2005).

Evaluation of the candidacy criteria for cochlear implantation is done by a multidisciplinary team and includes a medical evaluation, cochlear imaging and audiologic evaluation (Heman-Ackah, Roland Jr et al. 2012, Vincenti, Bacciu et al. 2014) that are explained as follow:

**Medical evaluation**

At this step, a complete medical history of candidature including information about the birth, family, otologic and immunization disease along with a physical examination is recorded in order to find the main origin of HL. Furthermore, individual’s general health conditions required for surgery is considered.

**Cochlear imaging**

This evaluation provides information about the presence of the auditory nerve and any cochlear anomalies precluding implantation or at least limiting insertion depth of the electrode array. Therefore, it can help to select the most appropriate ear for implantation. Some findings that may complicate the surgery or subsequent management are identified via this imaging.
Audiological evaluation

The main aims of the audiological evaluation are to determine the severity of hearing loss and the efficiency of hearing aid. These fulfil by measuring unaided pure tone thresholds and speech perception test, assessing development of auditory skills by hearing aid and performing electrophysiological tests like otoacoustic emission and auditory brain stem response.
Chapter 3: Cochlear implant programming
Cochlear implantation process is not limited to just the placement of the device through surgery. It still continues after operation, where the main focus is on the presentation of the most optimal electrical signals that reflect the sounds almost as real as they exist in surrounding environment. To achieve this, obviously, the electrical signals should somehow reflect the original features of incoming sounds. Therefore, some additional settings must be performed on the speech processor, where the environmental acoustic sounds are converted to the electrical signals.

Speaking about the post-operation settings, there are two different terms called “programming” and “mapping”. Programming refers to the overall setting function that covers the three main characteristics of pitch, loudness and temporal cues of the sounds. Among these, the loudness of delivered stimuli is of more importance. Actually, the main step to maximize the speech information, as the main targets for CI recipients, is to preserve the loudness of its different components. Mapping refers to the setting function that specifically aimed on the loudness of delivered electrical signals. It is the most vital part of the programming, which takes the majority of the time. This chapter will focus on the mapping of CI, explaining the process for child CI recipients in more details.

**What is mapping?**

Mapping is the fundamental part of the post-operation management, which is performed by clinicians. What are measured during this event, are the highest and the lowest stimulation levels admitted by CI recipient. The minimum audible electrical signal that creates a soft perception of sound is considered as the threshold level (T-level). The maximum amount of electrical signal that leads to a comfortable loud perception of sound is called the comfortable level (C-level). The difference between these two parameters is known as the electrical dynamic range (DRs).

In the programming session, T- and C-levels must be set for each available active electrode on the array. It can be addressed through either comprehensive or streamlined methods. In comprehensive method, T and C- levels are directly measured for every single available electrode. This is rather time-consuming as it requires delivering different amounts of the
electrical signal to each electrode and ask CI recipient to respond. In streamlined method, T- and C-levels are measured directly for just some electrodes. Then, these measured values are used to estimate the mapping parameters of the rest available electrode (interpolation) in order to save the time. It has been reported that interpolation has no negative effect on the speech perception, provided the streamlined electrodes are not spaced excessively (Plant, Law et al. 2005).

A set of T- and C-levels defined for all available electrodes creates the individual’s map, which is stored in the speech processor. This allows speech processor to direct the incoming acoustic sounds into the determined electrical dynamic range. So, it makes audible the sounds that are really quiet or too loud via increasing and decreasing them respectively to the previously measured T- and C-levels.

**The importance of mapping:**

To maximize the potential of CI system, providing recipients with a proper map can be beneficial. Reasonably, better outcomes after implantation can be expected, when the mapping is in a manner that the loudness of all components has still been maintained in a realistic way to some extent (Lee, Jeong et al. 2012). The environmental sounds are presented to listeners at largely variable intensity levels. For example, speech, as the most important auditory signal for CI users, is complex and consists of vowels and consonants, having very different and wide intensity range. Thus, the aim of CI mapping should be more than providing an audible and tolerable sounds for the recipients. That is, in addition to enabling the recipients to recognize very soft sounds and comfortably participate in conversations occurring at average levels, CI should help them to understand speech signal at many levels and distances in everyday situation. To achieve such optimal outcome, it may be also essential to evaluate smaller differences in T- and C-levels during the measurement of the mapping parameters. If T- and C-levels have been underestimated, even in some electrodes on the array, the hearing sensitivity is adversely affected. This ends up a decrease in the speech perception ability due to perceiving degraded quality of sounds by the brain (Sainz, Torre et al. 2003). In the case of overestimation, these inappropriate high mapping parameters can even impose more consequences along with
the speech perception ability. In this case, recipients may suffer from background noise, unpleasant expressive voice quality and speech production, pain in non-auditory organs or aggressive behaviours (Mertes and Chinnici 2006). Meanwhile, the accurate assessment of C-levels should be paid more attention to, as its contribution to the sound perception has been found more than that of T-levels (Sainz, Torre et al. 2003).

The mechanism CI system works based on totally differs from what is happening in the normal ear. In this technology, the stimulating signals are delivered by the electrodes substituted for the damaged inner ear structures. Therefore, the hair cells are bypassed by CI and the auditory nerve is directly stimulated by the electrodes. Due to the lack of this natural mechanical compression, the dynamic range of the recipients is substantially confined relative to the normal-hearing individuals. While there is a potential to process sounds within a large range of 120dB in normal condition, the electrical dynamic range in CI recipients is limited to narrow 10-20 dB (Zeng 2004). Such a small range leads to higher sensitivity to the loudness changes and reduces individual’s tolerance relative to the loud sounds. CI system must, actually, fit the vast range of 120 dB in to the narrow range of 20 dB. To achieve this, an intense compression of the incoming sounds is imposed that, in turn, leads to the deterioration of the quality of the sounds. Thus, the effectiveness of CI system in speech perception and language ability depends to high extent on the fact that how precisely the electrical DRs are measured.

Generally, it appears that a wide DRs contributes to more satisfying outcomes post-operation. The reason lies in the growth in the neural excitation following increase in the electrical current levels. With higher level of electrical current, current spread expands leading to larger activating potential fields. The larger activating potential field results in stimulating a higher number of neural population. When higher number of neurons contribute to carrying the information, improvement in the psychophysical and speech perception is expected). In normal individuals provided with simulated situation of CI, the speech performance ability was remarkably deteriorated subsequent to the intentional decrease of their dynamic range, particularly vowel and consonant components (Loizou, Dorman et al. 2000). However, speech perception ability has been found less dependent on or no related to the magnitude of DRs in CI recipients (Fu and Shanon 2000, Franck, Xu et al. 2002). One possibility for the lack of such a
direct and robust relationship between DRs and post-operation outcomes might be a normal-like loudness growth over dynamic range for CI users. Adult CI users have been reported to have the most optimal performance in the case that a normal loudness growth function was restored by speech processor (Fu and Shannon 1998). In other words, abnormal loudness perception may adversely affect the outcomes with CI. In the study by Steel, Abbasalipour et al. (2014), it has been reported a similar loudness growth rates between adolescent CI users and their counterparts with normal hearing, showing a normal loudness growth over DRs for CI users. That result can be an indication of the fact that CI users having limited DRs may learn to effectively benefit from the available condition.

Cochlear implant mapping is not a challenge-free work because; it is a time-consuming process that needs the participation of the CI recipients as well. It becomes more problematic when children are the cases, so that clinicians should have enough experience to recognize their real and correct responses (Mertes and Chinnici 2006). Most child CI recipients have no prior experience of the sound, so that it is difficult for them to precisely judge the loudness of the delivered electrical signals. In addition, the expressive language of this group of children is not good enough to give feedback about what they are hearing with CI system.

Measurement of T- and C- levels in children

Given that young children have limited ability to respond verbally and their responses are less reliable, the measurement of their mapping parameters rather differs from that of their adult counterparts. In addition to the behavioural tests, several objective tests are also used in order to assist to create a precise map for children. The current behavioural and objective tests used for mapping the speech processor of the children are explained as follows:

Behavioural tests

The behavioural tests are currently the gold method used for mapping in children. As in standard pediatric audiometry, three methods including: Behavioural Observation audiometry (BOA), Visual Reinforcement Audiometry (VRA) and Conditioned Play Audiometry (CPA) are considered to measure T- levels in child CI recipients (Gordon, Papsin et al. 2004a).The selection
of the most appropriate approach substantially depends on the several factors like the developmental age, physical skills and child cooperation. BOA has been found useful for infants younger than 6 months old. Any changes in behaviour are actually considered as the response to the sound. These changes are usually seen in the forms of widening of the eyes, touching the headset, stilling, change in facial expression, even adverse reaction and etc. VRA is considered as an appropriate test in children as young as 6 months up to 2.5 years old. Older children can successfully perform CPA, provided the task is matched with the child's ability (Johnson 2002).

The onset level of the electrical signal delivered to assess T-levels is determined by the lowest level suggested by manufacture or based on the objective test performed peri-operation (Wolfe and Schafer 2010). This manner will decrease the likelihood of the adverse reaction to the stimulation by child, which may result in child refuse to cooperate further.

Behavioural C-levels are measured in children in two ways with respect to their age (Henkin, Kaplan-Neeman et al. 2003). The observation of an inconvenience feeling following stimulation is useful for preschool-age or younger children. While child is distracted through engaging in an activity, the stimulation level is steadily increased until the point emerging the inconvenience feelings. For older children, a simplified psychophysical loudness scaling task is efficient. In this method, child is asked to judge the loudness of the electrical signal through mentioning to the categories on a loudness scale.

**Objective tests**

As the behavioural tests have relatively been found time-consuming and some younger children stop cooperation after a while, clinicians can use objective tests to predict the mapping parameters (Gordon, Papsin et al. 2004a). Indeed, information obtained by these methods assists clinician to determine the starting point for threshold measurement and the levels to avoid overstimulation. Since the measured levels with this type of tests are not accurate enough, clinician should prevent to directly utilize them as the real T- and C-levels (Gordon, Papsin et al. 2004b).
The most current objective tests used for mapping are Electrically Evoked Stapedial Reflex (ESR), Electrically Evoked Compound Action Potential (ECAP) and Electrically Evoked Auditory Brain Stem Response (EABR).

**Electrically Evoked Stapedial Reflex (ESR)**
ESR is a quick and clinically feasible test to predict C-levels (Gordon, Papsin et al. 2004b, Brickly, Boyd et al. 2005). It is acquired through administrating an ordinary acoustic reflex test peri- and post-operation or even through a direct inspection of the stapedious bone movement during the operation (Gordon, Papsin et al. 2004a). Cautiously, C-levels are considered lower than the stimulating intensity level in order to avoid the persistent stapedial reflex as environmental sounds usually exist at moderate levels.

**Electrically Evoked Compound Action Potential (ECAP)**
The more recent technologies of the CI manufactures have been equipped for the acquisition of the ECAP response, which is very easy to record. Several studies carried out in this area have shown that the ECAP thresholds often fall between the behavioural T- and C-levels (Brown, Hughes et al. 2000, Potts, Skinner et al. 2007). This means, presenting stimuli at this levels will bring confidence about the audibility of them. As a result, ECAP thresholds are trustful for training the children to participate in the behavioural test. Gordon, Papsin et al. (2004a) well showed the usefulness of ECAP thresholds to predict T-levels. However, the ECAP response may be absent in some recipients benefitting from CI.

**Electrically Evoked Auditory Brain Stem Response (EABR)**
The purpose of recording EABR responses for CI recipients is twofold: confirmation of the integrity of the CI system during surgery and as a tool to assist the mapping of the CI recipients, particularly children (Hodges, Ruth et al. 1994). Like ECAP, the EABR threshold often falls between the behavioural limits of DRs, ensuring the reliability of it as a starting point.

Although the accuracy of EABR threshold-based map and ECAP threshold-based map are reported comparable (Brown, Hughes et al. 2000), clinicians do not often use the former test to date. The reasons have lied in the fact that the measurement of ECAP thresholds is easier than
that of EABR thresholds. Because, during ECAP test, not only external recording electrode is not required, but also there is no problem with individual’s movements. However, EABR test is helpful in condition that the ECAP threshold is difficult to be recorded. For example, in children with abnormal cochlea such as cochlear ossification (Gordon, Papsin et al. 2004b).

**Factors affecting the mapping parameters**

The magnitude of the mapping parameters mainly depends on the distance between the modiolus and electrode array, the amount of neural survival and the developmental status of the auditory system (Kawano, Seldon et al. 1998). Every factor that changes these parameters has the potential to have effect on the mapping parameters. It can be either an individual-related factor, such as age at implantation, the presence of malformation in the cochlea and having previous experience of hearing, or a device-related factor, such as electrode array region, stimulation mode and device type.

With regard to age at implantation, there are two opposite perspectives. One perspective indicates higher T-levels with older age at implantation (Vargas, Sainz et al. 2013). The higher levels are attributed to the likelihood of reduction in the sensitivity of the auditory system due to longer deprivation from auditory stimulation with older age at implantation. The other perspective indicates lower T-levels with older age at implantation (Gordon, Papsin et al. 2004b). The lower levels are attributed to the fact that the intensity of the stimulation may need to be higher than threshold level in order to be detected by younger children. However, it seems that the magnitude of C-levels is not significantly affected by age at implantation. A side from the magnitude, age at implantation can affect the mapping parameters in another way. It has been shown that the mapping parameters of individuals implanted at an older age are not consistent across the electrodes on the array and there is larger difference in levels between adjacent electrodes (Sainz, Torre et al. 2003).

The presence of malformation in the cochlea has been found to result in higher T- and C-levels (Zwolan, Sullivan et al. 2008, Vargas, Sainz et al. 2013). On the other hand, it causes an inconsistency in the magnitude of the mapping parameters across the electrodes on the array, with larger differences in levels between adjacent electrodes (Sainz, Torre et al. 2003, Vargas,
Sainz et al. 2013). Some etiologies, such as meningitis, cause a growth of pathological tissue within the cochlea. Such tissue can result in the electrode array being further from the modiolus and. It also can cause an additional degeneration of the neural fibers and decrease neural survival (Vargas, Sainz et al. 2013).

The mapping parameters have been found to be lower in the recipients who have had experience of hearing before implantation. Vargas, Sainz et al. (2013) have reported an average of 41% increase in T-levels of recipients with no experience of hearing before implantation in comparison to their age-matched counterparts who had some experience before implantation. It was attributed to the fact that longer deprivation from the auditory stimulation imposed more degeneration of the auditory nerve.

In terms of the electrode array region, there are differences in the mapping parameters between the apical, medial and basal regions. Generally, the variability of the mapping parameters is higher in the basal region relative to the both medial and apical regions (Domville-Lewis, Santa Maria et al. 2015). Moreover, electrodes located in the apical region have lower T-and C-levels in comparison to those located in the medial and, particularly, in the basal region on the array (Henkin, Kaplan-Neeman et al. 2003, Sainz, Torre et al. 2003, Vargas, Sainz et al. 2013). Consistent with the difference in the behavioural T- and C-levels, Gordon, Papsin et al. (2004b) reported differences in the objective thresholds of EABR and ECAP between the three electrode array regions, with the lowest thresholds for electrodes located in the apical region. In addition to the magnitude of the mapping parameters, electrode array region can also affect the time the mapping parameters take to stabilize. The mapping parameters of the electrodes located in the apical region take a shorter time to stabilize in comparison to those located in the medial and, particularly, in the basal region (Domville-Lewis, Santa Maria et al. 2015). These superior outcomes in the apical region are attributed to the possibility of higher neural survival in this region (Kawano, Seldon et al. 1998).

The stimulation mode has also potential to affect the mapping parameters as the magnitude of the electrical field varies in different stimulation modes. In other words, different stimulation modes involve different numbers of ganglion cells to contribute to the hearing of sounds. The
complete explanation regarding the stimulation mode and the different types of it will be provided later in this chapter (pages 28-29). Generally speaking, the broader electrical field recruits higher number of spiral ganglion cells for stimulation. As a result, it decreases the amount of electrical signal required to reach T- and C-levels. Considering this, by monopolar mode, T- and C-levels are smaller than by both bipolar and common ground modes, with the largest levels for bipolar mode (Sainz, Torre et al. 2003). However, the size of effectiveness is not identical for these two parameters, so that T-levels are less influenced than C-levels (Chatterjee 1999). In addition, the mapping parameters are not consistent across the electrodes on the array with the bipolar stimulation. Against this, the mapping parameters gradually change across the electrodes on the array with the monopolar stimulation. That is, interpolation of T- and C-levels applying bipolar mode will not end up to a map as fairly precise as that created by monopolar mode (Sainz, Torre et al. 2003).

The magnitude of the mapping parameters can be affected by device type implanted for the recipients. The reason lies on the difference in the electrode array designs for different types of a CI system. The electrode array designs generally varies in terms of the position of the stimulating electrodes and the magnitude of the trauma during the surgery. Over time, it has been aimed to reduce the distance between the stimulating electrodes and the modiolus in order to more effective excitation of the auditory neural fibers. Additionally, it has been attempted to decrease the chance for additional damage to the neural survival during surgery. Due to these two developmental changes, theoretically, the mapping parameters are expected to be lower for the more recent type of a CI system relative to the older ones. Studies on different types of Nucleus system have shown lower mapping parameters for Nucleus systems with precurved electrode arrays like CI24R and Freedom relative to those with straight electrode array like CI24M (Saunders, Cohen et al. 2002, Gordin, Papsin et al. 2009). Such a difference in the mapping parameters were also reported between the different types of Nucleus systems with precurved electrode arrays, with lower mapping parameters for Freedom system than CI24R (Walravens, Mawman et al. 2006, Gordin, Papsin et al. 2009). However, there are some other studies indicating that the developmental changes in the electrode array design may not necessarily meet the predicted aims (Polak, Hodges et al. 2005, Hughes and
Abbas 2006). Therefore, it is possible that the mapping parameters do not differ between different types of a CI system.

**Changing T- and C- levels over time**

Aside from the mentioned individual-related and device-related factors, the mapping parameters are susceptible to change overtime as well. This often attributed to the numerous reasons including: later alterations in the physiological, anatomical and psychological status, early conservative attitude of clinicians and learning effect over time. Meanwhile, changes in the mapping parameters of children are larger, faster and continue for a longer time in comparison to adults (Hughes, Vander Werff et al. 2001).

Regarding the perceptual T-levels alteration, there are two opposite perspective, indicating increment or decrement over time. Many studies have demonstrated an incremental tendency among children, although there were still few cases with decreased or stable threshold values over time. Henkin, Kaplan-Neeman et al. (2003) followed the amount of the current levels needed to reach T- levels among child CI recipients of the Nucleus 22 device as long as 2 years post-operation. They found an increasing trend for T-levels, which stabilized after 12 months. The later study by this group (Henkin, Kaplan-Neeman et al. 2006) was still showing the increasing trend but, for a shorter time of 3 months post-operation. The earlier stabilization time was attributed to the difference of the CI system used in this study, where children received the newer type of Clarion system. It was rather confirmed by (Hughes, Vander Werff et al. 2001), where the participants were children receiving Nucleus 24M, benefitting from features comparable to the Clarion device. The latter authors considered objective ECAP thresholds in addition to the behavioural T-levels. Although behavioural T-levels kept rising up to 12 months post-operation, the variation rate was higher for the first 3 months. In addition, the ECAP thresholds start to stabilize earlier between 3-8 months. This group of studies attributed the increase of T-levels partly to the appearance of the new physical structures like bony or fibrosis tissues within the individuals’ cochlea or other physiological changes after a while.
By contrast, Gordon, Papsin et al. (2004b) has reported steady reduction during the first year post-operation across children receiving Nucleus 24M. The authors didn’t find any sign of development in the auditory nerve or brain stem based on recorded ECAP and EABR thresholds. So, the reduction of T-levels was related to children’s increased hearing experience during CI use and providing more reliable responses over time.

Changing trend for C-levels differs from that of T-levels in several ways: First of all, C-levels only tend to increase over time. Two reasons were suggested for that. Development of the central auditory pathway following exposure to the auditory stimulation that rationally helps CI recipients to tolerate the louder sounds (Gordon, Papsin et al. 2004b). On the other hand, clinicians are very conservative initially post-operation and underestimate C-levels, particularly for children. But over time, not only children can get familiar with the concept of the loudness of sound, but also the language ability of them improves. As a result, children can provide clinicians with verbal feedback about the sound they are listening and clinicians can set C-levels with more confidence and avoid underestimation (Hughes, Vander Werff et al. 2001). Second of all, the changing rate of C-levels has been found much larger in comparison to T-levels (Hughes, Vander Werff et al. 2001, Henkin, Kaplan-Neeman et al. 2003, Henkin, Kaplan-Neeman et al. 2006).

