# Baseline Hearing Levels Post-Surgery for the Southern Cochlear Implant Program

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# Abstract

This study aims to obtain baseline data on the levels of post-surgery acoustic hearing for adult cochlear implant (CI) users in the Southern Cochlear Implant Program (SCIP), and to compare these to their pre-surgery hearing levels. The surgical techniques for implanting the CI are constantly being improved, with current trends aiming to preserve as much residual hearing as possible. Up until 2007, no specific measures were employed by surgeons involved with the (SCIP) to preserve residual hearing during the implantation procedure. It is hypothesised that: i ) Although post-surgery hearing thresholds will be significantly lower than pre-surgery levels, numerous patients will still have some degree of residual hearing remaining in their implanted ear; and ii) That participants with greater levels of residual hearing in the implanted ear will perform better on speech perception tests. The study included 25 postlingually-deafened adults (18 yrs and above) who were implanted through the SCIP, and who had pre-surgery hearing levels of 100dB or better at 250, 500 & 1000 Hz. There were 6 males and 19 females with a mean age of 57.4 years (SD = 13.89). Their average experience with a CI was 28.12 months (SD = 19.14). Hearing thresholds using puretones as well as speech perception of the participants was assessed. The Consonant-Nucleus-Consonant (CNC) test for words as well the Hearing-In-Noise Test (HINT) for sentences were used to assess speech perception.

The mean post-surgery puretone average (PTA) (i.e. average of hearing thresholds of 250, 500, 1000 & 2000 Hz) was found to be 117 dB HL, as compared to 89 dB HL pre-surgery. Thirteen of the 25 participants (52%) presented with measurable levels of

acoustic hearing levels in their implanted ear. The participants showed significant improvement in their pre-surgery to post-surgery speech perception scores in quiet (Sentences: pre- 19%; post- 82%. Words: pre- 7%; post- 55%).However, participants with greater levels of residual hearing in the implanted ear did not perform better on speech perception tests. These speech perception results suggest that the current implant recipients from the SCIP are obtaining significant improvement in speech perception outcomes post-surgery. Results suggest that hearing can be preserved in CI surgery even without specific techniques being employed. Therefore, there is a potential for greater levels of hearing to be preserved if surgeons start to use modified techniques. This may impact on pre- and post-surgery clinical counselling, as well as when determining the future CI candidacy criteria.

# 1 Introduction

This study aims to establish baseline data on the levels of post-surgery acoustic hearing for adult cochlear implant (CI) users in the Southern Cochlear Implant Program (SCIP), and to compare these to pre-surgery hearing levels. The surgical techniques for implanting the CI are constantly being improved, with current trends aiming to preserve as much residual hearing as possible. It is hoped that results obtained in this study will help in improving the outcomes for individuals who will receive a CI in the future, as well as provide up-to-date data on the current outcomes for CI users in the SCIP.

Chapter 2 provides an overview of hearing and hearing loss as it relates to this study, followed by an overview of the cochlear implant system, cochlear implant surgery and then takes up a comparison between hearing aids and cochlear implants. This is followed by a review of the current outcomes for CI users, and how these outcomes relate to the expanding criteria for cochlear implant candidacy. Chapter 3 discusses electro-acoustic stimulation and looks at the preservation of residual hearing during CI surgery. The background information from Chapters 2 & 3 lead into Chapter 4 which presents the rationale and hypotheses of the study.

The methods used to test these hypotheses will be discussed in Chapter 5, with the results and the subsequent discussion being presented in Chapters 6 and 7 respectively and Chapter 8 summarises the findings of this study.

# 2 Overview of the Cochlear Implant

This chapter provides an overview of hearing and hearing loss as applicable to this study (Sections 2.1 and 2.2). This then leads to a brief outline of the cochlear implant and the speech processing strategies implemented in the implant (Sections 2.3 and 2.4). Section 2.5 discusses the basics of CI surgery with Section 2.6 comparing the CI to the other major rehabilitative device, the Hearing Aid (HA). Section 2.7 looks at the current outcomes for CIs, and the final Section of this Chapter, Section 2.8 discusses the criteria for implantation, which incorporates the information discussed in the preceding Sections.