Due to the different tendency seen for the changes of T- and C-levels over time, electrical DRs of the recipients are affected in a positive way, so that it starts to become wider over time (Henkin, Kaplan-Neeman et al. 2003, Henkin, Kaplan-Neeman et al. 2006).

The following sections of this chapter will focus on the detailed programming process which is administrated in clinical practice.

**Preprogramming**

Although the efficiency of CI system is partly determined peri-operatively, the active speech processor is not attached to the implanted part immediately post-operation. This is because of the requirement of a time period for the healing of the incision site after surgery.
Until the onset of the practical usage of implant, CI recipients along with clinicians can spend the time to prepare for a facilitated programming session (McCormick and Archbold 2003, Zwolan and Griffin 2005). This time interval can be considered as a worthwhile opportunity to lower child CI recipient’s resistance against admission of the implant. To achieve this, clinician can apply different manners like giving them a chance to wear a real but inactive speech processor. Clinician can also appreciate this time to prepare for creation a precise map through a rather facilitated programming process. They can get surgery report and post-operation X-ray in order to find information regarding the peri-or post-operation complications, the position of the inserted electrode array and the number of available electrode contacts.

As an important point to be considered during this time interval is maintaining the connection with the sound. Fitting an appropriate HAs, FM system or even vibrotactile aids are the solutions to meet their hearing demands to some extent.

**Initial programming**

There is no accurate consensus regarding the first time of connecting and activating the speech processor to the implanted internal part of CI system (switch-on session) across different clinics worldwide. The current opinion about the switch-on session varies between several days and several weeks post-operation (Zwolan and Griffin 2005, Shapiro and Bradham 2012). Prior to start programming, some considerations by clinician can be helpful in working with young children recipients. For example, physical environment should be arranged in a way that provides both convenient feeling in children and optimal situation for behavioural tests.

Now, it is the time to attach the speech processor to the programming computer. Before delivering electrical signals to the electrodes, clinician should take in to account the electrode impedance telemetry, choosing the appropriate stimulation mode, signal processing strategy and stimulation rate. It will be explained about these important facts in more detail in the next parts of this chapter (pages 27-31). Then, clinician can start the crucial and most time-consuming part of the programming which is measurement of the electrical stimulation levels for each individual active electrode (mapping).
Since children's capability to cooperate for a long time is limited, in clinical practice, the direct assessment of every single electrode is not possible. Therefore, clinicians usually apply streamlined method. They routinely start direct measurement of T- and C-levels for the most apical, most basal and a few electrodes among them. For the remained subset of the active electrodes, the mapping parameters are predicted through interpolation.

It is worth bearing in mind that a precise map doesn’t come out following the initial programming. Indeed, the switch-on session just leads the way for primary familiarization with the electrical signals delivered through CI system. The precise map will gradually be accessed, when CI recipients get used to the sound and their auditory pathway acquires enough sensitivity.

**Electrode impedance telemetry**

The effectiveness of cochlear implant primarily depends on two main facts: the communication between the internal and external parts as well as the interaction between the electrodes and the auditory nerve fibers. To be sure that these functions occur properly, clinicians can use the electrode impedance telemetry considered in CI system. This technique actually evaluates the electrode’s resistance relative to the electrical current flow (Wolfe and Schafer 2010). The ultimate goal of telemetry is to determine electrodes with unusual high or low impedance (known as open and short circuits respectively). The reasons which lead to a short circuit are physical connection between two electrodes, electrical fault within the electrode lead and extreme tension on the electrode array. The reasons which lead to an open circuit are the presence of an air bubble, protein build up, anomalies like ossification and broken electrode lead. These electrodes should be inactivated since they cause unpleasant non-auditory sensation, provide poor sound quality and deteriorate speech recognition performance. Although open circuits can turn to normal electrodes over time with a period of electrical stimulation, short circuits should be inactivated forever (Wolfe and Schafer 2010).

It is now well documented that electrode impedance varies over time and that the pattern of variation differs between children and adults (Hughes, Vander Werff et al. 2001, Henkin, Kaplan-Neeman et al. 2006). In general, electrical impedance significantly increases from
operation room to switch-on session, and then decreases dramatically up to 1 to 2 months post-operation. The difference between children and adults is revealed from this time. It starts to increase up to 6 to 12 months following operation in all electrodes of children. In opposite, it gets stable in adults at the same 1-2 months following operation, except to their basal electrodes. Therefore, the assessment of the electrodes impedance should not be confined to just the switch-on session and clinician must perform the telemetry at each subsequent programming session.

**Stimulation mode**

The CI system establishes hearing sense through distributing electrical signal from an active electrode to a reference electrode, arousing action potential in the auditory nerve fibres. The location of the reference electrode relative to the active electrode determines the stimulation mode. Based on this, there are 3 main stimulation modes known as monopolar, bipolar and common ground, which the clinician must choose the most appropriate one.

**Bipolar mode**

With this stimulation mode the electrical field is generated between active and reference electrodes both located on the electrode array within the cochlea. The term “bipolar” (BP) refers to the pattern in which the active and reference electrodes are adjacent, providing a focused excitation. If the interval between the active electrode and the reference electrode increases to 1, 2 or 3 electrodes, a larger number of auditory fibers are excited and the terms BP+1, BP+2 and BP+3 are used respectively.

**Monopolar mode**

When the reference electrode is outside of the cochlea and distant from the electrode array, a wide electrical field forms that is called monopolar stimulation mode (MP). There are different types of MP mode, including MP1 (reference electrode located in the temporalis muscle), MP2 (reference electrode located on the implant package) and MP1+2 (a combination of MP1 and MP2). Generally, a monopolar mode provides a tonotopic signal across the cochlea due to the fact that the current density is greatest around the active electrode. As a result, the CI
recipients can perceive a decrease in the pitch with a change in the stimulated electrode from the base to the apex of the cochlea (Kwon, Perry et al. 2011).

Common ground mode
Another type of the stimulation mode is the common ground mode, in which the electrical current spreads from the active electrode to all other intra-cochlear electrodes. Employing this mode is not suitable for children with a partial insertion of the electrode array as it may result in non-auditory sensation. It is due to spreading a small amount of the electrical current to electrodes outside the cochlea, even the inactivated ones (McCormick and Archbold 2003).

Signal processing strategy
In CI system, this is originally the signal processing strategy that defines how the amplitude, frequency and temporal information of the outside sounds are coded by the speech processor to deliver to the receptive neural fibers. It, indeed, interprets these nuance features of the acoustic stimuli into the electrical codes through the determined stimulation pattern of the auditory system. Thanks to advances in the engineering field, speech coding strategies has substantially been improved relative to the earlier times.

The preliminary strategies only emphasized on the spectral resolution area to express the frequency characteristic (pitch) of the arrived sounds. The first type of this generation was known as F0F2 (CLARK, Tong et al. 1984), extracting the second formant along with the fundamental frequency. It was followed by adding the first formant known as F0F1F2 (Dowell, Seligman et al. 1987) and subsequently Multi-peak strategy with six spectral peaks (Dowell, Whitford et al. 1990). Despite the better performance with each of these strategies in comparison to the previous versions, the fine structures of the speech had not yet been addressed. Therefore, the attentions were drawn toward the extraction of the temporal envelope rather than spectral envelope in order to provide recipients with more details.

The most recent signal processing strategies encode more fine temporal structures. This can happen through two partly different procedures known as continuous interleaved sampling (CIS) and n-of-m strategies.
Continuous Interleaved Sampling (CIS)

In this approach, the captured acoustic signal is detached to different frequency bands via a number of band pass filters. These products are then sent to a rectifier, followed by a low-pass filter to provide a temporal envelope. Then, the extracted envelope signals are compressed to accommodate the wide acoustic signal into the CI recipient's narrow electrical dynamic range. The output of each band-pass channel is conducted to a pulse generator to modulate a fixed-rate biphasic carrier ranged typically from 800 to 1400 pulse per second (PPS). Since the pulse trains for the different channels and corresponding electrodes are time interleaved, all electrodes are stimulated sequentially and, as a result, the channel interaction is largely eliminated.

n-of m strategy

The basic manner of this strategy is similar to CIS, except that an extra channel selection activity (spectral peak picking) is administrated here as well. To put it another way, the amplitude envelope for all available channels (m channels) is estimated in order to identify the channels with the highest amplitude (n channels). The aim of such a selection is to reduce the number of active electrodes. To address this, the stimulus pulses are only sent to the related "n" electrodes rather than all “m” electrodes in any period. This, in turn, increases the temporal resolution of the remaining channels due to faster stimulation rate on these selected channels. Thus, it leads to progress in the speech perception compared to CIS strategy (Buechner, Frohne-Buechner et al. 2009). The "n" is referred to maxima which are usually varied from 10 to 12. Two common strategies working on the basis of this approach in current Cochlear corporation products are as follows:

Spectral Peak (SPEAK) strategy

With this strategy, the number of maxima differs in each cycle between 6 to 8 channels from a total of 20 active channels. The intensity level and spectral content of the incoming signal determines the required number of the maxima per cycle. Although the applied stimulation rate is constant at an average 250 pps, the strategy can work at an adaptive rate between 180 to 300 pps. The rule is the greater the number of maxima, the lower the stimulation rate. The
outcomes with SPEAK strategy were improved over the previous Multi-peak strategy (Skinner, Clark et al. 1994).

**Advanced combined encoder (ACE) strategy**

ACE is considered as the default strategy of all Cochlear Ltd productions. It is a fast and flexible form of n-of-m strategy in which up to 22 channels of stimulation are used. The number of maxima with highest amplitude can be up to 20, although it commonly ranges from 8 to 12. The major difference between ACE and SPEAK strategies arise from their stimulation rate, with a higher rate (up to 2400 pps/channel) for the ACE strategy. As a result, ACE has more focus on fine temporal structures. That is, this strategy retains greater temporal details, leading to better speech perception (Kiefer, Hohl et al. 2001).

Today's advanced speech processors have the capability to store several programs using different signal coding strategies. This characteristic provides patient with the opportunity to experience the different strategies in different environments and to determine their preferred strategy. The alternation of the strategies can even be applied daily and started from the initial stimulation, although some CI recipients need time to determine the best one (Tyler, Witt et al. 2008). However, identification of the most beneficial speech processing strategy is not a simple task in children. Johnston and Verschuur (2005) proposed using the speech pattern audiometry (SPA) as an appropriately quick tool to easily compare the effectiveness of different strategies in children.

**Creating map**

The mapping process is not finished by the determination of the upper and lower levels of dynamic range for all available electrodes. After storing these mapping parameters in the speech processor, clinicians must confirm that loudness summation following the stimulation of all active electrodes together does not result in an uncomfortably loud percept. To achieve this, the implant is operated under live-speech condition and recipient’s reaction is examined to reject any likelihood of uncomfortable feeling (Henkin, Kaplan-Neeman et al. 2003). In the case of any discomfort, the C-levels should be reduced. McCormick and Archbold (2003) have proposed a global reduction of 30% of the electrical dynamic range from adjusted C-levels. At
the final step of the switch-on session, the clinician can ask recipient to perform the test called Ling Sound. During this test, they are asked to repeat six phonemes delivered to their implant including /ah/, /oo/, /ee/, /s/, /sh/ and /m/. The aim is to ensure that the sounds in the speech frequency range are heard (Hedley-Williams, Sladen et al. 2003, Wolfe and Schafer 2010).

Follow-up programming sessions

As mentioned before, the optimal map will emerge gradually, when recipients gain enough experience with the electrical signals and audiologists gently achieve more reliable responses. That is, the speech processor is in need of a periodical programming over time after switch-on session to address the actual requirements of the recipients.

Considering that the significant variations of the mapping parameters mainly occurs during early months of the first year post-operation, this time period encompasses the majority of the programming sessions and, thereafter, the number of appointments will be reduced. However, there is no unanimous programming schedule worldwide and the number of appointments varies across different clinics. Furthermore, factors such as recipient age, progress and distance to the implant center can influence the number of the follow-up appointments (Wolfe and Schafer 2010, Shapiro and Bradham 2012).

Since the present study involved data from children who received their implants at the Royal Victorian Eye and Ear Hospital Cochlear Implant Clinic (RVEEH Clinic) in Melbourne, Australia, as an example of a follow-up schedule for children, the RVEEH Clinic schedule is shown in Table 1-1. This schedule is for attending sessions if there was no issues and parent and educators considered progress to be appropriate.
### Programming appointments vs Post-operation time interval

<table>
<thead>
<tr>
<th>Programming appointments</th>
<th>Post-operation time interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>3 weeks</td>
</tr>
<tr>
<td>Second</td>
<td>4 weeks</td>
</tr>
<tr>
<td>Third</td>
<td>6 weeks</td>
</tr>
<tr>
<td>Fourth</td>
<td>11 weeks</td>
</tr>
<tr>
<td>Annual mapping</td>
<td>12 months</td>
</tr>
<tr>
<td>Subsequent appointments</td>
<td>Every 6 month till school age of 5 years old</td>
</tr>
</tbody>
</table>

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**Programming approach at the RVEEH Clinic**

Given its long history of CI surgery, the RVEEH Clinic is staffed by highly experienced clinicians, providing the recipients with high quality, behaviorally-based programming. Due to this advantage, all mapping parameters were well evaluated behaviorally in this clinic. The clinicians considered both the age and the developmental stage of the child in order to select the most appropriate methods for behavioral tests. In addition, for more accuracy, one speech pathologist always assisted the audiologists during the assessment of children. This assistant helped to manage children behavior and to facilitate their cooperation, which was essential to acquiring reliable response.

At the RVEEH Clinic, each programming session starts with electrode impedance telemetry, with the speech processor connected to the computer running the Cochlear programming software Custom Sound™. Open and short circuits are recognized based on the impedance limits defined by Cochlear Limited for different Nucleus systems. For CI24M and CI24RE (ST) Nucleus systems, the electrodes with >20 Kohms impedance, and, for CI24R (CS or CA), CI24RE (CA) and CI512 Nucleus systems, the electrodes with > 30Kohms impedance were inactivated as open circuits. The electrodes with < 0.565 Kohms impedance were inactivated as short circuits.
for all Nucleus systems. To measure the mapping parameters, clinicians usually chose the default settings provided in Custom Sound™. That is, measurement with MP 1+2 stimulation mode, ACE strategy, 25 µs pulse width, 900 pps stimulation rate and 8 maxima. Each of these settings was changed if a difficulty was identified and the clinician obtained better outcomes with other available options for that setting.

The normal trend in the measurement of the mapping parameters was toward the streamlined method. In Custom Sound™ default, electrodes 22, 16, 11, 6 and 1 were chosen to be directly measured through behavioral testing; clinicians also did this for as many as electrodes possible. The initial programming sessions aimed to introduce sounds to child. Therefore, with very young children, the measurement of T- and C-levels for even one or 2 electrodes could be a satisfying outcome in the switch-on session. Measurement of the mapping parameters were started from electrode 22 due to two reasons: firstly, the assumption of the presence of a higher auditory survival in the apical region of the cochlea, and secondly, stimulation of the apical electrodes was less likely to cause non-auditory sensations. The measurements continued toward the medial electrodes and, finally, the basal electrodes. In the measurement of the mapping parameters, an ascending procedure was used. The starting stimulation level could be 80 CLs as the Custom Sound™ default, or levels slightly lower or higher than that (considering the peri-operation objective test thresholds) in the switch-on session. The electrical signal was increased in small step sizes (5 CLs as the Custom Sound™ default) until a reliable response was observed. However, the magnitude of changes could be decreased when closer to the actual T- and C-levels to ensure accurate measurement. In the next programming sessions, the measurements were started by taking the previous map into account if that map was reported as being comfortable for the child in use. This map was called parent map and clinicians changed T- and C-levels of parent map according to the child’s responses to provide a new map.

As a general rule in the RVEEH Clinic, C-levels were not measured directly until the third or the fourth programming session. During this time, clinicians tried to behaviorally measure T-levels and then to add a fix amount of CLs to set C-levels. In other words, all available electrodes on the array had similar DRs during the first three or four programming sessions. However, this
rule was not applied for all children. In some children, both T- and C- levels could be independently set from the switch-on session, particularly for their second ear. Conversely, there were some children for whom direct measurement of C-levels was not feasible until 3 months or more post-operation.

Although it is possible that the individual clinician influenced the results, it should be emphasized again that the staff at the RVEEH Clinic were highly trained clinicians using the same mapping protocol. Due to the long-term experience in the Clinic (first child implanted in 1985), the mapping protocol was well-established by the time the earliest data included in this study was collected (in 2003), so that there were no significant changes to the approach used to set t- and c-levels over the period of time data was collected for this study. It should also be noted that, as far as possible, and frequently for younger children, the same audiologist would be mapping the child over a period of years, such that the audiologist mapping at switch-on of CI2 was the same as the audiologist at switch-on of CI1.
Chapter 4: Bilateral cochlear implant
Despite considerable benefits that a unilateral CI brings, the recipients still experience some difficulties, especially in noisy situations or when there are multiple acoustic signals. Such challenging situations can raise some concerns regarding effective communication, social relationships and safety. For child recipients, there might be a greater concern as school environments, in which children spend their time, are often noisy and reverberant. In order to reduce these difficulties faced by unilateral recipients, implantation of both ears is recommended. Nowadays, it is well known that bilateral hearing can provide additional advantages relative to unilateral hearing. The additional advantages of bilateral hearing result in improved spatial hearing and speech perception, particularly in noise, which are explained in more detail in the following sections. These advantages result from the combination of central auditory processing (binaural processing) and the physical effect of the head.

**Spatial hearing**

Spatial hearing is the ability by which individual can identify the location and direction of sound sources. The specific acoustic cues underlying spatial hearing are the inter-aural time differences (ITDs) and the inter-aural level differences (ILDs). Due to the physical presence of the head, as well as the orientation of the two ears, the sound originating from a sound source will arrive earlier to the ear closer to the sound source relative to the further ear, which results in ITDs. Likewise, the sound will have a higher intensity at the ear closer to the sound source relative to the further ear, which results in ILDs. The central auditory system can process these ITDs and ILDs cues in a way that establishes a perception about the location of the sound source. However, ITDs and ILDs are not equally useful for locating sounds of different frequencies. ITDs are more useful for locating sounds with low frequencies, while ILDs are more useful for locating sounds with high frequencies (Moor 1998). The normal central auditory system has the potential to distinguish ITDs and ILDs as small as 0.1 msec and 1dB respectively (Dillon 2012).
Speech perception

Three mechanisms which may contribute to improved speech perception using bilateral hearing are described below.

Binaural summation and redundancy

Binaural summation refers to a phenomenon during which the loudness of the ongoing sound is enhanced. When sound is received by two ears, the central auditory system combines the signals received by each ear in a way that the sound is perceived as louder than it would be by a single ear. Another phenomenon that occurs along with binaural summation is binaural redundancy. Binaural redundancy is generally available in the cases that the signal is similar at each ear. When a similar signal is presented at each ear, the brain can have two looks at the same signal and this can improve detection or recognition of the signal (Dillon 2012).

Binaural unmasking

Binaural unmasking is a phenomenon that improves speech perception ability when speech and noise arrive from separate locations. When speech and noise come from different locations, the signal-to-noise ratio is different at each ear. The brain can then compare the signals arriving at each ear. In order to improve speech perception, the noise waveform at the ear with the lower signal-to-noise ratio is used to partially cancel out the noise from the signal at the ear with the higher signal-to-noise ratio. The result provides a central representation of the signal with a higher signal-to-noise ratio relative to that at either ear.

Head shadow effect

In contrast to the two former binaural phenomena, the head shadow effect is a physical effect that arises from the role of the head as an acoustic barrier. When sounds reach the head, the intensity is lower at the ear further from the sound source. When speech and noise come from different locations, the intensity of the noise is lower at the ear further from the noise source, leading to higher signal-to-noise ratio at that ear. By attending to this ear with the higher signal-to-noise ratio, the listeners can improve their speech perception. Due to the variation in the
wavelength of the sounds, higher frequency sounds are subject to greater intensity reduction at the further ear in comparison to low frequency sounds. It is worth bearing in mind that the head shadow effect is effective even with unilateral hearing, provided the noise is contralateral to the hearing ear.

**Bilateral Cochlear Implants (BICIs)**

BICIs are an option to provide children with severe to profound hearing loss with bilateral auditory stimulation with the aim of gaining bilateral hearing advantages. BICIs can be provided through either simultaneous or sequential implantation. In simultaneous implantation, two implants are received during one surgery. In sequential implantation, two implants are received during two separate surgeries, with a time period of weeks or years between them.

The number of children undergoing bilateral implantation is increasing worldwide, with a shift toward implantation at an early age of under 3 years (Peters, Wyss et al. 2010). As reviewed below, the outcomes of studies evaluating the advantages of BICIs relative to a unilateral CI have shown significant improvements in spatial hearing and speech perception.

**The advantages of BICIs**

**Spatial hearing**

BICIs have been found to be beneficial in spatial hearing for children. The effectiveness of BICIs in this area has been assessed using different tasks in different studies. Some studies performed a left/right lateralization task, with a pair of loudspeakers positioned at a fixed angle of ±90° (Steffens, Lesinski-Schiedat et al. 2008, Galvin, Hughes et al. 2011, Sparreboom, Snik et al. 2011). The majority of children could make the left versus right lateralization at an above chance level in the BICIs condition against either the CI1 or CI2 alone conditions. Some children were able to score 100% correct when lateralizing sound in the BICIs condition (Vincent, Bébéar et al. 2012). Other studies evaluated minimum audible angle (MAA), the smallest angle of separation between a pair of loudspeakers at which child could identify the sound as from the right or left loudspeaker. Children achieved a smaller MAA in the BICIs condition relative to the unilateral CI condition (Litovsky, Johnstone et al. 2006, Sparreboom, Snik et al. 2011). However,
the mean MAA with BICIs was still larger than that of their counterparts with normal hearing
(Litovsky, Goupell et al. 2012). The third group of studies assessed sound source identification
using an array of multiple loudspeakers spaced apart with a similar angle. To evaluate the effect
of BICIs, root mean square (RMS) error, representing the average angle of error from the
location of the sound source, was compared between the BICIs and the unilateral CI conditions.
Although some degree of benefit has been reported from BICIs, there is still a large variability in
recipients’ performance (Galvin, Mok et al. 2007, Van Deun, van Wieringen et al. 2010).
Furthermore, not all children who successfully perform the left/right lateralization task can
localize a sound source in a multi loudspeaker array (Grieco-Calub and Litovsky 2010).

Speech perception

The advantage of BICIs over a unilateral CI for speech perception has been reported in both
noise and quiet (Johnston, Durieux-Smith et al. 2009, Litovsky, Goupell et al. 2012, Lammers,
Venekamp et al. 2014). Children who received BICIs have demonstrated significantly better
speech perception in quiet using BICIs relative to using CI1 alone, and this has been attributed
to binaural summation (Scherf, Van Deun et al. 2009, Sparreboom, Snik et al. 2011, Strøm-
Roum, Laurent et al. 2012). Although the additional benefit provided by BICIs in quiet can
increase over time, the children generally do not achieve performance similar to their
counterparts with normal hearing (Murphy, Summerfield et al. 2011, Nittrouer, Caldwell-Tarr et
al. 2013). In contrast to the within-subject comparison, between-subject comparison of
children with BICIs and children with a unilateral CI have not shown a bilateral benefit in the
quiet (Murphy, Summerfield et al. 2011, Sparreboom, Snik et al. 2011, Nittrouer, Caldwell-Tarr
et al. 2013). It is suggested that the benefit identified in the within-subject comparison may be
due to poorer performance in the unfamiliar unilateral CI condition. With regard to speech
perception in the presence of interfering noise, multiple studies have assessed performance of
children with BICIs and with CI1 alone in different conditions of noise from the front, from the
CI1 side and from the CI2 side (Galvin, Mok et al. 2007, Peters, Litovsky et al. 2007, Galvin, Mok
2011). The general findings indicated that the majority of children show improved speech
perception with BICIs in the case of noise from the CI1 side, while fewer children can take
advantage of BICIs in the case of noise from the front or from the CI2 side. Additionally, the amount of improvement with BICIs was reported to be much higher in the case of noise from the CI1 side relative to the other two noise conditions. Another approach to evaluate the benefit of BICIs in the presence of noise is measuring spatial unmasking. Spatial unmasking is measured as the improvement in speech perception when noise is moved from the front to the either side. Children with BICIs usually show better speech perception when noise is moved to the side of either implant relative to the condition of speech and noise presented from the front. By contrast, for children with unilateral CI, the performance usually become worse if noise is moved from the font toward CI side (Murphy, Summerfield et al. 2011). Taking all of these results together, the magnitude of improvement in speech perception in noise with BICIs essentially depends on the direction of the incoming noise and the improvement is mainly due to the head shadow effect.

Language

Research on the development of language in children with BICIs is relatively new and limited. At the preverbal level of language ability, BICIs have been reported to be beneficial for very young children in acquiring vocal ability and using it for communication instead of gestural language. Tait, Nikolopoulos et al. (2010) recorded children’s interaction with their parents or carer before and 12 months after implantation. The children were divided in two groups of BICIs and unilateral CI, with a comparable mean age at implantation of 13 and 12 months respectively. Before implantation, both groups were similarly interested to communicate using silent sign or gesture more than using voice. After implantation, there was a significant difference between the two groups, with the BICIs group being significantly more interested to communicate vocally without any visual interaction. However, development in the higher levels of language ability still seems to be rather challenging when using two implants. Phonological awareness, vocabulary, literacy and reading are receptive and expressive language abilities that can reflect semantic and synthetic language skills. Different studies used different test materials to compare these higher level aspects of language between children with unilateral CI and those with BICIs (Niparko, Tobey et al. 2010, Boons, Brokx et al. 2012, Nittrouer, Caldwell et al. 2012, Sarant, Harris et al. 2014). Although some of these studies involved children with up to 5 years
BICIs use, generally, no advantage has been reported for BICIs. The first exception was Sarant, Harris et al. (2014) who showed an advantage for BICIs in the development of vocabulary for all pre-school and school-age children, as well as in the development of expressive language for school-age children. The second exception was Boons, Brokx et al. (2012) who reported the effectiveness of BICIs in the development of expressive and receptive language ability.

Quality of life
Considering that obtaining a second implant brings additional risks and costs for families, it is relevant for families to know how, and to what extent, bilateral implantation will change children’s quality of life. Applying questionnaires, the rate of improvement in the health related quality of life has been reported to be similar by the parents of children who have used BICIs or a unilateral CI for about 19 months (Lovett 2010, Sparreboom, Leeuw et al. 2012). This finding suggests that BICIs may not impact on quality of life more than a unilateral CI in terms of overall health status. However, there are some reports from parents and older children indicating improvement in everyday life after receiving BICIs relative to the time of using unilateral CI. For example, some parents reported less need for repetition, faster and more responses, improved participation in conversation, better hearing at distance, more involvement in their surroundings, increased attention, and increased sense of security for their children after receiving CI2 (Galvin, Mok et al. 2008, Galvin, Holland et al. 2013). Likewise, some older children reported increased ease of listening in a variety of situations, such as team sports, feeling more involved in everyday conversations, feeling more confident and more independent in everyday life, and improved sound clarity and quality (Galvin, Hughes et al. 2010, Redfern and McKinley 2011).

Factors contributing to the outcomes
Variation in outcomes has been shown for children with BICIs. A number of factors have been identified as contributing to this variation as described below.
Age at bilateral implantation

Age at bilateral implantation has frequently been found as a major influencing factor on the outcomes with BICIs, so that younger children are likely to gain greater benefits from BICIs relative to older children. In the study by Galvin, Mok et al. (2007), participants who were older children (mean age at bilateral implantation = 8.4 years) did not achieve any improvement in spatial hearing ability even after one year BICls use. In addition, none of those children showed an advantage of BICIs in speech perception in noise, while the noise was presented from CI2 side. In contrast, in another study by these authors (Galvin, Mok et al. 2008) that involved children who received bilateral implantation before 4 years of age, some participants showed some degree of benefit to spatial hearing as well as to speech perception in noise, with noise from the CI2 side. In addition to greater benefits, younger children also develop benefits more quickly relative to older children (Scherf, Van Deun et al. 2009).

Generally, lower benefits from BICIs in the case of implantation at an older age can be due to the lack of effective development in their central auditory pathways. The central auditory system is not fully mature at birth and continues to develop after birth. It is a highly plastic system that requires auditory input to achieve normal development (Firszt, Reeder et al. 2008). However, there are reports indicating that plasticity can decrease over time and providing auditory stimulation very late is less likely to promote normal development. In the study by Sharma, Dorman et al. (2002), the latency of the cortical response evoked by the implanted ear reached the normal range after 6 months for deaf children who received a unilateral CI before 3.5 years old. In contrast, the majority of children who received an implant after 3.5 years old did not reach the normal range even with longer periods of auditory stimulation. Petrovic (2011) reviewed the effect of various periods of auditory deprivation on the development of the central auditory system of children. Although no upper age limit was found, the results indicated the possibility of a sensitive time period, beyond which providing auditory stimulation may fail to cause normal activation in the central auditory system. Auditory deprivation can affect the central auditory system in multiple ways including degeneration of the spiral ganglion cells, reduction in the neural cell size or the inter-neural connections and abnormal neural synapses (Firszt, Reeder et al. 2008). It seems it is possible to reverse such abnormal changes by
providing early auditory stimulation, when the degree of plasticity is still high. When auditory deprivation lasts for a longer time, the central auditory system may undergo reorganization. It has been reported that the areas of the brain related to the auditory sense can be occupied by the neural systems related to the other senses, such as the visual and somatosensory systems in deaf people (Charroó-Ruíz, Picó et al. 2013). As a result, the plasticity of the central auditory system may be reduced and it may become more difficult for normal development to occur after auditory stimulation is provided.

Time between implants

Time between implants is another factor which may contribute to the outcomes with BICIs. The majority of studies have highlighted the advantage of simultaneous BICIs over the sequential BICIs (Chadha, Papsin et al. 2011, Gordon, Jiwani et al. 2011, Boons, Brokx et al. 2012) that is explained in more detail in the next section (simultaneous or sequential BICIs pages 48-50) of this chapter. With regard to the children implanted sequentially, generally, the shorter the time between implants is, the greater the improvement will be after receiving CI2. Strøm-Roum, Laurent et al. (2012) compared monosyllabic word recognition ability in quiet across children with time between implants ranging from 12.3 to 142.2 months. It was reported that children with a shorter time between implants achieved higher scores with BICIs. This was attributed to the greater contribution of CI2 in hearing with BICIs, as these children achieved higher scores with CI2 alone. In another study by Peters, Litovsky et al. (2007), speech perception in quiet was tested for three groups of children which were different in terms of time between implants. All children received their CI1 before five years old, whilst their age at CI2 was before five (group 1), between 5 and 8 (group 2) and after 8 years old (group 3). Although all children benefitted from bilateral implantation by 12 months post-operation, the children in group 3, who had the longest time between implants, achieved the least benefit. The reason was that children in groups 1 and 2 achieved almost similar performance with CI1 and CI2, while the performance with CI2 was still considerably lower than that with CI1 in group 3. The mean score with CI2 alone was 32% at 12 months post-operation for group 3 compared to 83.9% and 60% for group 1 and group 2 respectively.
With a long time between implants, it may be very difficult for children to achieve a similar outcome with CI2 versus CI1. This is because there is an increased likelihood of abnormality of the central auditory pathway related to CI2 that may impact on the development of the pathway. Gordon, Wong et al. (2013) showed that the central auditory pathway related to CI2 was more likely to be occupied by the neural connections related to CI1 when children received CI2 a long time after CI1. The authors compared the patterns of cortical activity after stimulation of the two ears in children with normal hearing, with simultaneous BICIs, or with sequential BICIs. With the exception of children with a long time between implants, stimulation of each ear resulted in similar patterns of activation in the contralateral auditory cortex. For children who received CI2 a long time after CI1, reduced activation in the contralateral auditory cortex, along with some degree of activation in the ipsilateral auditory cortex, was found following CI2 stimulation. In addition, stimulation of CI1 in these children caused larger activation in the contralateral auditory cortex compared to the remaining children. These abnormal changes can be an indication of spreading neural connections of CI1 throughout the central auditory system and the dominance of CI1 following a long period of unilateral hearing using CI1. In the study by Gordon, Valero et al. (2008), there was no difference between the latency of brainstem responses evoked from both implants for children with simultaneous BICIs at switch-on and thereafter. For children who received both implants at an early age, and within less than 1 year, the initial difference between the latency of the responses evoked by CI1 and CI2 was almost resolved after 9 months experience of hearing with two implants. The reduction was mainly due to significant decreases in the latency of the prolonged responses evoked by CI2 and almost no changes in the latency of response evoked by CI1. In contrast, children who received CI2 more than 2 years after CI1, still had a significantly prolonged response evoked by CI2 relative to that evoked by CI1. At the auditory cortex level, Sharma, Gilley et al. (2007) showed that the initial difference between the latency of P1 wave evoked by CI1 and by CI2 could disappear a few months post-operation when the two implants were received before 3 years old with a short time between them.
**Age at CI1**

Age at CI1 is a factor that can ameliorate the negative effect of older age at bilateral implantation or a longer time between implants. Vischer, Senn et al. (2011) found high variability in speech perception performance with CI2, ranging from 5% to 82%, across adolescent participants. One thing that was common among participants with poor CI2 scores was late implantation of CI1. The positive effect of early age at CI1 can be due to its possible role in maintaining the activity of the central auditory pathway related to CI2 before implantation. Sharma et al 2005 found that the latency of the cortical response initially evoked by CI2 was shorter than that evoked initially by CI1. Scheffler, Bilecen et al. (1998) compared the pattern of auditory cortex activity following monaural stimulation between individuals with normal hearing and those with unilateral hearing loss. For individuals with normal hearing, stimulation of each ear caused strong activation in the contralateral cortex and a minor activation in the ipsilateral auditory cortex. In contrast, for individuals with unilateral hearing loss, strong activation of the ipsilateral auditory cortex was found, in addition to strong activation of the contralateral auditory cortex, following stimulation of their better ear. This finding, on the one hand, can suggest occurrence of such a result for unilateral CI users, where stimulation provided by CI can cause more activation in the central auditory pathway related to the non-implanted ear. On the other hand, it can suggest the possibility of more effective activation in the non-implanted ear with providing CI at younger age. Considering these, in the case of sequential BICIs, development of the central auditory system in response to CI2 may be more possible, if CI1 is received at younger age.

**Experience of hearing with two implants**

It seems BICIs recipients usually require a period of experience in order to show improvement in spatial hearing and speech perception in both quiet and noise post-operation. Scherf, Van Deun et al. (2009) followed the outcomes of children with BICIs from initial to 36 months post-operation and did not find a significant benefit of BICIs before 6-months post-operation. However, it may take a longer time, even more than 24 months, for some children to achieve bilateral hearing benefits (Peters, Litovsky et al. 2007, Sparreboom, Snik et al. 2011). In
addition, increased experience of hearing with two implants is related to greater bilateral benefits over time (Litovsky, Johnstone et al. 2006, Scherf, Van Deun et al. 2009). Off course, BICIs experience is not only about the time since bilateral implantation, it is also about using the two implants together, particularly in children with sequential BICIs. There are some factors that may contribute to consistent use of CI2 in children with sequential BICIs. Good speech perception scores with CI2 alone, a positive attitude toward CI2, easy adaptation to CI2 and, in the case of older children, self-motivation as well as involvement in decision making has been found to be related to consistent use of CI2 (Sparreboom, Leeuw et al. 2012, Emond, Moore et al. 2013, Fitzgerald, Green et al. 2013, Galvin, Holland et al. 2013). Achieving the additional benefits provided by BICIs depends on the development of the central auditory pathways related to each implant. Gordon, Valero et al. (2007a) showed that initial stimulation of both implants in simultaneously implanted children evoked similar but prolonged brainstem responses. For sequentially implanted children, the response evoked by CI2 was found to have prolonged latency in comparison to that evoked by CI1. The prolonged latency of the response evoked by CI2 was also found to be similar to the latency of the response evoked by the non-implanted ear of age-matched children with a unilateral CI. The prolonged latencies can indicate that the electrical signals are carried more slowly along the pathway to the brain. With auditory stimulation over time, the central auditory pathways undergo development and can process sounds in an appropriate way. Gordon, Valero et al. (2008) tracked the responses evoked by both implants of children up to nine months post-operation. For the simultaneous group, a similar pattern of decreasing latency was found in the responses evoked by each implant over time. For the sequential group, there was a significant decrease over time in the latency of the response evoked by CI2 compared to that evoked by CI1. Sharma, Gilley et al. (2007) also reported development of the auditory cortex following simultaneous or sequential BICIs. The authors recorded the latency of the cortical P1 wave evoked by the two implants for two groups of children with simultaneous and sequential BICIs at different time points from initial to 15 months post-operation. All children received their two implants before 3.5 years of age. For all children, the latency of the P1 wave evoked by either implant significantly
decreased over time, with the latency of the responses evoked by either implant reach the normal range by 3 months post-operation.

**Hearing aid use:**
As with early age at CI1, previous hearing aid use on the CI2 side can ameliorate the negative effect of older age at bilateral implantation and a longer time between implants. Van Deun, van Wieringen et al. (2010) found a supporting role for hearing aid use in the emergence of spatial hearing ability for children who received CI2 late. It seems auditory stimulation provided through hearing aid use has the potential to prevent complete reorganization, where it possibly helps the central auditory system to somehow stay active and to retain its plasticity. In line with this, Sakhuja, Munjal et al. (2010) reported developmental changes in the auditory brainstem and cortex following 2 months of hearing aid use for adults with sensory neural hearing loss.

**Simultaneous or sequential BICIs:**
To date, many studies have compared the outcomes with simultaneous versus sequential BICIs in different aspects in order to provide evidence-based information regarding the advantages and disadvantages of each procedure.

One area of comparison between the two procedures is related to safety and medical issues. According to a recent study by Lopez-Torrijo, Mengual-Andre’s et al. (2015), the overall hospital stay, the complication rate, and medication use are similar for both procedures. For the simultaneous procedure, there are the advantages of only requiring one operation and lower overall use of anaesthetic use. The disadvantages of the simultaneous procedure are the possibility of bilateral vestibular alteration and the longer operation time.

As explained earlier in this chapter (section of factors contributing to the outcomes), electrophysiological studies have indicated the positive effect of simultaneous BICIs on the development of the central auditory system post-operation. In terms of post-operation functional benefits, the majority of studies have demonstrated the advantage of simultaneous BICIs over sequential BICIs implantation. Boons, Brokx et al. (2012) assessed the language development of two groups of children with simultaneous or sequential BICIs, who had
comparable age at bilateral implantation. Although the two groups achieved similar receptive language scores, the simultaneous group achieved significantly superior expressive language scores. In another study, Chadha, Papsin et al. (2011) compared spatial unmasking between two groups of children with simultaneous and sequential BICIs with comparable age at BICIs and experience with BICIs. The simultaneous group showed significantly greater spatial unmasking (mean = 7.2 dB) than the sequential group (mean= 3.9 dB). Likewise, in a review by Gordon, Jiwani et al. (2011), greater bilateral benefit to speech perception in both noise and quiet were reported for simultaneously implanted children relative to their sequentially implanted counterparts with long time between implants. However, when Vincent, Bébéar et al. (2012) performed a retrospective analysis of speech perception results in noise or in quiet, their simultaneous group had no significant advantages over their sequential group. The superior post-operation benefit with BICIs for children with simultaneous BICIs is likely due to the equivalent contribution of their two implants to the auditory function. This is in contrast to what happens for children with sequential BICIs, particularly when the time between implant is longer, where contribution to auditory function is greater with CI1 than with CI2 contribution. Chadha, Papsin et al. (2011) reported that, for children with simultaneous BICIs, the advantage due to spatial unmasking was equivalent whether the noise was shifted to the right or to the left. By contrast, for children with sequential BICIs, the advantage due to spatial unmasking was higher with noise shifted to the CI2 side compared to the CI1. In the review by Gordon et al 2011, simultaneously implanted children with simultaneous BICIs were reported to have similar speech perception ability with each implant alone. By contrast, children who received sequential BICIs with long time between implants were reported to have better performance with CI1 than with CI2. However, Peters, Litovsky et al. (2007) showed that achievement of equivalent performance with each implant alone for children with sequential BICIs depends on the time between implants. These authors reported that, if both implants were received before 5 years old, and with a short time between them, children could achieve similar speech perception ability with each implant alone by 12 months post-operation.