## 2.1 Anatomy of the Cochlea

The inner ear is situated in the petrous part of the temporal bone of the skull, and contains the organs related to both hearing and balance functions. The cochlea is a small snail-shaped structure that transduces the mechanical energy of sound waves into nerve impulses that are transmitted by the cochlear nerve to the brain (Figure 2.1). It resembles a 30 millimetre (mm) long tube coiled approximately two and three quarters in humans (Rappaport & Provencal, 2002). The cochlea terminates blindly at the apex (Figure 2.2), and measures about one centimetre (cm) wide at the base and five mm

from the base to the apex in humans (Dowell, Martin, Clark, & Brown, 1985). The central axis of the cochlea acts as an inner wall and is known as the modiolus.

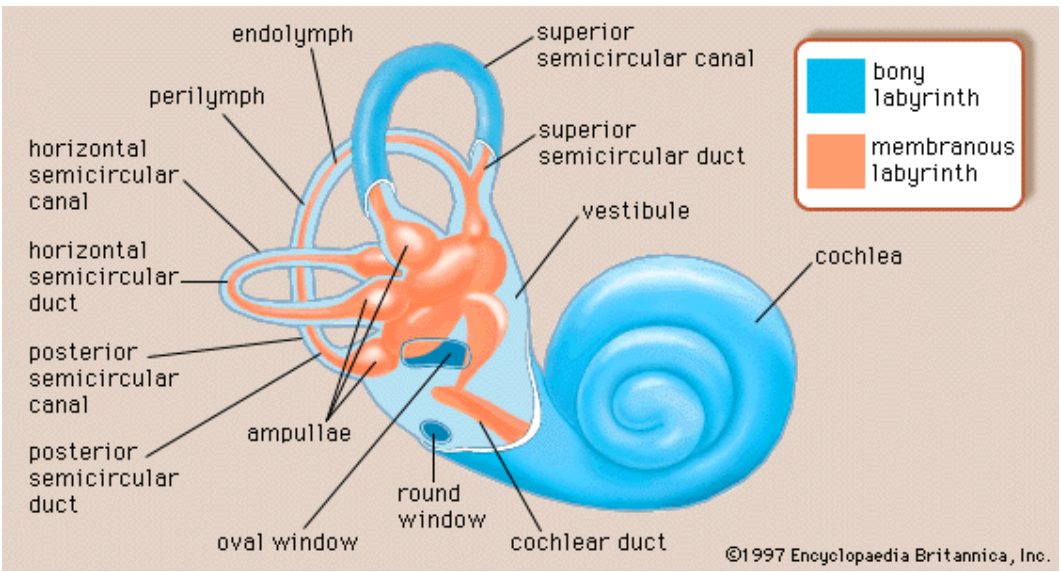



**Figure 2.1: The inner ear**

Figure from http://www.britannica.com/eb/art-532

The cochlea is divided into three parallel running ducts (Figure 2.3). Reissner's membrane separates the scala vestibuli from the scala media, where as the basilar membrane separates the scala media and the scala tympani. The scala vestibuli extends from the oval window in the vestibule to the helicotrema (a small passageway at the apex of the cochlea between the scala vestibuli and scala tympani), and the scala tympani extends from the round window in the vestibule to the helicotrema. The scala

media, which is sometimes referred to as the cochlear duct runs the entire length of the cochlea, except at the apex.