In terms of device use, adaptation to the two implants together seems to be easier for children with simultaneous BICIs relative to their sequential counterparts. Full time use of the two
implants together can be achieved earlier and from switch-on for children with simultaneous BICIs relative to their sequential counterparts (Galvin and Hughes 2012). In the study by Galvin, Holland et al. (2013) that involved a large number (n= 50) of children with sequential BICIs, 72% of children could adapt to use both implants by 6 months post-operation, while 26% of them failed to adapt even by 3.5 years post-operation. Device preference has been found to be more common across this group of children as they are more likely to use CI1 alone rather than BICIs. Reluctance to use CI2 along with CI1 is sometimes reported to be due to the poor quality of the sound coming from CI2. Additionally, compared with the improvement due to CI1, adding CI2 provides a relatively small degree of improvement. Therefore, there is less requirement for CI2 as children can still function using CI1 alone (Emond, Moore et al. 2013). With simultaneous BICIs, sound is perceived via the two implants from the time of switch-on, and there is no previous experience of unilateral CI use for comparison. It is also possible that the sound perceived via each implant has a similar quality and information.

Overall, studies have shown very few disadvantages and numerous advantages for simultaneous BICIs relative to sequential BICIs. The potential disadvantages for simultaneous BICIs are the possibility of bilateral vestibular alteration and the longer operation time. The advantage of simultaneous BICIs are positive effect on the development of the central auditory system, greater functional benefits to speech perception and language ability as well as higher possibility of using the two implants together.

**Current BICIs programming**

For recipients of simultaneous or sequential BICIs, the programming of each implant is performed separately. Although there is no universal programming protocol, there is, generally, a difference between the simultaneous and sequential groups of children in terms of the time at which each implant should be programmed. For simultaneous cases, Shapiro and Bradham (2012) have recommended that the two implants either be programmed together in the switch-on session or one implant be left for the next day in the case the child does not continue to cooperate. For sequential cases, CI1 should be usually programmed before CI2 implantation and the main focus should be on the programming of CI2 during the first few sessions after
bilateral implantation. When the mapping parameters of CI2 become stable, both implants will be programmed in subsequent sessions.

The programming process of BICIs is basically similar to that of a unilateral implant. That is, connecting the speech processor to the programming computer, performing electrode impedance telemetry, selecting the stimulation mode, signal processing strategy and stimulation rate, and, finally, setting T- and C-levels of all active electrodes. However, there are some additional considerations for mapping BICIs users to maximize the benefits from bilateral hearing. These are the management of potential loudness summation and providing similar loudness at each implant (Galvin, Leigh et al. 2009, Wolfe and Schaefer 2010).

According to clinical experience, for the management of unacceptable loudness summation following activation of both implants together, an overall reduction can be applied to the C-levels of CI2. The reduction is applied for every single active electrode by a specified percentage of its DR. In order to provide similar loudness perception at each implant, subjective judgment about the loudness at each implant in live mode is important. To achieve this, clinicians balance C-levels between matched electrode pairs based on verbal feedback of older children about the loudness of sound coming from each implant. However, the result of studies on BICIs map suggests that manipulating the mapping parameters of each implant separately are not helpful for predicting a balanced levels between the two implants (Gordon et al 2012, Gordon et al 2016). Younger children are not able to provide verbal feedback or their feedback may be unreliable. Recently objective electrophysiological measures have been suggested to be a helpful method to achieve similar loudness perception at each implant for young children (Salloum, Valero et al. 2010, Gordon, Chaikof et al. 2012). Despite all of these recommendations, mapping BICIs users, specifically paediatric BICIs users, is not always straightforward and desired mapping-related outcomes are not achieved for all children with BICIs.

**Symmetrical hearing**

Although the first requirement for bilateral hearing is receiving bilateral sound input, the auditory system is structured to function optimally with symmetrical hearing in each ear. The
central auditory system applies a complicated mechanism to process sounds received by the two ears. Auditory signals received by the two ears are processed along the two auditory pathways, which do not work completely independently. The presence of neural interactions in different parts of this system allows both excitatory and inhibitory activities to occur, based on differences in the features of the signals arriving at each ear. In the case of asymmetrical sound input, the magnitude of the excitatory and inhibitory activities of the relevant auditory pathway can be altered and the sounds arriving at each ear may not be effectively integrated (Vale, Juíz et al. 2004).

A simple way to reveal the importance of symmetrical hearing in both ears is the examination of individuals with normal hearing when they are subject to symmetrical and asymmetrical sound input. In an early study (Prasher, Sainz et al. 1981) the binaural summation mechanism of individuals with normal hearing was tested under bilateral stimulation with various ILDs using the ABR test. When the ILD was zero, the greatest increase was found in the amplitude of the eV wave evoked from bilateral stimulation relative to that evoked from unilateral stimulation. When the ILD was 10dB, the amplitude of the eV wave evoked from bilateral stimulation was significantly reduced. With a greater ILD, there was no longer any difference between the amplitude of the eV wave evoked from bilateral and unilateral stimulation, indicating the lack of binaural summation. These findings are in accordance with the outcomes in the functional ability of individuals with normal hearing under symmetrical and asymmetrical hearing conditions. Compared to the unilateral hearing threshold, Pollack (1948) found a lower bilateral hearing threshold with similar sensational levels between the two ears than with different sensational levels. More importantly, the improvement in the bilateral hearing threshold decreased as the difference in the sensational levels between the two ears increased. A similar trend was reported for the speech reception threshold using word stimuli by Shaw, Newman et al. (1947). These findings for individuals with normal hearing indicate that asymmetrical hearing can compromise the advantages of bilateral hearing. However, it might be assumed that these findings are likely due to the temporary nature of the asymmetrical hearing condition in these studies, so that the conclusions cannot be extended to individuals with permanent hearing impairment. With permanent asymmetrical hearing impairment, the situation might be
different as it is possible that the individuals adapt to asymmetrical hearing. Looking at studies on individuals with hearing impairment shows that such an assumption is not correct and the advantage of symmetrical hearing over asymmetrical hearing can be extended to these individuals as well. Keys (1947) measured the magnitude of improvement in both bilateral hearing and speech reception thresholds relative to unilateral thresholds under asymmetrical and symmetrical hearing conditions for individuals with asymmetrical sensory-neural hearing loss. When stimuli were presented to the two ears at the same dB HL (hearing level), there was no significant difference between bilateral and unilateral thresholds. By contrast, there was a significant decrease in bilateral thresholds relative to unilateral thresholds following manipulation of stimuli in a way that provided similar sensational levels between the two ears. These findings reflected the advantage of symmetrical hearing over asymmetrical hearing for individuals with hearing impairment, in terms of providing additional benefits of bilateral hearing. In the study by Breakey, Davis et al. (1948), the speech reception threshold using word and sentences stimuli were measured in two conditions of unilateral and bilateral hearing for two groups: individuals with normal hearing and those with asymmetrical hearing impairment. When the stimuli were presented at similar sensational levels between the two ears for individuals with hearing impairment, their improvement in bilateral speech threshold was found to be similar to that for normal group.

The general conclusion that can be made from the above mentioned studies is that the optimal situation for bilateral hearing is provided when the two ears are stimulated similarly. Therefore, in an effort to promote bilateral hearing advantages for children with BICIs, attention should be given to providing similar stimulation to the two ears. Accurate programming of each implant independently does not necessarily result in similar perception of loudness at each ear. Although there are some recommendations about bilateral cochlear mapping in order to provide similar loudness perception, there is still no standard universal protocol in this regard. Prior to developing such a protocol, it is necessary to increase knowledge regarding mapping-related outcomes.

A few studies have focused on the mapping–related outcomes of the two implants for pediatric recipients of BICIs. The first study in this regard was performed by (Weberling, Firzt et al.
where T- and C-levels were compared between the two implants at two time points of 6 and 12 months post-operation. Participants were nine children with simultaneous BICIs received before 4.5 years of age, nine children with sequential BICIs who had undergone implantation of CI1 before 3 years of age, and nine children with sequential BICIs who had undergone implantation of CI1 after 3 years of age. For the simultaneous group and the younger-implanted sequential group, the T- and C-levels of the two implants were not different from each other at both 6 and 12 months post-operation. For the older implanted sequential group, C-levels were found to be significantly lower for CI2 relative to CI1 at both time points, while T-levels were not significantly different between the two implants. In another study, Gordon, Chaikof et al. (2012) compared T- and C-levels, and DRs of the two implants for 19 children with sequential BICIs, applying both behavioral pediatric audiometry approaches and objective tests of ECAP and ESR. The participants had BICIs experience ranging from 0.4 to 45 months. The outcomes of both behavioral and objective tests indicated significantly lower T- and C-levels, and DRs for CI2 in comparison with CI1. However, it was suggested that the children perceived similar loudness with each implant, despite the presence of differences in the mapping parameters between the two implants. The evidence for this suggestion came from the subjective experience of some of these children that had been examined in a separate study (Salloum, Valero et al. 2010). In that study, bilateral stimuli with varying ILDs were presented in order to find the bilateral stimuli which elicited a similar loudness perception at each implant. The ILDs at which children were equally likely to perceive sound as coming from either CI1 or CI2 was assumed to be the point indicating bilaterally balanced input in terms of loudness. The majority of children described sound as coming from either CI1 or CI2, with equal possibility, when more electrical current was delivered to CI1 relative to CI2. Gordon, Chaikof et al. (2012) found a significant relationship between the difference in the ECAP thresholds of the two implants of these children and the difference in the electrical current levels that elicited equal loudness perception at each implant in the study by Salloum, Valero et al. (2010). In a third study, Domville-Lewis, Santa Maria et al. (2015), compared the time required for the stabilization of the mapping parameters for each implant. The study involved a mixed group of participants aged 2 to 81 years who had received sequential BICIs. The criterion for stability was
considered as the time when each of T-levels, C-levels and DRs were within 10% of each other for three consecutive programming sessions. The outcomes of this study showed that the mean time taken for the mapping parameters to stabilize was significantly shorter for CI2 than for CI1, being 57 and 77 days respectively.
Chapter 5: Method
Participant selection:

As mentioned earlier, this retrospective study involved children who received BICIs at RVEEH Clinic in Melbourne, Australia. These children received their first implant (CI1) before 18 years of age. The RVEEH Clinic started pediatric implantation in 1985. Initially, only children with total hearing loss were eligible for CI surgery. Over time, the reasonably satisfying outcomes encouraged more families to consider CI as an option for their child with significant hearing loss. Following changes in the criteria for cochlear implantation, children with profound and even severe hearing loss could also undergo implant surgery. As a result, the number of child CI recipients increased, so that by the end of 2013, a total of 754 children had undergone CI surgery at the RVEEH Clinic. The first bilateral implantation of a child at the RVEEH Clinic was performed in 2003. At this time, only sequential cochlear implantation was offered. The first simultaneous cochlear implantation of a child was performed in 2007. By the end of 2013, a total of 248 children had received bilateral implants.

The participants of this study were selected from children who were bilaterally implanted at least two years prior to the commencement of the study. This group numbered 205 children who were bilaterally implanted at the RVEEH Clinic between September 2003 and December 2011.

The following criteria were used to select potential participants:

1. Implantation in both ears with relatively recent versions of the Nucleus system: Nucleus 24M, Nucleus 24R, Nucleus 24RE (Freedom) or Nucleus 512.
2. Full insertion of the electrode array; children with double electrode arrays were excluded since double electrode arrays were used if the cochlea was not surgically accessible for full insertion.
3. Programming data from the specified post-operation time points of initial and, 2 years and 5 years post-operation

For the 110 children who fulfilled criteria 1 to 3 above, an initial examination was made of their programming data. During this initial examination of the programming data, 17 children were excluded for the following reasons:
1. A stimulation rate of 900 pps in one implant and 250 pps in the other implant (n=1), because doubling the stimulation rate results in a decrease in T- and C- levels by 2.4 and 1.2 dB respectively (Kreft, Donaldson et al. 2004). The remaining children either had the same stimulation rate in each implant, or a difference of less than 200 pps.

2. A pulse width greater than the default of 25 µs (n=16), because an increase in the pulse width results in an increase in T- and C-levels. A higher pulse width is applied in order to provide the required loudness if current saturation is reached (Wolf and Schafer 2010).

Finally, a total number of 93 children remained in the study group.

Demographic and implant information:

Hearing loss onset, etiology and progression for the participants is shown in Table 5-1. Sixty-nine participants had congenital onset of hearing loss due to various etiologies. For 24 participants, the exact hearing loss onset was unknown. It was known that, at the time of the first implantation, all 93 children had at least a bilateral severe (4-frequency PTA ≥ 80dBHL) hearing loss, with the majority having bilateral profound (4-frequency PTA ≥ 90dBHL) hearing loss.
Table 5-1: Hearing loss onset, etiology and progression for the 93 participants.

<table>
<thead>
<tr>
<th>Etiology</th>
<th>Congenital</th>
<th></th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Progressive</td>
<td>Non-progressive</td>
<td></td>
</tr>
<tr>
<td>Meningitis</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Genetic</td>
<td>0</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>CMV*</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>LVA**</td>
<td>0</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Mondini</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Unknown</td>
<td>2</td>
<td>21</td>
<td>15</td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5</td>
<td>64</td>
<td>24</td>
</tr>
</tbody>
</table>

*Cytomegalovirus ** Large Vestibular Aqueduct

Of the 93 participants, 29 participants received simultaneous and 64 participants received sequential bilateral implants. Table 5-2 provides information about the characteristics of the simultaneous and the sequential groups in terms of the age at CI1 and at CI2 and the time between implants. In the simultaneous group, 28 participants were implanted before three years of age and one participant was implanted at 6 years of age. The distribution of participants in the sequential group based on their age at CI1 and at CI2 is illustrated in Figure 5-1.
Table 5-2: Range, mean and standard deviation in years for the age at CI1 and at CI2 and for the time between implants for the simultaneous (n=29) and sequential (n=64) groups.

<table>
<thead>
<tr>
<th>Bilateral group</th>
<th>Age at CI1 (Years)</th>
<th>Age at CI2 (Years)</th>
<th>Time between implants (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Mean ± SD*</td>
<td>Range</td>
</tr>
<tr>
<td>Simultaneous</td>
<td>0.7 - 6.1</td>
<td>1.7 ± 0.98</td>
<td>0.7 - 6.1</td>
</tr>
<tr>
<td>sequential</td>
<td>0.53 - 13.7</td>
<td>2.7 ± 2.55</td>
<td>0.86 - 19</td>
</tr>
</tbody>
</table>

*Standard Deviation

Figure 5-1: Distribution of the participants in the sequential group (n=64) based on the age at CI1 and at CI2.
The Nucleus implant system varied across participants, and between the ears for some participants in the sequential group. Considering the different current output of different Nucleus systems, which will be explained in the next section of this chapter (Conversion of data pages 65-66), the systems are categorized as follows:

- Nucleus systems with CIC3 chipset: CI24R and CI24M systems
- Nucleus systems with CIC4 chipset: CI24RE and CI512 systems

Table 5-3 provides more information regarding the combination of Nucleus systems implanted in the two ears for participants in the simultaneous and sequential groups.

### Table 5-3: Combination of Nucleus systems provided as CI1 and CI2, and the number of participants for each combination, in the simultaneous and sequential bilateral groups.

<table>
<thead>
<tr>
<th>Nucleus chipset</th>
<th>Nucleus system</th>
<th>Bilateral group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CI1</td>
<td>CI2</td>
</tr>
<tr>
<td>CIC3</td>
<td>CI24R</td>
<td>CI24R</td>
</tr>
<tr>
<td>CIC3 and CIC4</td>
<td>CI24M</td>
<td>CI24RE</td>
</tr>
<tr>
<td></td>
<td>CI24R</td>
<td>CI24RE</td>
</tr>
<tr>
<td></td>
<td>CI24R</td>
<td>CI512</td>
</tr>
<tr>
<td></td>
<td>CI24R</td>
<td>CI512</td>
</tr>
<tr>
<td>CIC4</td>
<td>CI24RE</td>
<td>CI24RE</td>
</tr>
<tr>
<td></td>
<td>CI24RE</td>
<td>CI512</td>
</tr>
<tr>
<td></td>
<td>CI512</td>
<td>CI24RE</td>
</tr>
<tr>
<td></td>
<td>CI512</td>
<td>CI512</td>
</tr>
</tbody>
</table>

The majority of the participants (n=88) were programmed using the default settings provided in the Cochlear programming software Custom Sound™. That is, the ACE strategy, the MP1+2 stimulation mode, 25 µs pulse width and 900 pps stimulation rate were used in both implants. As shown in Table 5-4, for the remaining participants (n=5), who were all in the sequential group, one or more of these settings were changed at least at one time point and in one implant.
Table 5-4: Strategy, stimulation mode, stimulation rate and number of maxima in CI1 and CI2 for individual participants whose implants were not programmed with default settings at the three time points. The participant number is indicated in brackets.

<table>
<thead>
<tr>
<th>Time point</th>
<th>Strategy</th>
<th>Stimulation mode</th>
<th>Stimulation rate</th>
<th>Number of maxima</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial</strong></td>
<td>SPEAK/ACE [81*]</td>
<td>–</td>
<td>250/250 [81]</td>
<td>6/8 [81]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>720/900 [52]</td>
<td>10/8 [73]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1200/1200 [37]</td>
<td></td>
</tr>
<tr>
<td><strong>2-year</strong></td>
<td>SPEAK/ACE [81]</td>
<td>–</td>
<td>250/250 [81]</td>
<td>6/8 [81]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>720/900 [52]</td>
<td>10/8 [73]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1200/1200 [37]</td>
<td></td>
</tr>
<tr>
<td><strong>5-year</strong></td>
<td>–</td>
<td>MP1/MP1+2 [78]</td>
<td>720/900 [52]</td>
<td>10/8 [73]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1200/1200 [37]</td>
<td></td>
</tr>
</tbody>
</table>

*Participant number 81 had no map at 5-year post-operation time point

Procedure:

The data utilized in this study were the T- and C- levels that were measured for the participants between the time of CI switch-on and late July 2013 (the beginning of the study). As discussed in Chapter 3 (Programming of the cochlear implant), T-levels were the measured electrical current level which resulted in the softest percept of sound for each electrode. C-levels were the measured electrical current levels which resulted in a comfortably loud perception of sound for each electrode. T- and C-levels were measured in Current Levels (CLs) using the Custom Sound™ during standard post-operation programming sessions held in the RVEEH Clinic.

Choice of maps:

- For each participant, one map from each implant was required to represent each of the three time points of initial, and 2-year and 5-year post-operation respectively. The map at the 2-year post-operation time point was considered to represent a stable map and the map at the 5-year post-operation time point was considered to represent a map with long-term BICIs experience. Given that not all participants had maps obtained at
exactly these three time points, the required maps were obtained from the following three time ranges:

- First 10 weeks post-operation (the initial map); the first 2 to 3 maps of CI2 were excluded as the behavioral measurement of C-levels was started from the third or fourth programming session.
- 17-26 months post-operation (the 2-year map)
- 4-5 years post-operation (the 5-year map)

All maps for each implant that fell within these three time ranges were extracted from the Custom Sound™. From within each time range, a map for CI1 and a map for CI2 were selected. The optimal case was a map for CI1 and a map for CI2 created within the same session. If this occurred more than once, the earliest session in the time range was utilized. If there was no single session in which a map for each CI was created, the following procedure was applied: the first map created within the time range for CI2 was selected and the CI1 map closest in time to the CI2 map was selected.

Some participants had less than five years of experience with bilateral implants. Consequently, 85 participants (28 participants from the simultaneous group and 57 participants from the sequential group) contributed data for the 2-year post-operation time point, whilst only 45 participants (10 participants from the simultaneous group and 35 participants from the sequential group) contributed data for the 5-year post-operation time point. It should be noted that 8 participants (1 participant from the simultaneous group and 7 participants from the sequential group) did not contribute a map for the 2-year post-operation time point but had map for the 5-year post-operation time point.