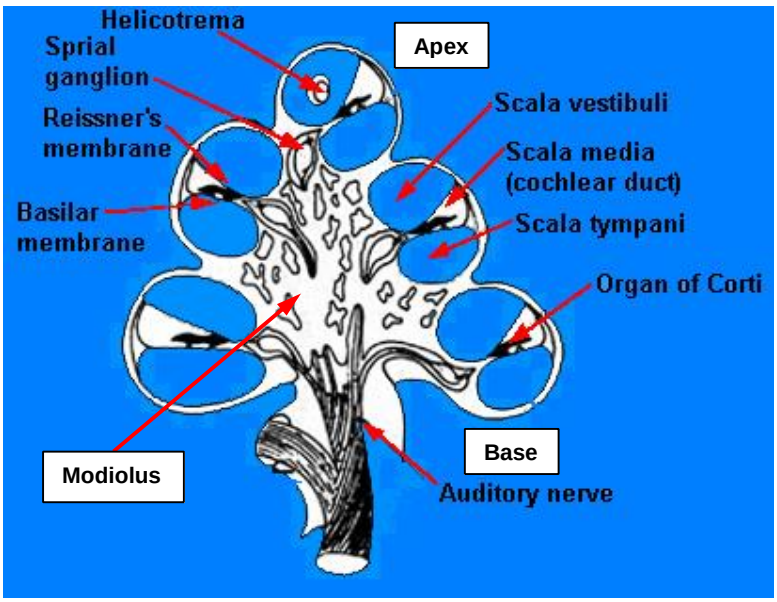



**Figure 2.2: Cross section of the cochlea**
Apex, Base, Modiolus

Figure adapted from Martin & Clark (1985)

The organ of Corti, which is the end organ of hearing lies along the full length of the scala media on the medial surface of the basilar membrane. The outer and inner hair cells are part of the organ of Corti, with the inner hair cells serving to transduce mechanical energy into nerve impulses. The cell bodies of the nerve afferents that synapse with the inner hair cells are found in the spiral ganglion which is located within

the modiolus. The axons of these nerve afferents from the inner hair cells collectively form the auditory nerve. The fibres of the auditory nerve leave the inner ear through the internal auditory canal to terminate in the cochlear nucleus complex in the brainstem (Yost, 2000).

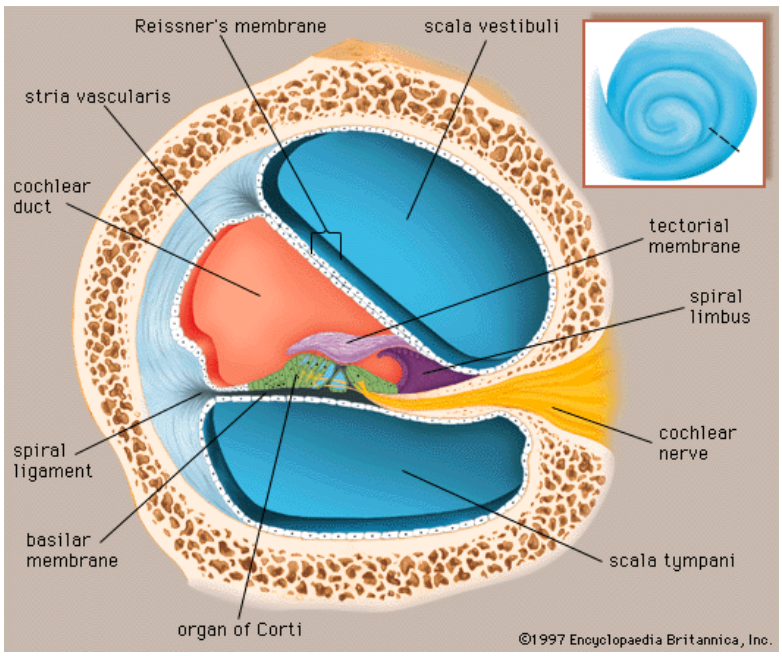



**Figure 2.2: Cross section of the Cochlear tube**
Scala Vestibuli, scala media (cochlear duct), scala tympani, organ of Corti

Figure from http://www.britannica.com/eb/art-534

The variation in the width, stiffness and thickness of the basilar membrane gives the cochlea its tonotopicity. The travelling wave generated by the input sound travels along

the basilar membrane from the base to the apex. Different frequencies result in maximal displacement of the different sections of the basilar membrane, with the low frequencies stimulating the apical regions and the higher frequencies stimulating more basal regions. Thus the lowest frequency that the ear responds to (approximately 20 Hz in humans) stimulates at the apex of the cochlea and the highest (approximately 20000 Hz in humans) stimulates the basal end of the cochlea. This organisation of spatial representation of frequencies is maintained throughout the auditory system up to the auditory cortex in the brain (Yost, 2000).