**The electrodes:**

From each of the chosen maps, T- and C-levels were extracted for three specified electrodes in each of the three electrode array regions as follows:
• Basal region: electrodes number 3, 5 and 7. According to the clinical records, the first two basal electrodes (1, 2) were more likely to be inactivated so these were not extracted.
• Medial region: electrodes number 11, 13 and 15
• Apical region: electrodes number 18, 20 and 22

If one of the above specified electrodes was inactive, T- and C-levels were extracted for an adjacent alternative electrode as shown in Table 5-5.

Table 5-5: The three specified electrodes and the alternative electrodes in each electrode array region.

<table>
<thead>
<tr>
<th>electrode array region</th>
<th>Specified electrode</th>
<th>Alternative electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal</td>
<td>3, 5, 7</td>
<td>4, 6, 8</td>
</tr>
<tr>
<td>Medial</td>
<td>11, 13, 15</td>
<td>10, 12, 14</td>
</tr>
<tr>
<td>Apical</td>
<td>18, 20, 22</td>
<td>17, 19, 21</td>
</tr>
</tbody>
</table>

If both the specified electrode and the alternative electrode were inactive, T- and C- levels were extracted for only two electrodes in that electrode array region for that time point. As shown in Table 5-6, 11 participants, had inactive specified electrodes. The final data set involved T-and C-levels for 4002 electrodes extracted from 446 maps.
Table 5-6: Inactive specified electrodes at each of the time points of initial, 2-year and 5-year post-operation in 11 participants.

<table>
<thead>
<tr>
<th>Participant number</th>
<th>Initial CI1</th>
<th>Initial CI2</th>
<th>2-year CI1</th>
<th>2-year CI2</th>
<th>5-year CI1</th>
<th>5-year CI2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>–</td>
<td>–</td>
<td>7</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>18</td>
<td>–</td>
<td>18</td>
<td>–</td>
<td>18</td>
</tr>
<tr>
<td>25</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>11</td>
<td>–</td>
<td>11</td>
</tr>
<tr>
<td>38</td>
<td>3</td>
<td>–</td>
<td>3</td>
<td>–</td>
<td>No map</td>
<td>No map</td>
</tr>
<tr>
<td>42</td>
<td>3, 5</td>
<td>–</td>
<td>3, 5</td>
<td>–</td>
<td>No map</td>
<td>No map</td>
</tr>
<tr>
<td>46</td>
<td>13</td>
<td>–</td>
<td>13</td>
<td>–</td>
<td>13</td>
<td>–</td>
</tr>
<tr>
<td>58</td>
<td>22</td>
<td>–</td>
<td>22</td>
<td>–</td>
<td>No map</td>
<td>No map</td>
</tr>
<tr>
<td>61</td>
<td>–</td>
<td>–</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>64</td>
<td>22</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>22</td>
<td>–</td>
</tr>
<tr>
<td>70</td>
<td>–</td>
<td>–</td>
<td>No map</td>
<td>22</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>99</td>
<td>22</td>
<td>–</td>
<td>22</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

*Bold font indicates that the alternative electrode was also inactive, such that T- and C-levels were extracted for only two electrodes for that electrode array region at that time point.

Conversion of data

There is a slight difference in the current output of the two categories of Nucleus systems (CIC3 and CIC4 chipset) as defined in the previous section of this chapter (Demographic and implant information page 61). Considering some participants had a different Nucleus system in each ear, T- and C-levels were converted to microampere (μA) as a consistent charge unit. To achieve this, the following formulas were used:

- For Nucleus systems with CIC3 chipset (CI24M and CI24R systems):

  \[ \text{Electrical current (μA)} = 10 \times 175^{\text{CL}/255} \]
For Nucleus systems with CIC4 chipset (CI24RE and CI512 systems):

\[
\text{Electrical current (µA)} = 17.5 \times 100^{(\text{CL}/255)}
\]

Following the conversion of T- and C-levels from CLs to µA, the DR was obtained by subtracting T-levels (µA) from C-levels (µA).

For each map of each participant, a mean (n=3) T- or C-level was calculated for each of the three electrode array regions. For participants who had an inactive specified and the adjacent alternative electrode was also inactive, the mean was an average of T- or C- levels of two electrodes.

To address the main aim of this study, a value to represent the difference between the two implants was required. To achieve this, the mean T-levels, C-levels and DRs of each electrode array region of CI2 were divided by those of CI1 to calculate a T-ratio, C-ratio and DR-ratio, respectively, for each of the three electrode array regions. For the simultaneous group, the left implant was considered as CI2 and the right implant was considered as CI1. A T-ratio, C-ratio or DR-ratio of 1 would indicate that the relevant T-levels, C-levels or DRs were the same for each implant.

Analysis

The statistical analyses were performed separately for the simultaneous and sequential groups in this study. For each group, and for each of the T-ratio, C-ratio and DR-ratio, a General Linear Model with main effects of post-operation time point (initial, 2-year, and 5-year), the electrode array region (apical, basal and medial), and the post-operation time point × the electrode array region interaction was fitted to the data. For the sequential group, the main effect of device type (a similar Nucleus system and a different Nucleus system in each ear), the post-operation time point × the device type, the electrode array region × the device type and the post-operation time point × the electrode array region × the device type interactions were also fitted to the data. Age at bilateral implantation was included as a covariate for both groups, and time between implants was also included as covariate for the sequential group. The factor of participant was not included in any of the analyses.
Chapter 6: Result
Sequential group:

There were 64 participants in the sequential group. All participants contributed data for the initial time point, while only 57 and 35 participants contributed data for 2-year and 5-year post-operation time points respectively.

T-ratio, C-ratio and DR-ratio of the two implants were separately fitted in a General Linear Model with main effects for post-operation time point (initial, 2-year and 5-year), electrode array region (apical, medial and basal) and device type (a similar Nucleus system and a different Nucleus system in each ear), and interactions of the post-operation time point × electrode array region, of the post-operation time point × the device type, of the electrode array region × the device type and of the post-operation time point × the electrode array region × the device type interactions. Age at bilateral implantation and time between implants were considered as covariates in the analysis of the sequential group.

Analysis of the T-ratio

Figure 6-1 shows the boxplot of the T-ratio of the two implants at the three electrode array regions of apical, basal and medial over three time points of initial, and 2-year and 5-year post-operation. In this boxplot, the lower and upper ends of boxes indicate the first and the third quartiles, the horizontal lines within the boxes indicate the median, the circles indicate the mean, the whiskers indicate the minimum and maximum values (excluding outliers) and the asterisks indicate the outliers. The bold dashed red line shows the T-ratio of 1, where T-levels of CI2 were similar to those of CI1.
Figure 6-1: The boxplot of the T-ratio for the sequential group at the three electrode array regions of apical, basal and medial over three time points of initial (n=64) and, 2-year (n=57) and 5-year (n=35) post-operation.

At the initial time point, the mean of the T-ratio was between 0.85 and 1.06 for each of the three electrode array regions, while the median ranged from 0.76 to 0.90. The range (excluding outliers) was 0.24 to 2.12 respectively, with 50% of T-ratios falling between 0.47 and 0.69.

At the 2-year time point, the mean of the T-ratio was between 0.94 and 1.11 for each of the three electrode array regions, while the median ranged from 0.90 to 0.97. The range (excluding outliers) was 0.31 to 2.06 respectively, with 50% of T-ratios falling between 0.34 and 0.57.

At the 5-year time point, the mean of the T-ratio was between 0.87 and 0.97 for each of the three electrode array regions, while the median ranged from 0.92 to 0.95. The range (excluding outliers) was 0.25 to 1.49 respectively, with 50% of T-ratios falling between 0.34 and 0.41.

To determine if the T-levels were different between the two implants at the initial post-operation time point, a Z-sample test was performed with null hypothesis of the initial T-ratio
being equal to 1 across the three electrode array regions. For the medial and basal electrode array regions, the initial T-ratio was equal to 1 (Z ≥ -1.04, p ≥ 0.300), indicating a similar T-levels between the two implants. For the apical region, the T-ratio was not equal to 1 (Z = -3.09, p = 0.002), indicating a significant difference in the T-levels between the two implants, with the T-levels for CI2 significantly lower than those of CI1.

The analysis of T-ratios showed that the main factor of time point was not significant [F (2, 448) = 2.33, p = 0.099]. The main factor of electrode array region was significant [F (2, 448) = 5.75, p = 0.003]. Pair-wise comparison with “Tukey” method revealed a significant difference between basal and apical electrode array regions (p = 0.004). However, there was no significant difference between medial electrode array region and either basal or apical electrode array regions (p ≥ 0.139). The mean of the T-ratio was significantly higher in basal electrode array region (between 0.97 and 1.11) in comparison with that of apical electrode array region (between 0.85 and 0.94) at all three time points. The main factor of device type was not significant [F (1, 448) = 0.21, p = 0.648].

The interaction of time point and electrode array region was not significant [F (4, 448) = 0.14, p = 0.967]. The interaction of time point and device type was significant [F (2, 448) = 4.89, p = 0.008]. However, pair-wise comparison with “Tukey” method revealed significant differences between comparisons that were not actually meaningful. For example, the result showed a significant difference between initial time point and 2-year time point for the situation of a different device type in each ear. Nevertheless, the main aim was to compare between two situations of different device type in each ear and similar device type at the same time points.

The interaction of electrode array region and device type was significant [F (2, 448) = 5.12, p = 0.006]. However, again, pair-wise comparison with “Tukey” method revealed significant differences between comparisons that were not actually meaningful. For example, the result showed significant difference between apical and basal electrode array regions for the situation of a different device type in each ear. Nevertheless, the main aim was to compare between two situations of different device type in each ear and similar device type at the same electrode
array region. The interaction of time point and electrode array region and device type was not significant \( F(4,448) = 0.16, p = 0.958 \).

In addition, there was no statistically significant relationship between age at bilateral implantation or time between implants and T-ratio \( F(1, 191) \leq 0.430.27, p \geq 0.514 \).

**Analysis of the C-ratio**

Figure 6-2 shows the boxplot of the C-ratio of the two implants at the three electrode array regions of apical, basal and medial over three time points of initial, and 2-year and 5-year post-operation. The features of the boxplot are the same as those in Figure 6-1.

![Figure 6-2: The boxplot of the C-ratio for the sequential group at the three electrode array regions of apical, basal and medial over three time points of initial (n=64) and, 2-year (n=57) and 5-year (n=35) post-operation.](image)

At the initial time point, the mean of the C-ratio was between 0.64 and 0.73 for each of the three electrode array regions, while the median ranged from 0.59 to 0.66. The range (excluding outliers) was 0.16 to 1.54, with 50% of C-ratios falling between 0.35 and 0.45.
At the 2-year time point, the mean of the C-ratio was between 0.82 and 0.89 for each of the three electrode array regions, while the median ranged from 0.82 to 0.84. The range (excluding outliers) was 0.25 to 1.58, with 50% of C-ratios falling between 0.33 and 0.39.

At the 5-year time point, the mean of the C-ratio was between 0.77 and 0.79 for each of the three electrode array regions, while the median ranged from 0.76 to 0.81. The range (excluding outliers) was 0.20 to 1.80, with 50% of C-ratios falling between 0.43 and 0.63.

To determine if the C-levels were different between the two implants at the initial post-operation time point, a Z-sample test was performed with null hypothesis of the initial C-ratio being equal to 1 across the three electrode array regions. For all the three electrode array regions, the initial C-ratio was not equal to 1 ($Z \leq -6.09$, $p < 0.001$). The result indicated a significant difference in the C-levels between the two implants, with the C-levels for CI2 significantly lower than those of CI1, in all the three electrode array regions at the initial post-operation time point.

The analysis of C-ratios showed that the main factor of time point was significant [$F (2, 448) = 14.12, p < 0.001$]. Pair-wise comparison with “Tukey” method revealed a significant difference between the initial and 2-year post-operation time points ($p < 0.001$). However, there was no significant difference between the 5-year post-operation time point and either of the initial or 2-year post-operation time points ($p \geq 0.062$). The mean of the C-ratio was significantly higher at the 2-year post-operation time point (between 0.82 and 0.89) in comparison with that of the initial time point (between 0.64 and 0.73) at all electrode array regions. The main factor of electrode array region was not significant [$F (2, 448) = 1.70, p = 0.183$]. The main factor of device type was not significant [$F (1, 448) = 0.06, p = 0.803$].

The interaction of time point and electrode array region was not significant [$F (4, 448) = 0.16, p = 0.964$]. The interaction of time point and device type was significant [$F (2, 448) = 4.20, p = 0.016$]. However, pair-wise comparison with “Tukey” method revealed significant differences between comparisons that were not actually meaningful. For example, the result showed a significant difference between initial time point for the situation of a similar device type in each ear and 2-year time point for the situation of a different device type in each ear. Nevertheless,
the main aim was to compare between two situations of different device type in each ear and similar device type at the same time points.

The interaction of electrode array region and device type was significant \[F (2, 448) = 3.96, p = 0.020\]. However, again, pair-wise comparison with “Tukey” method revealed significant differences between comparisons that were not actually meaningful. For example, the result showed significant difference between apical and basal electrode array regions for the situation of a different device type in each ear. Nevertheless, the main aim was to compare between two situations of different device type in each ear and similar device type at the same electrode array region. The interaction of time point and electrode array region and device type was not significant \[F (4, 448) = 0.07, p = 0.991\].

In addition, there was no statistically significant relationship between age at bilateral implantation and C-ratio \[F (1, 448) = 0.1, p = 0.748\]. However, there was statistically significant relationship between the time between implants and C-ratio \[F (1, 448) = 32.09, p < 0.001\].

**Analysis of the DR-ratio**

Figure 6-3 shows the boxplot of the DR-ratio of the two implants at the three electrode array regions of apical, basal and medial over three time points of initial, and 2-year and 5-year post-operation. The features of the boxplot are the same as those in Figure 6-1.
Figure 6-3: The boxplot of the DR-ratio for the sequential group at the three electrode array regions of apical, basal and medial over three time points of initial (n=64) and, 2-year (n=57) and 5-year (n=35) post-operation.

At the initial time point, the mean of the DR-ratio was between 0.51 and 0.53 for each of the three electrode array regions, while the median ranged from 0.43 to 0.46. The range (excluding outliers) was 0.08 to 1.28 respectively, with 50% of DR-ratios falling between 0.39 and 0.44.

At the 2-year time point, the mean of the DR-ratio was between 0.75 and 0.80 for each of the three electrode array regions, while the median ranged from 0.72 to 0.79. The range (excluding outliers) was 0.11 and 1.68 respectively, with 50% of DR-ratios falling between 0.42 and 0.51.

At the 5-year time point, the mean of the DR-ratio was between 0.70 and 0.73 for each of the three electrode array regions, while the median ranged from 0.65 to 0.74. The range (excluding outliers) was 0.05 and 1.61 respectively, with 50% of DR-ratios falling between 0.58 and 0.84.

To determine if the DRs were different between the two implants at the initial post-operation time point, a Z-sample test was performed with null hypothesis of the initial DR-ratio being
equal to 1 across the three electrode array regions. For all the three electrode array regions, the initial DR-ratio was not equal to 1 (Z ≤ -12.03, p < 0.001). The result indicated a significant difference in the DRs between the two implants, with the DRs for CI2 significantly lower than those of CI1, in all the three electrode array regions at the initial post-operation time point.

The analysis of DR-ratios showed that the main factor of time point was significant [F (2, 448) = 30.70, p < 0.001]. Pair-wise comparison with “Tukey” method revealed a significant difference between the initial and both 2-year and 5-year post-operation time points (p < 0.001). However, there was no significant difference between the 2-year post-operation time point and 5-year post-operation time points (p = 0.061). The mean of the DR-ratio was significantly higher at the 2-year post-operation time point (between 0.75 and 0.80) in comparison with that of the initial time point (between 0.51 and 0.53) at all electrode array regions. The mean of the DR-ratio was also significantly higher at the 5-year post-operation time point (between 0.70 and 0.73) in comparison with that of the initial time point (between 0.51 and 0.53) at all electrode array regions. The main factor of electrode array region was not significant [F (2,448) = 0.14, p = 0.870]. The main factor of device type was not significant [F (1,448) = 0.16, p = 0.691].

The interaction of time point and electrode array regions was not significant [F (4,448) = 0.09 p = 0.985]. The interaction of time point and device type was significant [F (2, 448) = 3.22, p = 0.041]. However, pair-wise comparison with “Tukey” method revealed significant differences between comparisons that were not actually meaningful. For example, the result showed a significant difference between initial time point for the situation of a similar device type in each ear and 5-year time point for the situation of a different device type in each ear. Nevertheless, the main aim was to compare between two situations of different device type in each ear and similar device type at the same time points.

The interaction of electrode array region and device type was not significant [F (2, 448) = 1.83, p = 0.161]. The interaction of time point and electrode array region and device type was not significant [F (4, 448) = 0.31 p = 0.872].
In addition, there was no statistically significant relationship between age at bilateral implantation and DR-ratio [F (1,448) = 0.06, p = 0.805]. However, there was statistically significant relationship between the time between implants and DR-ratio [F (1,457) = 34.43, p < 0.001].

**Simultaneous group:**

There were 29 participants in the simultaneous group. All participants contributed data for the initial time point, while only 28 and 10 participants contributed data for 2-year and 5-year post-operation time points respectively.

T-ratio, C-ratio and DR-ratio of the two implants were separately fitted in a general linear model with main effects for post-operation time point (initial, 2-year and 5-year) and electrode array region (apical, medial and basal) and the post-operation time point × electrode array region interaction. Only age at implantation was considered as a covariate in the analysis of the simultaneous group.

**Analysis of T-ratio**

Figure 6-4 shows the boxplot of the T-ratio of the two implants at the three electrode array regions of apical, basal and medial over three time points of initial, and 2-year and 5-year post-operation. The features of the boxplot are the same as those in Figure 6-1.
At the initial time point, the mean of the T-ratio was between 0.94 and 1.04 for each of the three electrode array regions, while the medians ranged from 0.92 to 0.95. The range (excluding outliers) was 0.48 to 1.47, with 50% of T-ratios falling between 0.79 to—and 1.13.

At the 2-year time point, the mean of the T-ratio was between 0.94 and 0.97 for each of the three electrode array regions, while the medians ranged from 0.90 to 0.95. The range (excluding outliers) was 0.53 to 1.35, with 50% of T-ratios falling between 0.80 and 1.12.

At the 5-year time point, the mean of the T-ratio was between 1.02 and 1.06 for each of the three electrode array regions, while the medians ranged from 0.93 to 1.05. The range (excluding outliers) was 0.52 to 1.54, with 50% of T-ratios falling between 0.80 and 1.24.

To determine if the T-levels were different between the two implants at the initial post-operation time point, a Z-sample test was performed with null hypothesis of the initial T-ratio...
being equal to 1 across the three electrode array regions. For all the three electrode array regions, the initial T-ratio was equal to 1 \((Z \leq 0.62, p \geq 0.185)\). The result indicated a similar T-levels between the two implants in all the three electrode array regions at the initial post-operation time point.

For T-ratio, the main factors of time point and electrode array region were not significant \([F(2, 191) \leq 0.68, p \geq 0.510]\) and the interaction of time point and electrode array region was not significant \([F(4, 191) = 0.11, p = 0.978]\). In addition, there was no statistically significant relationship between age at implantation and T-ratio \([F(1, 191) = 0.09, p = 0.762]\).

**Analysis of C-ratio:**

Figure 6-5 shows the boxplot of the C-ratio of the two implants at the three electrode array regions of apical, basal and medial over three time points of initial, and 2-year and 5-year post-operation. The features of the boxplot are the same as those in Figure6-1.

![Boxplot of C-ratio](image)

**Figure 6-5:** The boxplot of the C-ratio for the simultaneous group at the three electrode array regions of apical, basal and medial over three time points of initial \((n=29)\) and, 2-year \((n=28)\) and 5-year \((n=10)\) post-operation.
At the initial time point, the mean of the C-ratio was between 0.96 and 1.02 for each of the three electrode array regions, while the medians ranged from 0.95 to 0.99. The range (excluding outliers) was 0.57 to 1.34, with 50% of C-ratios falling between 0.81 and 1.12.

At the 2-year time point, the mean of the C-ratio was between 0.96 and 0.98 for each of the three electrode array regions, while the medians ranged from 0.93 to 0.98. The range (excluding outliers) was 0.52 to 1.40, with 50% of C-ratios falling between 0.82 and 1.15.