## 2.2 Sensorineural hearing loss

One way to classify hearing losses is based on what part of the auditory system is damaged. Conductive losses occur when sound is not conducted efficiently through the outer ear or the middle ear; in contrast sensorineural hearing losses occur when there is damage to the inner ear (cochlea) or to the nerve pathways from the inner ear (retrocochlear) to the brain. Sensorineural hearing loss as a result of the damage to the cochlea is the type of loss that is relevant to this thesis.

As mentioned above, the inner hair cells transduce mechanical energy into nerve impulses. Therefore, any damage to the inner hair cells in a particular region of the cochlea would lead to a lack of stimulation of the auditory neurons of that area. This presents as a sensorineural hearing loss for those regions. As the severity of the damage

increases so does the severity of the hearing loss. Figure 2.4 illustrates the classification of the degree of hearing loss.

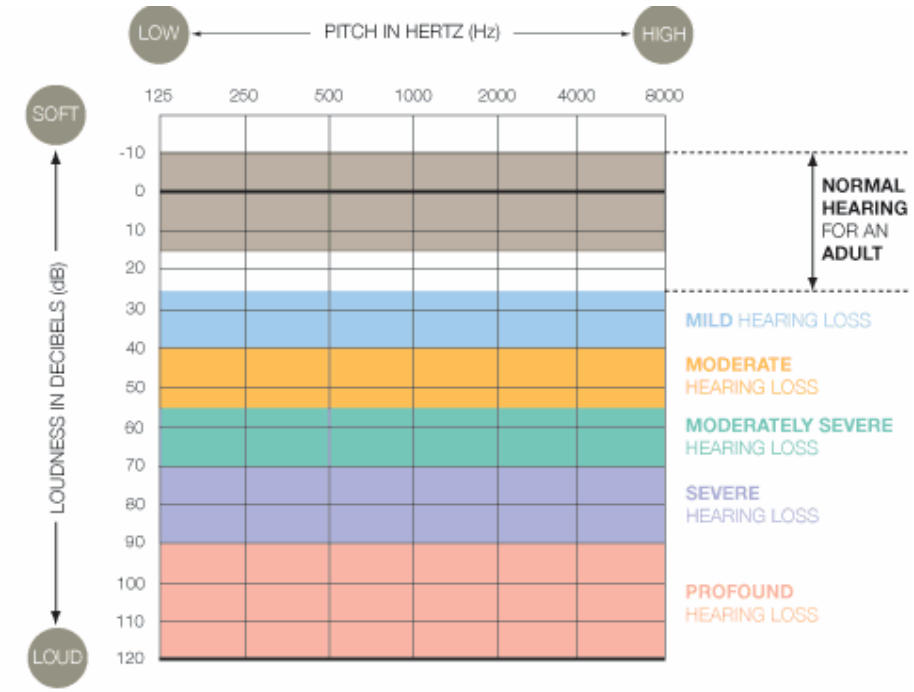



**Figure 2.4: Degrees of hearing loss**

Figure adapted from Understanding the Audiogram
http://www.lhh.org/about_hearing_loss/understanding/audiogram.html

For those with as severe to profound hearing loss, hearing aids as well as cochlear implants are two rehabilitative devices that may be used. They vary in how they stimulate hearing; this is discussed in more detail in section 2.6.

## 2.3 The Cochlear Implant

CIs are prosthetic devices that attempt to restore hearing by electrically stimulating the surviving spiral ganglion cells in the cochlea. The CI system has surgically implanted internal components connected to externally worn components that work together to give the CI user a percept of sound. The external components are the microphone, speech processor and the transmitting coil (Figure 2.5). The internal components (Figure 2.6) consist of a receiver-stimulator package which comprises a magnet, and receiving coil/internal processor, along with intra-cochlear and extra-cochlear electrodes.

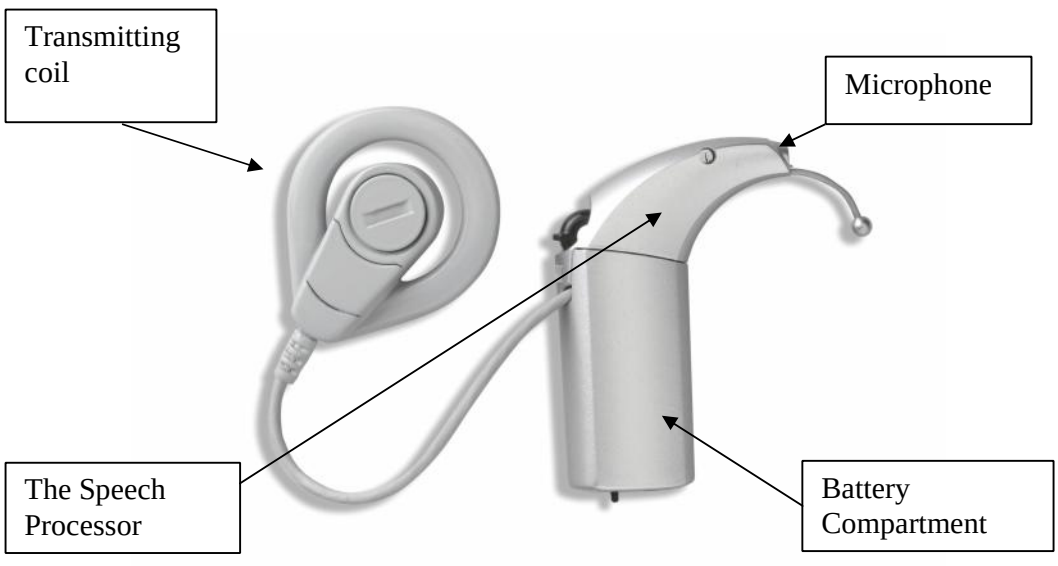



**Figure 2.5: External Components of the Cochlear Implant System**

Figure adapted from Cochlear Ltd (2005).

The external components of the CI system collect, process, and transmit sound information to the internal components. The acoustic signal is picked up by the microphone and converted into an electrical signal. This electrical signal is then sent to the speech processor which converts these input signals into patterns of electrical stimulation. This information is then encoded into a radio frequency signal for transmission to the internal receiver-stimulator package to activate the implant.
The receiver-stimulator package converts the radio frequency signal from the speech processor into an electrical current which is subsequently used to stimulate the cochlear nerve fibres via the implanted electrodes.