At the 5-year time point, the mean of the C-ratio was between 0.97 and 1.03 for each of the three electrode array regions, while the medians ranged from 0.89 to 1.04. The range (excluding outliers) was 0.52 to 1.51, with 50% of C-ratios falling between 0.75 and 1.19.

To determine if the C-levels were different between the two implants at the initial post-operation time point, a Z-sample test was performed with null hypothesis of the initial C-ratio being equal to 1 across the three electrode array regions. For all the three electrode array regions, the initial T-ratio was equal to 1 (Z ≤ 0.47, p ≥ 0.327). The result indicated a similar C-levels between the two implants in all the three electrode array regions at the initial post-operation time point.

The statistical analysis of C-ratio revealed the results like those for T-ratio in the simultaneous group. For C-ratio, the main factors of time point and electrode array region were not significant [F (2, 191) ≤ 0.47, p ≥ 0.628] and the interaction of time point and electrode array region was not significant [F (4, 191) = 0.08, p = 0.989]. In addition, there was no statistically significant relationship between age at implantation and of C-ratio [F (1, 191) = 0.13, p = 0.724].

**Analysis of DR-ratio**

Figure 6-6 shows the boxplot of the DR-ratio of the two implants at the three electrode array regions of apical, basal and medial over three time points of initial, and 2-year and 5-year post-operation. The features of the boxplot are the same as those in Figure 6-1.
Figure 6-6: The boxplot of the DR-ratio for the simultaneous group at the three electrode array regions of apical, basal and medial over three time points of initial (n=29) and, 2-year (n=28) and 5-year (n=10) post-operation.

At the initial time point, the mean of the DR-ratio was between 1.01 and 1.04 for each of the three electrode array regions, while the medians ranged from 0.94 to 1.04. The range (excluding outliers) was 0.47 to 1.63, with 50% of DR-ratios falling between 0.79 and 1.30.

At the 2-year time point, the mean of the DR-ratio was between 1 and 1.02 for each of the three electrode array regions, while the medians ranged from 0.89 to 0.97. The range (excluding outliers) was 0.51 to 1.61, with 50% of DR-ratios falling between 0.78 and 1.18.
At the 5-year time point, the mean of the DR-ratio was between 0.93 and 1.07 for each of the three electrode array regions, while the medians ranged from 0.90 to 0.99. The range (excluding outliers) was 0.55 to 1.48, with 50% of DR-ratios falling between 0.76 and 1.22.

To determine if the DRs were different between the two implants at the initial post-operation time point, a Z-sample test was performed with null hypothesis of the initial DR-ratio being equal to 1 across the three electrode array regions. For all the three electrode array regions, the initial DR-ratio was equal to 1 ($Z \geq 0.53$, $p \geq 0.485$). The result indicated a similar DRs between the two implants in all the three electrode array regions at the initial post-operation time point.

For DR-ratio, the main factors of time point and electrode array region were not significant [$F (2,191) \leq 0.43$, $p \geq 0.654$] and the interaction between time point and electrode array region was not significant [$F (4, 191) = 0.23$, $p = 0.924$]. In addition, there was no statistically significant relationship between age at implantation and DR-ratio [$F (1, 191) = 0$, $p = 0.994$].
Chapter 7: Discussion
The present study documented the mapping-related outcomes of a large number of children with BICIs for up to 5 years post-operation. The main focus was on the differences in the mapping parameters between the two implants for a simultaneous group and a sequential group. In an attempt to identify the influential factors, the relationship between the degree of difference between the implants and the demographic characteristics of age at bilateral implantation and time between implants was examined.

**Sequential group:**

**Difference in the T-levels:**

For the sequential group, the T-levels did not generally differ significantly between the two implants at the initial post-operation time point. The mean of the T-ratio was found to be close to 1, where the T-ratio was defined as the T-levels for CI2 divided by those for CI1. However, there was a significant difference between the two implants at the apical electrode array region, with a T-ratio of 0.85, indicating lower T-levels for CI2 relative to CI1. This is the first study in which the difference in the T-levels between the two implants was examined in the early post-operation period. In the present study, the map chosen for comparison at the initial post-operation time point was from a programming session within the first 10 weeks after implantation of CI2. This is a very short time after implantation of CI2 in comparison to the two previous studies by Weberling, Firzt et al. (2011) and by Gordon, Chaikof et al. (2012), in which participants had more experience of hearing with BICIs. Children in the study by Weberling, Firzt et al. (2011) had BICIs experience as long as 6 months at the time that the first comparison was performed between the T-levels of the two implants. Although the children in the study by Gordon, Chaikof et al. (2012) were heterogeneous in terms of BICIs experience, only 3 out of 19 children had less than 4 months of hearing experience with BICIs. The remaining children in that study were using BICIs for a longer time (4.8 to 45.5 months) when the T-levels between the two implants were compared.

At a superficial level, the result of no significant difference in the T-levels between the two implants at the initial time point may seem surprising, given that previous studies of children
with a unilateral CI have indicated significant changes in the T-levels over time post-operation (Hughes, Vander Werff et al. 2001, Gordon, Papsin et al. 2004b, Henkin, Kaplan-Neeman et al. 2006). At the time of CI2 switch-on for children with sequential BICIs, it might be thought that the T-levels for CI2 may still undergo some changes, raising expectation that the T-levels for CI2 should be different from those for CI1 at the initial time point. The fact that such an expectation was not met by the present result can be explained by considering the factors that may affect the T-levels of children. Studies examining the T-levels of children with a unilateral CI have indicated that the reliability of children’s responses to the electrical signal can affect the T-levels set by clinicians. Two factors may influence the reliability of children’s response to the electrical signal: experience with electrical hearing and age.

Increasing experience with electrical hearing over time has been shown to increase children’s awareness of sound and also to change clinician’s approach for setting T-levels. Gordon, Papsin et al. (2004b) showed that behaviourally set T-levels of 88 children (from infants to school-age) using the Nucleus CI system decreased over one year post-operation. However, no significant changes were found in the objective ECAP and EABR thresholds during that time period. Therefore, reduction in the T-levels was attributed to the increase in children’s awareness of sound over time through experience of hearing via their CI. The authors explained that, initially post-operation, the concept of sound was new for many of these children and, consequently, they could not reliably respond to the electrical signals at the levels which were their actual thresholds. With hearing experience through the CI over time, the children’s awareness of sound improved and they could provide reliable responses to the softer signals elicited by lower levels of electrical stimulation. In the study by Henkin, Kaplan-Neeman et al. (2006), the significant increase in the T-levels of children using the Clarion CI system was also shown. The authors suggested it was not a true change and more likely to be due to clinicians specifically setting the initial T-levels at lower levels. Clinicians applied that conservative approach as they were not sure whether any change in the child’s behavior was a real response to perceived sound or it was a chance response. However, with hearing experience through the CI over time, children gradually became accustomed to the electrical signals. Consequently, it was highly possible that children could provide more reliable responses, so that clinicians no longer
needed to specifically set the T-levels at lower levels. Children’s age can also affect the setting of T-levels by clinicians. With increasing age, children have better spoken language ability and concentration skills, so that their responses become more reliable. As a result, clinicians are more convinced that children’s responses represent true thresholds and, therefore, they do not set T-levels conservatively at lower levels.

In comparison to children with a unilateral CI, the situation differs for children with a second sequential CI in the early time post-operation. By definition, children receiving sequential BICIs have heard the electrical signal via CI1 for a period of time and participated in several programming session for that CI at the time of receiving CI2. In addition, the children are older at the time of CI2, and may have some spoken language and a greater ability to attend to, and concentrate on, the task. Therefore, it is possible that the children with sequential BICIs were able to provide clinicians with reliable responses from the switch-on session for CI2 and that the T-levels were set at their true thresholds.

It is interesting to note that some previous studies which have identified changes in the T-levels have suggested that the changes may be due to some anatomical and physiological changes post-operation (Hughes, Vander Werff et al. 2001, Henkin, Kaplan-Neeman et al. 2006). It has been reported that tissue and bone growth possibly occur within the cochlea post-operation. Such changes within the cochlea can change electrical current pathways and the number of excitable elements, resulting in an increase in the T-levels over time post-operation. However, the present result indicating no changes in the T-levels for CI2 post-operation is an interesting contrast to those previous studies. If anatomical and physiological changes affects the T-levels for unilateral CI users then they would also be expected to affect the T-levels for CI2. The stability of the T-levels for CI2 post-operation in the present study may show that the anatomical and physiological changes do not have significant effect on the T-levels. It is also possible that there is a variation across individuals in terms of intra-operative trauma or anatomical status and that these cause a difference between the findings of different studies.

The degree of difference in the T-levels over time post-operation did not change significantly for the present group. A ratio of 1 would indicate that the T-levels were the same for both
implants. The mean ratio remained around 0.9 even at 5 years post-operation, indicating similar T-levels between the two implants after a long period of experience of hearing with BICls. In line with the present study, Weberling, Firzt et al. (2011) also reported no difference in T-levels between the two implants for two groups of younger and older children at 6 and 12 months post-operation. In contrast to the present study, Gordon, Chaikof et al. (2012) found significantly lower T-levels for CI2 relative to CI1 for their group of children, even though the majority had more than 6 months experience of hearing with BICIs, and some of them had more than 3.5 years. This result was also reflected in the ECAP thresholds evoked by the two implants. The small number of 19 participants in the latter study may be the reason for the reported result that was different from that of the present study.

In order to investigate why the T-ratio did not change over time in the present study, further analyses were carried out to examine the change in the T-levels of each implant over time. For the T-levels of each implant, a one way ANOVA with factor of post-operation time point was performed. These analyses indicated no significant change in the T-levels for CI1 \[ F (2,467) = 0.86, P=0.424 \] or CI2 \[ F (2,467) = 2.22, P=0.109 \] over time. In order to find out that no significant change of the T-levels over time was real for CI1 and CI2, a repeated measures analysis was performed for a subgroup of 28 children who had data at all the three time points of initial, 2 year, and 5 year post-operation. The results showed no significant change in the T-levels for CI1 \[ F (2,249) = 0.54, P=0.581 \] or CI2 \[ F (2,249) = 0.18, P=0.834 \] again. As per the studies literature that reviewed before, changes for the T-levels were expected in CI1, however, the time for that had passed for many of the children in the present sequential group. The support for this suggestion is the finding of the previous studies on children with a unilateral CI, which indicate no significant changes in T-levels after one year post-operation. Two studies by Henkin, Kaplan-Neeman et al. (2006) and Hughes, Vander Werff et al. (2001) examined the T-levels of children up to 18 and 24 months post-operation respectively. Henkin, Kaplan-Neeman et al. (2006) reported no significant changes in behavioural T-levels after 3 months post-operation, and Hough et al 2001 reported no significant changes after one year post-operation. However, in the latter study, the objective ECAP thresholds that were usually used to predict T-levels were found to stabilize at an earlier time point (3 to 8 months post-operation). According
to those findings, if CI2 is implanted a maximum of 8 to 12 months after CI1, it is highly likely that the T-levels for CI1 are stabilized before implantation of CI2. In the present sequential group, more than two thirds of the children (n = 45) received their CI2 more than 8 months after CI1, and more than half of the children (n = 38) received their CI2 more than one year after CI1. This can indicate that, for the majority of children in the present sequential group, the major changes in the T-levels for CI1 have occurred prior to the implantation of CI2.

The stability of the T-levels over time found for CI2 of the present sequential group may result from relatively accurate measurement of the T-levels for CI2 at the initial time point. As discussed before, given the age and previous experience of electrical hearing, the T-levels for CI2 were set accurately at the initial time point.

It is worth noting that, for small proportion of children there was a significant difference in the T-levels between the two implants, with the T-levels for CI2 being higher than those for CI1. More details regarding this small group of children are provided in the clinical implication section of this chapter (pages 110 -111).

**Difference in the C-levels**

For the sequential group, the C-levels of the two implants were significantly different at the initial post-operation time point. A ratio of 1 would indicate similar C-levels in the two implants. The mean of the C-ratio was around 0.7, indicating that the C-levels for CI2 were significantly lower than those for CI1 at this time. As with the T-levels, this is the first study in which the difference in the C-levels between the two implants was examined in the early post-operation period. In the present study, the map chosen for comparison at the initial post-operation time point was from a programming session within the first 10 weeks after the implantation of CI2. This is a very short time after the implantation of CI2 in comparison to the two previous studies by Weberling, Firzt et al. (2011) and by Gordon, Chaikof et al. (2012), in which participants had more experience of hearing with BICIs, as explained in the previous section of this chapter.

Different C-levels between the two implants may be assumed to provide children with a different perception of loudness using each implant. However, there is evidence from the
subjective experience of children with sequential BICls that indicates that the perception of loudness with each implant can be similar. Salloum, Valero et al. (2010) performed a study to determine the electrical levels that provided a balanced loudness percept via each implant for 19 children with a mean age of 2.1 years at CI1 and 4.9 years at CI2. The children’s mean age at testing was 9.1 years, so that experience of hearing with BICls ranged from 0.5 to 4.6 years. During testing, electrical signals were delivered bilaterally with different ILDs of 0, ± 10 and ± 20 CLs, where + indicated higher CLs to CI2 and - indicated higher CLs to CI1. The children were asked to describe whether the electrical signal was perceived as coming from CI1, CI2, both CI1 and CI2, or the middle of the head. The ILDs at which the child described sound as perceived from both CI1 and CI2 was assumed to elicit a balanced loudness perception at each implant. For the majority of children, the perception of sound as being from both CI1 and CI2 occurred when a higher electrical signal was delivered to CI1 relative to CI2. However, with similar levels of electrical stimulations delivered to both CI1 and CI2, the children often perceived sound as coming from CI2. Loudness is a percept that requires neural processing in the central auditory system. When a lower electrical signal delivered to CI2 is perceived as being as loud as a higher electrical signal delivered to CI1, it may reflect different loudness growth functions in the central auditory pathways related to each CI. The possibility of different loudness growth functions in the central auditory pathways related to each CI can be supported by the findings of the objective tests for these children. In an attempt to record similar amplitude in eV wave of EABRs evoked by the two implants of the children, Salloum, Valero et al. (2010) found that a lower electrical signal was required to be delivered to CI2 relative to CI1. Importantly, the difference in the electrical levels evoking similar amplitude in eV wave of EABRs was significantly related to the difference in the electrical signals required to elicit a balanced loudness perception at each implant of the children. However, when similar electrical signals were delivered to the two implants of the children, the eV wave evoked by CI2 had a larger amplitude relative to that evoked by CI1. When some of these children participated in a later study by Gordon, Chaikof et al. (2012), ESR thresholds recorded for each implant showed lower thresholds for CI2 compared with CI1. These objective outcomes may reflect different loudness
processing in the central auditory pathways related to each of CI1 and CI2, with rapid loudness growth in response to changes in the sound level coming from CI2 side.

Different loudness processing in the central auditory pathway related to each CI may be a result of the differences in the development of these pathways. At the time of the implantation of CI2, the central auditory pathway related to CI1 has already achieved some degree of development in response to electrical stimulation provided by CI1. By contrast, the central auditory pathway related to CI2 has only started to receive direct stimulation from the CI2 ear, and will require time to reach a developmental level comparable to that of CI1. The initial developmental delay in the central auditory pathway related to CI2 compared to that of CI1 is supported by neurophysiological findings for children with sequential BICIs. Gordon, Valero et al. (2007a) evaluated the brain stem responses evoked by both implants for younger and older children who had recently received CI2. The latency of responses evoked by CI2 was prolonged relative to those evoked by CI1. In addition, the latency of responses evoked by CI2 was found to be similar to the latency of the brain stem responses evoked by stimulation of the non-implanted ear of age-matched children with a unilateral CI. The latter finding of that study indicated the lack of development in the central auditory pathway related to CI2 immediately after implantation of CI2. Gordon, Jiwani et al. (2011) also reported some differences between the responses evoked by CI1 and CI2 at the cortical level of the central auditory pathway for the same group of children. The cortical differences were observed in both latency and waveforms, whereby the responses evoked by CI2 had multiple peaks and prolonged latency relative to those evoked by CI1. Delayed responses evoked from different levels of the central auditory pathway related to CI2 may represent increased neural conduction time and decreased neural synchrony. These may be the possible reasons that children do not select C-levels for CI2 as high as those they had acceptable via CI1.

After some experience of hearing with BICIs by the present group of children, the degree of difference in the C-levels between the two implants was significantly reduced. The significant changes occurred between the initial and the 2-year post-operation time points, with the mean of the C-ratio increasing from around 0.6 to around 0.8. To determine if the C-levels were different between the two implants at the 2-year post-operation time point, a Z-sample test
was performed with null hypothesis of the 2-year C-ratio being equal to 1. The results indicated a significant difference in the C-levels between the two implants at the 2-year post-operation time point ($Z = -5.96, P < 0.001$). Between the 2-year and the 5-year post-operation time points, there was no significant change in the degree of difference between the two implants. Previous studies of children with sequential BICIs also reported a significant difference in the C-levels between the two implants after some experience of hearing with BICIs. In the study by Weberling, Firzt et al. (2011) the details of which were covered earlier in this chapter, the older group of children, who received both implants after three years old, still had significantly lower C-levels for CI2 compared with CI1 after 12 months of BICIs use. A similar result was reported by Gordon, Chaikof et al. (2012) for a group in which the majority of participants used BICIs for a longer time between 9 and 45 months. This result was also reflected in the ESR thresholds evoked from the two implants of these children in Gordon’s study.

In order to investigate why the C-ratio increased over time in the present study, further analyses were carried out to examine the change in C-levels of each implant over time. For the C-levels of each implant, a one way ANOVA with the main factor of post-operation time point was performed. The analyses indicated a significant increase in the C-levels for CI2 [$F (2,467) = 13.92, P < 0.001$]. Tukey pair-wise comparisons revealed a significant difference between the initial and each of the 2-year and the 5-year post-operation time points ($P \leq 0.001$). However, there was no significant difference between the 2-year and the 5-year post-operation time points ($P \geq 0.716$). In contrast, the C-levels for CI1 did not change significantly over the same time period after implantation of CI2 [$F (2,467) = 1.95, P = 0.144$]. The increased C-levels for CI2, the stable C-levels for CI1, and the decrease in the difference between the two implants is in line with the neurophysiological outcomes of children with sequential BICIs. Gordon, Valero et al. (2007b) recorded the brain stem responses evoked by each implant of children who had received BICIs. The initial difference between the latency of responses evoked from each implant gradually decreased over time. This decrease in the difference between the two implants over time was found to be due to a significant decrease in the latencies of responses evoked by CI2 and almost no change in those evoked by CI1. Sharma, Gilley et al. (2007) showed a similar trend at the cortical level of the central auditory pathways related to the two
implants. As children gained experience of hearing with BICls, the initial delayed latency of P1 wave evoked by CI2 became closer to the latency of P1 evoked by CI1 and the mismatch between the two implants decreased. When children receive a second CI, it seems there is more rapid development in the post-operative period in the central auditory pathway related to CI2 than in the pathway related to CI1. As a result children may select higher levels for CI2, so that the C-levels for CI2 become closer to those for CI1 over time. This is in agreement with the findings for children with a unilateral CI, as their C-levels have also been reported to increase following CI experience. Henkin, Kaplan-Neeman et al. (2006) reported a mean increase of 120 CLs for C-levels by three months post-operation for children with the Clarion CI system. Hughes, Vander Werff et al. (2001) reported a mean increase of 32.6 CLs and Gordon, Papsin et al. (2004b) reported a mean increase of 14 CLs for C-levels by one year post-operation for children with the Nucleus CI24M CI system. Despite variation in the magnitude of changes over time, all of these studies attributed the increase in C-levels partly to an increase in the acceptability of higher levels of stimulation for children with CI experience. Gordon, Papsin et al. (2004b) showed that an increasing trend of C-levels over time was reflected in the objective ESR thresholds of children. These authors suggested that higher levels of stimulation are selected by the children due to an improvement in the way that the central auditory system coded increases in the electrical signals. However, for children with a unilateral CI, initial underestimation of the C-levels by clinicians was also suggested to be a factor contributing to an increase in the C-levels over time. In the study by Hughes, Vander Werff et al. (2001) referred to above, the increase in the C-levels over time was partly attributed to the setting of initial C-levels at low levels of 10 to 30 units above measured T-levels. Gordon, Papsin et al. (2004b) also related the increase in the C-levels over time partially to the setting of small, fixed DRs above measured T-levels during initial programming sessions. The clinical rationale for such methods is that children have limited experience with their CI and are unfamiliar with the concept of judging loudness. Consequently, due to a lack of confidence in children’s responses, clinicians usually underestimated initial C-levels to ensure comfort and ease of acclimatization to the electrical signal. This reduced the risk of overstimulation, which might lead to rejection of the CI. For the present sequential group, initial underestimation is less likely to be a reason for
increases in the C-levels for CI2 over time for two reasons. Firstly, children with sequential BIC have experience of hearing with CI1 and have participated in several programming sessions by the time of implantation of CI2. It is highly possible that these children are already familiar with the concept of loudness, and reporting comfort in loudness, by the time of the CI2 switch-on session. In this situation, children are likely to be able to provide reliable responses and clinicians are likely to set C-levels at the actual levels.

Secondly, during the extraction of maps for the initial time point of the present study, the first two to three maps produced for CI2 were excluded as it was evident that C-levels were set through adding a fixed DRs above measured T-levels. Instead, the first map for CI2 in which C-levels were set based on behavioral measurement was extracted for the initial post-operation time point.

In summary, use of two implants by children with sequential BICIs resulted in a significant decrease in the difference in the C-levels between the two implants by the 2-year post-operation time point. However, a difference between the two implants remained. The decrease in the difference between the two implants was due to an increase in the C-levels for CI2 and no change in the C-levels for CI1. It seems receiving auditory stimulation from CI2 promoted development in the related central auditory pathway and enabled children to accept higher levels of stimulation, although the pathway did not reach a developmental level comparable to that of the pathway related to CI1.

The lack of significant changes in the C-levels for CI1 after bilateral implantation is likely due to major changes in the C-levels for CI1 having already occurred by the time of CI2 implantation. This can be supported by the findings for children with a unilateral CI. According to those findings, if the time between the two implants exceeds 12 months, it is highly possible that the C-levels for CI1 are stable at the time of implantation of CI2 and undergo no changes thereafter.

In the present sequential group, time between the two implants was one year for more than half of the children (n = 38). The lack of any significant change in the difference in the C-levels between the two implants from the 2-year to the 5-year post-operation time points is possibly due to stabilization of the C-levels for CI2 by 2-year post-operation.
As with T-levels, there was some variation in results across the group. In contrast to the typical pattern of lower C-levels for CI2 than for CI1, a small proportion of children had higher C-levels for CI2 or similar C-levels between the two implants. More details regarding this small group of children have been explained in the clinical implication section of this chapter (pages 110-111).

Differences in the DRs:

For the sequential group in the present study, there was a significant difference between the DRs of the two implants at the initial post-operation time point. A ratio of 1 would indicate similar DRs for the two implants. The mean of the DR-ratio was around 0.5, indicating that the DRs for CI2 were significantly narrower than those for CI1 at this time. The magnitude of the DR directly depends on the T- and C-levels. Since there was no significant difference in the T-levels between the two implants, the narrower DR for CI2 relative to CI1 was a result of the lower C-levels for CI2 at this time point.

There was a significant decrease in the difference between the two implants from the initial to the 2 year time points, with the mean of the DR-ratio increasing from 0.5 to 0.8.

To determine if the DRs were different between the two implants at the 2-year post-operation time point, a Z-sample test with null hypothesis of the 2-year DR-ratio equal to 1 was performed. The results indicated a significant difference in the C-levels between the two implants at the 2-year post-operation time point ($Z = -7.66, P < 0.001$).

There was no significant change in the degree of difference in the DRs between the two implants from the 2-year to the 5-year post-operation time points. Consistent with these results, significantly narrower DRs were found for CI2 than CI1 for children with sequential BICIs in the study by Gordon et al (2012) which was described earlier in this chapter.

In order to find out why the DR-ratio increased over time, further analyses were carried out to examine the change in the DR of each implant over time. For the DRs of each implant, a one way ANOVA with the main factor of post-operation time point was performed. The analyses indicated a significant increase in the DRs for CI2 [$F (2,457) = 29.60, P < 0.001$]. Pair-wise comparison with “Tukey” method revealed a significant difference between the initial and each of the 2-year and the 5-year post-operation time points ($P \leq 0.001$). However, there was no
significant difference between the 2-year and 5-year post-operation time points (P≥ 0.916). In contrast, the DRs for CI1 did not change significantly over the same time period after implantation of CI2 \( F (2,457) = 2.45, P = 0.08 \). The widening of the DR for CI2 by 2 years post-operation was due to the significant increase in the C-levels for CI2 from the initial to 2-year time point, and no change in the T-levels for CI2 during that time period. The lack of significant changes in the DR for CI1 after implantation of CI2 was due to the lack of changes in the T- and C-levels for CI1 during that time period. Since the C-levels for CI2 usually showed no further increase after the 2 years post-operation, no change is expected for the DR for CI2 after this time. So, the difference in the DRs between the two implants was expected to remain stable from the 2-year to 5-year post-operation time point.

Despite the increase in the DRs for CI2, and no changes in the DRs for CI1 over time, the DR for CI2 did not reach that for CI1, even at the 5-year post-operation time point for the present sequential group. This was consistent with the findings of the study by Gordon, Chaikof et al. (2012), who reported narrower DRs for CI2 than CI1 after a long period of BICI use by children. Although, in that study, the time at which the DRs of the two implants were compared was different across participants, the majority of children had used BICIs for more than one year. Among those children, there were some who had used their BICIs for as long as 3 to 4 years, but still had narrower DRs for CI2 than CI1.

**The effect of the electrode array region:**

For C-levels and DRs, the difference between the two implants did not vary significantly across the three apical, medial and basal electrode array regions. However, the difference in the T-levels between the two implants was significantly smaller in the basal region than in the apical region. Variation in mapping-related outcomes across the electrode array regions have been reported in previous studies involving users of unilateral CIs. When Henkin, Kaplan-Neeman et al. (2003) examined T- and C-levels of children using a unilateral Clarion CI system, significantly lower T- and C-levels were found for the apical region (electrodes 15-21) relative to the basal region (electrodes 1-7). Vargas, Sainz et al. (2013) reported that, T- and C-levels for the most apical electrodes were 41% and 22% lower, respectively, than those of the most basal
electrodes for a mixed group of children and adults using a unilateral COMBI 40+ CI system. Consistent with lower apical T- and C-levels, Gordon, Papsin et al. (2004b) showed that ECAP and EABR thresholds were also lower for electrodes in the apical region for a big group of children using unilateral Nucleus CI system. A difference between the apical and basal regions has also been found for individuals with BICIS. Domville-Lewis, Santa Maria et al. (2015) reported higher variability in T- and C-levels, and DRs of the basal region relative to those of the apical region for both CI1 and CI2 for a mixed group of children and adults using Nucleus CI system on both sides. Additionally, the time take for the mapping parameters of both implants to stabilize was shorter for the apical region compared to the basal region. For children with BICIs, binaural processing can also be affected by electrode array region. (Gordon, Valero et al. 2007a) compared the binaural difference responses evoked by apical and basal electrodes for children with simultaneous and with sequential BICIs using Nucleus CI system on both sides. To calculate the binaural difference response, the bilaterally evoked brainstem response was subtracted from the sum of the brainstem responses evoked by the right plus the left implant. The outcome showed a more detectable binaural difference response evoked by electrodes in the apical region compared to the basal region. All of these superior outcomes in the apical region, in comparison to the basal region, are attributed to possibly higher rates of neural survival rate in the apical region (Kawano, Seldon et al. 1998).

The comparison that was performed across the three electrode array regions in the present study differed from that in the above mentioned unilateral studies: the array regions were compared in terms of the difference in the mapping parameters between the two implants in the present study. Thus, differences across the electrode array regions could be expected if the rate of neural survival differed between the two ears in one region relative to the other regions on the basilar membrane. For example, if there was difference in the rate of neural survival between the two ears in just apical region of the basilar membrane, it would be expected that the difference in the mapping parameters between the two implants significantly differ in the apical electrode array region relative to the other medial and basal electrode array regions. The lack of a significant difference across the electrode array regions may be due to similar neural
survival rate in the two ears in the three apical, medial and basal regions of the basilar membrane.

The effect of device type

For T-and C-levels, and DRs, the difference between the two implants was not significantly affected by the difference in the type of Nucleus CI systems implanted on the two ears for the present sequential group. In other words, children with similar Nucleus systems on both sides did not differ from those with different Nucleus systems in terms of difference in T-and C-levels, and DRs between the two implants. With sequential BICIs, it is possible that children receive a more recent types of a CI system on the secondary-implanted ear relative to the first-implanted one, especially when there is a considerable time interval between two implantations. Different types of a CI system vary in terms of the electrode array design, where developmental changes have been performed on the more recent versions relative to the older ones over time. Some of these changes include replacement of the straight electrode array by precurved perimodiolar one, using half band electrodes instead of full band ones and adding some features in order to facilitate the insertion of the array and reduce the insertion force during surgery (Moctezuma and Tu 2011). Two main aims have been attempted to be achieved following those changes. The first aim is to place the stimulating electrodes closer to the exciting auditory neural fibers. The second aim is to decrease the magnitude and likelihood of the additional damage to the remaining auditory neural survival. As a result, it is expected that the mapping parameters be lower with more recent types of a CI system compared to the older versions. If so, children who have different types of a CI system in each ear should have higher difference in the mapping parameters between the two implants relative to those with similar CI system in each ear. However, it was not the case in the present study in which children were implanted with the Nucleus system. In order to find out the reason, it may be helpful to compare the outcomes of the studies on Nucleus system users.

With Nucleus system, there are two different prospective in this regard. On the one hand, the outcomes of some studies indicated the difference between the mapping parameters for different types of Nucleus system. Saunders, Cohen et al. (2002) reported a significantly lower
T- and C-levels for adults using Nucleus system with precurved perimodiolar electrode array relative to those using Nucleus system with straight electrode array. For children CI users, Gordin, Papsin et al. (2009) showed lower T-levels and objective ECAP thresholds, and higher ESR thresholds for both Nucleus 24R and Freedom (having precurved perimodiolar electrode array) users relative to Nucleus 24M (having straight electrode array) users. The main explained possibilities for their finding were the facts that the straight electrode array was usually placed close to the lateral wall of the modiolus relative to the precurved one that was placed close to the medial wall of the modiolus. Consequently, the distance between the stimulating electrodes and the exciting auditory neural fibers was shorter with precurved perimodiolar electrode array and less electrical current was required for neural excitation. Another explained reason was related to the fact that with straight electrode array, the insertion force was directly toward the inner wall of the cochlea. Therefore, during surgery, additional damage to the auditory neural survival was more likely with straight electrode array relative to the precurved perimodiolar ones. Comparing between different Nucleus systems with precurved perimodiolar electrode array, the outcomes of some studies also confirmed the advantage of Freedom to older version of 24R, with lower T-levels and higher C-levels for Freedom (Walravens, Mawman et al. 2006, Gordin, Papsin et al. 2009). The advantage of Freedom system was attributed to benefit from advanced off-stylet technique used during surgery. This technique resulted in positioning of the stimulating electrodes closer to the modiolus, decreasing the amount of force for insertion and reducing the possibility of insertion to the scala vestibuli.

Despite all these findings, on the other hand, there are other studies reporting no difference between the mapping parameters for different types of Nucleus systems. Polak, Hodges et al. (2005), compared behavioral T-and C-levels as well as objective ECAP and ESR thresholds for adults with CI24M and those with CI24R. The outcomes indicated almost similar behavioral and also objective measures of the mapping parameters between the two groups. In line with that, Hughes and Abbas (2006) did not find any significant difference between the behavioral T-levels of adults using CI24M and their counterparts using CI24R. Some possibilities have been considered for the lack of the effect of device type on the mapping parameters in those studies. The main possibility was that, in addition to the difference in the distance from the modiolus,
Nucleus 24M and 24R systems differed in terms of the shape of their electrodes. Nucleus 24M had full-band electrodes causing broader electrical field in comparison to Nucleus 24R, which had half-band electrodes causing narrower stimulation pattern. With broader electrical field, higher number of spiral ganglion cells could be recruited, and consequently, lower current levels were required to reach T- and C-levels. In other words, the broader electrical field occurred by Nucleus 24M may compensated its far distance from the modiolus, resulting in T- and C-levels similar to those achieved by Nucleus 24R system. The other possibility was that the precurved perimodiolar electrode array of CI24R system was not always placed at designed optimal perimodiolar position, where it may be placed rather far at intermediate position. Such possibilities can be the likely reasons for why, in the present study, children with different types of Nucleus systems in each ear did not differ from those with similar types of Nucleus systems. 11 children in the present group had received CI24M on CI1 side and Freedom (with half-band electrodes) system on CI2 side. The other 22 children received different types of Nucleus with precurved perimodiolar electrode array on both sides. For these children, the X-ray information was not available to know about the real position of the electrode array of each implant after surgery. However, it may be likely that the more recent type of Nucleus system was placed at less-than-optimal position, and did not produce significantly lower mapping parameters. Another possible reason for the present sequential group might be difference in the auditory neural survival between two sides. Although some children received more recent type of Nucleus system on CI2 side, the auditory neural survival in CI2 side may be less than CI1 side. In that case, implantation of a more recent Nucleus system did not end up lower mapping parameters at CI2 side, and consequently, higher difference in the mapping parameters between the two implants.

The effect of time between implants:

For C-levels and DRs, the difference between the two implants was significantly related to the time between implants. Children with a longer time between implants had a lower C-ratio and DR-ratio, indicating a greater difference between the two implants compared to those with a shorter time between implants. Two possible explanations can be considered for the direct
relationship between the time between implants and the degree of difference in the C-levels and DRs between the two implants.

One possibility can be that the longer time between implants increases the chance for reorganization of the central auditory pathway related to CI2. When CI2 is implanted a long time after CI1, the pathway related to CI2 is subjected to a longer period of auditory deprivation. In this situation, there is a possibility of the occupation of the central auditory pathway related to CI2 by neural connections related to the other senses. Charroó-Ruíz, Picó et al. (2013) showed that, following auditory deprivation, visual and somatosensory neural connections can extend toward the auditory cortex and occupy that area. Lee et al 2001 showed that, with a longer time period of auditory deprivation, a larger area of the auditory cortex may be occupied by the other senses, possibly limiting normal development after receiving a CI. It is also possible that the central auditory pathway related to CI2 is partially occupied by the neural connections related to CI1. Gordon, Wong et al. (2013) reported that longer auditory deprivation on the CI2 side increased the chance for the dominance of the neural connections related to CI1 in all auditory cortex areas of the brain. As a result of these two forms of reorganization, it is less likely that the stimulation via CI2 will promote normal development in the relevant auditory pathways, so that a persistent difference appears in the C-levels, and consequently in the DRs, between the two implants. This is consistent with the neurophysiological findings for sequentially implanted children with a long time versus a short time between implants. In the study by Gordon, Valero et al. (2008), differences between the latencies of the brainstem responses evoked by each implant were recorded after bilateral implantation. For children who received CI2 at less than one year after CI1, the initial delay in the response evoked by CI2 was no longer evident by three months post-operation. In contrast, for children who received CI2 more than three years after CI1, the delayed response evoked by CI2 relative to CI1 was still evident even at 9 months post-operation. Sharma, Gilley et al. (2007) also showed that, when children received sequential BICIs before three years of age, the latency of the cortical P1 wave evoked by CI2 could reach normal limits, equivalent to that evoked by CI1, by three months post-operation. According to these neurophysiological findings, with a longer time between implants, the central auditory pathway related to CI2 is unlikely to
reach the developmental level of the pathway related to CI1. The likely result is a greater
difference in the C-levels between the two implants that, in turn, causes a greater difference in
the DRs between the two implants.

The other possibility can be that the longer time between implants increases the chance for
perceptual acclimatization effect to occur, whereby the entire central auditory system is
accustomed to stimulation from CI1 only. The perceptual acclimatization effect results from the
fact that the central auditory system has the potential to become accustomed to a specific
pattern of stimulation that is received consistently for a period of time. When the pattern of
incoming stimulation changes, the central auditory system may not easily process the new
stimulation in an effective way. Evidence for this has been shown in adult unilateral hearing aid
users. Gatehouse (1989) found that, as expected, at high presentation level, perception of
speech in noise was superior with the aided ear than the unaided ear after a period of
unilateral hearing aid use. However, at low presentation levels, where the stimulation differed
from that received every day, performance was poorer with the aided ear than the unaided ear.
These results were attributed to the fact that the central auditory pathway related to the aided
ear was accustomed to receiving speech primarily at higher intensity levels. Consequently, it
was possibly accustomed to processing speech at the higher intensity levels and did not
adequately process speech presented at lower intensity levels. Another form of the perceptual
acclimatization effect has also been reported by Gatehouse (1992) following unilateral hearing
aid use. In that study, speech perception ability of both the aided and the unaided ears was
assessed for up to 12 weeks after receiving unilateral hearing aid. The results indicated a
reduction in the speech perception performance with unaided ear over time relative to the
performance with that ear prior to fitting of the hearing aid in the contralateral ear. These
results were again attributed to the fact that the entire central auditory system was
accustomed to receiving stimulation from the aided ear and, therefore, accustomed to
processing speech coming via the aided ear. In contrast, the presentation of speech via the
unaided ear was an unfamiliar condition and, therefore, the central auditory system did not
effectively process speech presented via the unaided ear.
With a longer time between implants in children with BICIs, the central auditory system receives stimulation from CI1 alone for a longer time. This increases the chance for the central auditory system to become accustomed to processing this pattern of auditory stimulation. Following the introduction of CI2, the pattern of incoming auditory stimulation changed, however, the way that the auditory stimulation was being processed may not have altered sufficiently. In other words, the auditory stimulation received from CI2 may not effectively be processed, leading to a difference in the C-levels and DRs between the two implants.

The magnitude of the difference in the T-levels between the two implants was not significantly related to the time between implants. This is possibly due to the fact that T-levels are not influenced by the development of the central auditory system to the same extent as C-levels. T-levels are the product of sound detection and represent auditory sensitivity level. Among the auditory skills, sound detection is a basic ability requiring less complex auditory processing. Therefore, the developmental differences between the central auditory pathways related to CI1 and CI2 resulting from a longer time between implants may not cause a significant difference in the T-levels between the two implants.

The effect of age at bilateral implantation:

For T- and C-levels, and DRs, the difference between the two implants was not significantly related to the age at bilateral implantation for the present sequential group. Previous studies have found two opposite outcomes in this regard. Consistent with the present study, Gordon, Chaikof et al. (2012) did not find any significant effect for age at bilateral implantation on the difference in the mapping parameters between the two implants, measured either behaviorally or objectively. In contrast, Weberling, Firzt et al. (2011) found that older age at bilateral implantation was related to a greater difference in the mapping parameters between the two implants. In that latter study, T- and C-levels for the younger group of children showed no significant difference between the two implants at one year post-operation. However, the older group showed a significant difference in the T- and, especially, in the C-levels between the two implants at one year. In order to find out the reason for the different results regarding the effect of age at bilateral implantation, age at CI1 was compared between the children
participating in the three studies. The mean age at CI1 for children participating in the present study was 2.7 ±2.55 years, which was consistent with that in the study by Gordon, Chaikof et al. (2012) (mean of 2.1 ± 1 years) and with that of the younger group in the study by Weberling, Firzt et al. (2011) (mean of 1.9, with a range of 1.2 to 3 years). In contrast, for the older group in the study by Weberling, Firzt et al. (2011), the mean age at CI1 was 5.5 years. Therefore, the absence of a negative effect of the older age at bilateral implantation in the present study might be due to the young age of participants at CI1. The possible reason for the positive effect of younger age at CI1 may be related to the influence of stimulation received via CI1 on the development of the central auditory pathway related to CI2. Unilateral hearing with a CI can cause more minor activation in the central auditory pathway related to the non-implanted ear, in addition to the major activation in the central auditory pathway related to the implanted ear (Scheffler, Bilecen et al. 1998). With early implantation of CI1, it is possible that more effective activation occurs in the central auditory pathway related to the non-implanted ear (Sharma, Dorman et al. 2005). As a result, even if CI2 is implanted late, there is more potential for development of the central auditory system in response to CI2. This can be supported by the fact that reasonably good speech perception ability using CI2 have previously been found for children who were older at bilateral implantation but received their CI1 at a young age (Vischer, Senn et al. 2011).

Another possible factor that has the potential to alleviate the negative effect of older age at bilateral implantation is pre-operative hearing aid use on the non-implanted side. Beneficial functional outcomes in sound localization have previously been reported with older age at bilateral implantation for children who had some experience of hearing aid use on the non-implanted side (Van Deun, van Wieringen et al. 2010). Using a hearing aid provides auditory stimulation to the central auditory pathway which will be subsequently be stimulated by CI2. Although this stimulation may be limited, it has the potential to promote some degree of development and to reduce the reorganization in the pathway. However, for the sequential group in the present study, it was difficult to consider the contribution of hearing aid use to the present results. This was because the information regarding hearing aid fitting and/ or actual use of a fitted hearing aid was often not adequately recorded in the children’s medical files.
Simultaneous group:

Difference in the mapping parameters

For the simultaneous group, the T- and C-levels, and DRS did not differ significantly between the two implants at the initial post-operation time point. The mean of each of the T-ratio, C-ratio and DR-ratio was around 0.95, where the ratios were defined as the values of the left ear CI divided by those of the right ear CI. As with sequential BICIs, this is the first study examining the difference in the mapping parameters between the two implants of children with simultaneous BICIs in the early post-operation period. In the present study, the map providing T- and C-levels for the initial time point was created a maximum of 10 weeks after implantation. In the only previous study including children with simultaneous BICIs, the early post-operation period was not examined and only T- and C-levels for the 6-months post-operation time point were compared (Weberling, Firzt et al. 2011).

With simultaneous BICIs, both implants are received at the same time. This means that the central auditory pathway related to each implant was likely to be subject to auditory deprivation for a similar time period before implantation. As a result, it is expected that the two central auditory pathways have been affected in a similar way as a result of auditory deprivation. This expectation has been supported by the findings of previous neurophysiological studies on children with simultaneous BICIs. The latencies of the brainstem or cortical responses initially evoked by each implant have been found to have a similar delay (Sharma, Gilley et al. 2007, Gordon, Valero et al. 2007a, Gordon, Valero et al. 2007b). Similar development in the central auditory pathways relating to each CI will result in a comparable loudness processing and loudness growth function. As a result, a similar amount of electrical current provided via each implant will be perceived as similarly loud by the child.

As expected, when the mapping parameters of the two implants were examined over time, there was no significant change in the degree of the difference between the two implants. The T-ratio, C-ratio and DR-ratio remained around 0.95 at 5 years post-operation. The lack of changes in the difference between the two implants over time could result from either no
changes or similar changes in the mapping parameters of the two implants over time. Further analyses were carried out to examine the change in the mapping parameters of each implant over time. For each of T-levels, C-levels and DRs of each implant, a one way ANOVA with factor of post-operation time point was performed. The analysis indicated a significant increase in the mapping parameters of both implants over time ($F = (2, 200)$, $P \leq 0.028$). Pair-wise comparison with “Tukey” method revealed a significant difference between the initial and either of the 2-year or the 5-year post-operation time points for all mapping parameters of each implant ($P \leq 0.001$). That is, higher T- and C-levels, and DRs at 2-year and 5-year post-operation time points compared with initial time point. However, there was no significant difference between the 2-year the 5-year post-operation time points ($P \geq 0.993$). Unlike with sequential BICIs, children with simultaneous BICIs are unfamiliar with the sound percept via any implant at the time of initial programming. As such, their ability to perform the detection and loudness judgment tasks required during programming of each implant is similar. Over time, the children gradually acquire some hearing experience and their improved ability to perform the required tasks is applied to programming for each implant. Most importantly, since both implants are received at the same time, the mapping parameters of the two implants are expected to change and to become stable at a similar time. This can be mainly attributed to the fact that simultaneous auditory stimulation will drive similar developmental changes over time in the central auditory pathways related to each implant. The evidence that can support this suggestion comes from neurophysiological studies evaluating the development of the two central auditory pathways of children after simultaneous BICIs. Gordon, Valero et al. (2007b) compared the brainstem responses evoked by each implant at 15 months post-operation relative to those at the switch-on session. Changes in the latency of eV waves revealed a significant decrease over time, however, the latencies remained similar between the two implants. These results reflected a similar development over time in the auditory brainstem related to the two implants. In the study by Sharma, Gilley et al. (2007), the cortical responses evoked by the two implants were compared at different time points up to 15 months post-operation. The results showed a similar decrease in the latency of P1 waves, so that there were no latency differences between the two implants at any point. Gordon, Wong et al. (2013) found similar cortical lateralization to
the contralateral hemisphere following electrical stimulation of each implant for children with mean 3 years use of BICIs. According to these findings, for simultaneously implanted children, it seems that development in the auditory cortex related to each implant occurs in a similar way.

As with children with sequential BICIs, a small proportion of children in the present simultaneous group showed a different pattern in terms of difference in the mapping parameters between the two implants. In contrast to the typical pattern of similar mapping parameters between the two implants, some children had significantly higher mapping parameters in one implant relative to the other implant. More details regarding this small group of children have been explained in the clinical implications section of this chapter (pages 110-111).

**The effect of age at implantation:**

There was no significant relationship between the degree of the difference in the mapping parameters between the two implants and age at implantation for the simultaneous group of the present study. With simultaneous BICIs, theoretically, implantation at any age can cause similar effect on the central auditory pathways related to the two implants. Therefore, both pathways will be in similar situations in terms of reorganization and the capability of activation by auditory stimulation. This is in agreement with the findings of the studies investigating the neurophysiological responses evoked from each implant for children with simultaneous BICIs. Gordon, Jiwani et al. (2011) recorded cortical waveforms in response to each implant during the first week of BICIs use for a large number of children. The majority of children had undergone implantation at younger age (mean = 1.6 years), while a small number (n =7) had received their implants at an older age (mean = 8.8 years). Although the morphology and latency of the waveforms were found to be different across children, similar waveforms were reported in response to the two implants of individual children irrespective of the age at implantation. These results can indicate that, despite the effect of auditory deprivation on the development of the auditory system, varying with duration of deprivation, the effects are similar for the auditory pathway related to each ear.
Clinical implications:

The outcomes of the present study provide detailed information about the mapping-related outcomes of children with BICIs. In the current situation, with very limited evidence guiding bilateral mapping, such knowledge can be helpful for clinicians worldwide. In the present study, the results were presented as a ratio of the mapping parameters between the two implants, while in the clinical practice mapping parameters are set in CLs for the two implants. Presenting some example participant results in CLs will give a more clinically relevant idea of a typical and an atypical pattern of results. This will help clinicians to know what they should expect and also to more easily recognize the situations that are different from what is expected. Table 7-1 shows the mean T-levels of the two implants in CLs, and the difference between them, for a representative participant in each of the sequential and simultaneous groups with a typical pattern for the difference in the T-levels between the two implants in the present study. The T-ratio in µA is generally around 1 (range: 0.9 to 1.11) at the three electrode array regions over the three time points, although each participant demonstrated one exception, with a T-ratio of less than 1 for one electrode array region at one post-operation time point. Consistent with the T-ratio being generally around 1, there is generally a small difference between the T-levels of the two implants in CLs at the three electrode array regions over the three time points (range: 1.7 to 7.7 CLs). Table 7-2 shows the mean C-levels of the two implants in CLs and the difference between them for a representative participant in each of the sequential and simultaneous groups with a typical pattern for the difference in the C-levels between the two implants in the present study. For the sequential participant, the C-ratio in µA is generally less than 1 (range: 0.31 to 0.68) at each of the three electrode array regions at each of the three time points. Consistent with the general C-ratio, there is a large difference between the C-levels of the two implants in CLs (range: 21 to 64.7 CLs), with lower C-levels in CI2 than CI1. However, for the simultaneous participant, the C-ratio in µA is around 1 at the three electrode array regions over the three time points. Consistent with the C-ratio, there is a small difference between the C-levels of the two implants in CLs (range: 0.7 to 11 CLs).
Table 7-1: The mean T-levels in CLs for each implant and the difference between them in three electrode array regions (apical, medial and basal) at each of three post-operation time points (initial, 2-year and 5-years) for a representative participant in each of the sequential and simultaneous groups with a typical pattern for the difference in the T-levels between the two implants. The T-ratio is provided in bracket.

<table>
<thead>
<tr>
<th>Participant group</th>
<th>Electrode array region</th>
<th>Apical</th>
<th>Medial</th>
<th>Basal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Time-point</td>
<td>Time-point</td>
<td>Time-point</td>
</tr>
<tr>
<td></td>
<td>CI</td>
<td>Initial</td>
<td>2-year</td>
<td>5-year</td>
</tr>
<tr>
<td>Sequential</td>
<td>CI1-CI2</td>
<td>-6</td>
<td>-3.3</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.11)</td>
<td>(1.07)</td>
<td>(0.91)</td>
</tr>
<tr>
<td></td>
<td>CI2</td>
<td>108.6</td>
<td>111.6</td>
<td>99.3</td>
</tr>
<tr>
<td></td>
<td>CI1</td>
<td>102.6</td>
<td>108.3</td>
<td>104.6</td>
</tr>
<tr>
<td>Simultaneous</td>
<td>CI1-CI2</td>
<td>3.3</td>
<td>-3</td>
<td>-7.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.94)</td>
<td>(1.05)</td>
<td>(1.08)</td>
</tr>
<tr>
<td></td>
<td>CI2</td>
<td>111</td>
<td>134</td>
<td>151.5</td>
</tr>
<tr>
<td></td>
<td>CI1</td>
<td>114.3</td>
<td>131</td>
<td>147</td>
</tr>
</tbody>
</table>
Table 7-2: The mean C-levels in CLs for each implant and the difference between them in three electrode array regions (apical, medial and basal) at each of three post-operation time points (initial, 2-year and 5-years) for a representative participant in each of the sequential and simultaneous groups with a typical pattern for the difference in the C-levels between the two implants. The C-ratio is provided in bracket.

<table>
<thead>
<tr>
<th>Electrode array region</th>
<th>Apical</th>
<th>Medial</th>
<th>Basal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time point</td>
<td>Time point</td>
<td>Time point</td>
</tr>
<tr>
<td>Participant group</td>
<td>Initial</td>
<td>2-year</td>
<td>5-year</td>
</tr>
<tr>
<td>CI1-CI2</td>
<td>48.4 (0.42)</td>
<td>21.3 (0.68)</td>
<td>21 (0.68)</td>
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<tr>
<td>Sequential CI2</td>
<td>119.6</td>
<td>151</td>
<td>152.3</td>
</tr>
<tr>
<td>CI1</td>
<td>168</td>
<td>172.3</td>
<td>173.3</td>
</tr>
<tr>
<td>CI1-CI2</td>
<td>-11 (1.24)</td>
<td>-7 (1.15)</td>
<td>4.4 (1.09)</td>
</tr>
<tr>
<td>Simultaneous CI2</td>
<td>134.6</td>
<td>146.6</td>
<td>148</td>
</tr>
<tr>
<td>CI1</td>
<td>123.6</td>
<td>139.6</td>
<td>143.6</td>
</tr>
</tbody>
</table>

If a child shows an unexpected pattern for differences in the mapping parameters between the two implants, clinicians need to review the map in order to find possible reasons. For example, for a child with sequential BICIs, if the C-levels for CI2 were similar to or higher than those for CI1, clinicians should take care to ensure overstimulation is avoided. Factors which may contribute to this outcome are the parent’s pressure on the child to achieve similar auditory ability with CI2 as shown with CI1, or the child’s lack of attention to the task. Over time, the DR for CI2 is expected to become wider, whilst that for CI1 is expected to remain stable, especially
if there is a long time between implants. The difference between CI1 and CI2 should, therefore, decrease over time. The widening DR for CI2 is usually due to a considerable increase in the C-levels, while the T-levels are expected to remain relatively stable. If the clinician does not see the expected pattern, there may be some underlying issues. One important issue may be lack of CI2 use by the child. When two implants are received sequentially, adapting to bilateral hearing from unilateral hearing may be challenging for the child. Since, in this situation, sound is available via CI1, it is possible that the child may have less motivation to put effort into adapting to listening with the two implants. Anecdotal reports and clinical experience have suggested that consistent use of CI2 can contribute to progress in functional abilities with CI2 alone and, consequently, with BICIs. If the child’s CI system cannot record data about device usage, it would be useful for clinicians to ask parents to pay particular attention and check device use. The lack of increase in the C-levels for CI2 over time may occasionally be due to some issues in the external or internal parts of the CI system preventing the electrical signal from being delivered to the auditory nerve. The issue can be minor, such as a faulty coil cable, which can be easily detected through examination by clinicians. The issue can also be major, such as displacement of the electrode array within the cochlea, which requires X-ray imaging to be identified.

Despite the improvement over time, C-levels for CI2 should not generally be expected to reach those for CI1. Although there is some research evidence indicating that sounds provided by each implant may be perceived as similarly loud, some children dislike the quality of the sound provided by CI2. Clinical experience suggests that these children usually prefer CI1 to be louder and to dominate the combined sound percept received when using both implants. Therefore, it would be useful for the clinicians to identify whether or not the difference in C-levels between the two implants results in a difference in perceived loudness. If there is a difference, it might be helpful to gradually increase the C-levels for CI2 and to see whether the child can accept C-levels which provide a similar percept of loudness via each implant.

For children with simultaneous BICIs, conversely, almost similar T- and C-levels should be expected for the two implants from the switch-on session. Generally, any changes in the magnitude of the mapping parameters of the two implants are expected to occur in parallel
over time. Attention should be given to any atypical differences in the mapping parameters between the two implants at any time point.

An important point to be considered by clinicians is that a small proportion of children in both the simultaneous and sequential groups may not follow the expected patterns described in the present study. Table 7-3 shows the mean T- and C-levels for the two implants in CLs, and the difference between them, for a representative participant in each of the sequential and simultaneous groups with an atypical pattern for the difference in the mapping parameters between the two implants in the present study. For the sequential participant, the T-ratio and C-ratio in µA are higher than 1 (range: 1.54 to 2.33) at each of the three electrode array regions at each of the three time points. Consistent with the T-ratio and C-ratio, there is a large difference between the T-levels and C-levels of the two implants in CLs (range: 24 to 47 CLs), with higher T- and C-levels for Cl2 than Cl1. In the present study, 4.7 % of children (3 out of 64) with sequential BICIs had a T-ratio as well as a C-ratio higher than 1 at least at one electrode array region at one post-operation time point; although, it should be noted that some ratios greater than 1 may have represented a clinically insignificant difference in CLs. Likewise, for the simultaneous participant in Table 7.3, the T-ratio and C-ratio in µA are higher than 1 (range: 1.24 to 2) at each of the three electrode array regions at each of the three time points.

Consistent with the T-ratio and C-ratio, there is a relatively large difference between the T-levels and C-levels for the two implants in CLs (range: 11 to 51 CLs). In the present study almost 10 % of children (3 out of 29) with simultaneous BICIs had a T-ratio as well as a C-ratio higher than 1 at least at one electrode array region at one time point post-operation.
Table 7-3: The mean T- and C-levels in CLs for each implant and the difference between them in three electrode array regions (apical, medial and basal) at each of three post-operation time points (initial, 2-year and 5-years) for a representative participant in each of the sequential and simultaneous groups with an atypical pattern for the difference in the mapping parameters between the two implants. The ratio representing the difference between the implants is provided in brackets.

<table>
<thead>
<tr>
<th>Participant group</th>
<th>Electrode array region</th>
<th>Time point</th>
<th>Time point</th>
<th>Time point</th>
<th>Time point</th>
<th>Time point</th>
<th>Time point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Apical</td>
<td>Medial</td>
<td>Basal</td>
<td>Apical</td>
<td>Medial</td>
<td>Basal</td>
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<tr>
<td></td>
<td></td>
<td>T-levels</td>
<td>C-levels</td>
<td>T-levels</td>
<td>C-levels</td>
<td>T-levels</td>
<td>C-levels</td>
</tr>
<tr>
<td>Sequential</td>
<td>CI1-CI2</td>
<td>Initial</td>
<td>-30</td>
<td>-32</td>
<td>-29</td>
<td>-24</td>
<td>-30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-year</td>
<td>-46</td>
<td>-37</td>
<td>-47</td>
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<td></td>
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<td>(1.67)</td>
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<tr>
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<tr>
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<td></td>
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<td>(2.46)</td>
<td>(1.31)</td>
<td>(1.48)</td>
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<tr>
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<td>Initial</td>
<td>84</td>
<td>130</td>
<td>75</td>
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<td>133</td>
<td>76</td>
<td>132</td>
<td>109</td>
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<td>(1.11)</td>
<td>(1.00)</td>
<td>(1.04)</td>
<td>(1.04)</td>
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<tr>
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<td>CI1-CI2</td>
<td>Initial</td>
<td>-49</td>
<td>-36</td>
<td>-23</td>
<td>-15</td>
<td></td>
</tr>
<tr>
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<td>2-year</td>
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<tr>
<td></td>
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<td>Initial</td>
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<td>126</td>
<td>132</td>
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<tr>
<td></td>
<td></td>
<td>2-year</td>
<td>109</td>
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<td>(1.11)</td>
<td>(1.04)</td>
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</table>
Conclusion:

To develop more efficient mapping procedures for the two implants in children with BICIs, increasing knowledge about the mapping-related outcomes of the two implants is necessary. This retrospective study provided evidence-based information regarding mapping-related outcomes for a sequential and a simultaneous group of children fitted with the Nucleus CI system. Findings of the present study showed that children with sequential BICIs differ from those with simultaneous BICIs in terms of difference in the mapping parameters between the two implants. According to these findings, children who receive sequential BICIs are likely to have similar T-levels, but significantly different C-levels and DRs between the two implants soon after switch-on of their CI2. This group of children usually has significantly lower C-levels and narrower DRs for CI2 relative to CI1, even if they are implanted with similar device type at each ear. The lower mapping parameters for CI2 relative to CI1 may result from less development in the central auditory pathway related to CI2 compared to that of CI1. The degree of difference in C-levels and DRs decreases over time as the children accept higher stimulation levels provided by CI2; however, the difference between the two implants may remain up to 5 years post-operation. A longer time between implants has been found to be related to a greater difference in the C-levels and DRs between the two implants for this group of children. The situation is different for children with simultaneous BICIs as the mapping parameters of the two implants are similar from switch-on of their bilateral implants and remain so up to 5-years post-operation. Interestingly, age at bilateral implantation and electrode array region have not been found to affect the degree of difference in the mapping parameter between the two implants for both sequential and simultaneous group.

In clinical practice, clinicians can use the findings of the present study as a guideline to provide optimal maps for children with BICIs. The typical pattern between the mapping parameters of the two implants that clinicians should expect for children with sequential BICIs differs from that for those with simultaneous BICIs. Additionally, when a child shows the pattern that differs from the findings of the present study, clinicians should be suspicious about the presence of an issue. The issue may be related to child’s attention to the task or to the lack of using the two
implants together. The issue may also be related to some problems in the external and internal parts of CI system. When the issue is recognized and resolved, it should be expected that the difference in the mapping parameters between the two implants starts to follow the typical pattern. Otherwise, the child is considered one of the small proportion of children with atypical pattern for the difference in the mapping parameters between the two implants.

**Future research:**

An extension of this study would be identification of the characteristics of the children with sequential BICIs who have higher mapping parameters in CI2 than CI1 and of children with simultaneous BICIs who have significantly different mapping parameters between the two implants. To do this, it will be required to recruit a larger number of children with atypical patterns for difference in the mapping parameters between their two implants as larger number of children will increase the power of the study. More children with simultaneous BICIs would be needed as the number of children with atypical pattern was very few in the present study and it was hard to identify predictive characteristics. More children with sequential BICIs would be needed as there are many potential predictive characteristics that may interact and make the outcome unclear. Another area for the future research is to try to find more efficient and straightforward approaches for mapping the two implants for children with simultaneous BICIs by taking the advantage of the likelihood of similar maps between the two implants for these children. For example, it may be possible that mapping parameters can be measured for different electrodes of each implant and then applied to the contralateral implant. This can reduce the number of electrodes measurement and save the time in working with children, who may not cooperate for a long time.
References


Petrovic, M. (2011). Using cortical auditory evoked potentials (CAEP) as the outcome measure of cortical maturation, is there an optimal age to implant deaf children to provide better auditory development? University of Western Ontario: School of Communication Sciences and Disorders.


Author/s: Abdi, Roghayeh

Title: Analysing the maps of the children using bilateral cochlear implants

Date: 2016

Persistent Link: http://hdl.handle.net/11343/127307

File Description: Analysing the maps of the children using bilateral cochlear implant

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