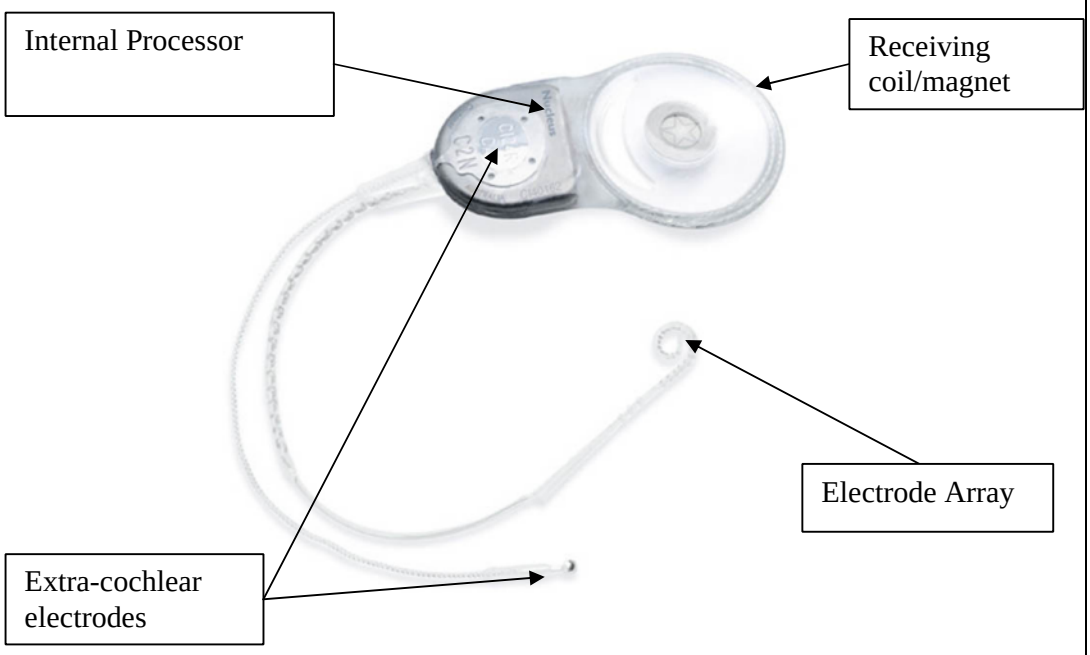



**Figure 2.6 Internal components of the Cochlear Implant System**

Figure adapted from Cochlear Ltd (2005).

The receiver-stimulator package is surgically placed in the temporal bone. It is housed in a ceramic or titanium casing and contains a magnet to help in the attachment of the external components. This package is attached to the extra-cochlear and intra-cochlear electrodes. The extra-cochlear electrodes are placed outside of the cochlea, either on the plate of the internal processor and/or under the temporalis muscle. The intra-cochlear electrodes are housed along a carrier known as the electrode array, and are surgically placed inside the cochlea (Surgery for the implant is discussed in section 2.4). The intra-cochlear electrodes vary in number, material, shape, size and spacing along the electrode array, depending on the manufacturer and model of the CI system.

Modern CIs have evolved from single electrode, single-channel devices in the 1970s, to multi-channel devices with up to 24 implanted electrodes. In single-channel devices, the same information is delivered to each stimulating electrode, and usually only one active electrode is used. Multi-channel devices have more than one electrode, and aim to stimulate different neural populations in order to take the advantage of the tonotopic organisation of the cochlea. Different processed information is delivered to each electrode.

## 2.4 Speech processors and speech processing strategies

As multi-channel devices use multiple electrodes, there arose the question of how the acoustic signal received by the microphone should be processed so that the electrodes could be activated in a manner to optimise hearing. Speech processing (or sound

processing) strategies process the sound received by the microphone in to electrical patterns that can then be transmitted to the electrode array in the cochlea. These strategies are programmed into the CI's speech processor. The sound processing strategies attempt to convey the most important features of speech (Loizou, 1999). Currently, the strategies in most common clinical use for Nucleus devices are: Continuous Interleaved Sampling (CIS) (Tyler et al., 2002), Spectral Peak (SPEAK) (McDermott, McKay, & Vandali, 1992; Skinner et al., 1994), and the Advanced Combination Encoder (ACE) (Vandali, Whitford, Plant, & Clark, 2000) strategies. For the MED-EL implant, the default switch on strategy is currently the FSP strategy (Hochmair et al., 2006).

Although these strategies vary in their parameters, all of them attempt to present a representation of the acoustic signal's spectrum through the electrode array implanted in the cochlea. The following is a brief description of how the speech processor achieves this. A schematic diagram of the speech processor is shown in Figure 2.7. More detailed description is available from Loizou (1999). The input received by the microphone is passed through a pre-emphasis filter which attenuates frequencies below 1 kHz, in order to make the vowels and the consonants more equal in terms of intensity. This is to prevent the louder low frequency vowel sounds from masking out the quieter high frequency consonant sounds (Tyler et al., 2002). The signal is then passed through a number of band-pass filters, with the exact number of filters varying according to the strategy being used. The band-pass filters separate the incoming sound signal into a series of discreet frequency bands. The envelopes of the filtered waveforms (Figure2.8) are then extracted by the envelope detectors. These envelope outputs are finally

compressed by the amplitude compressors and used to modulate electrical pulses sent to the electrode array. The amplitude compression is required as the acoustic dynamic range is considerably larger than the electrical dynamic range of a CI user.

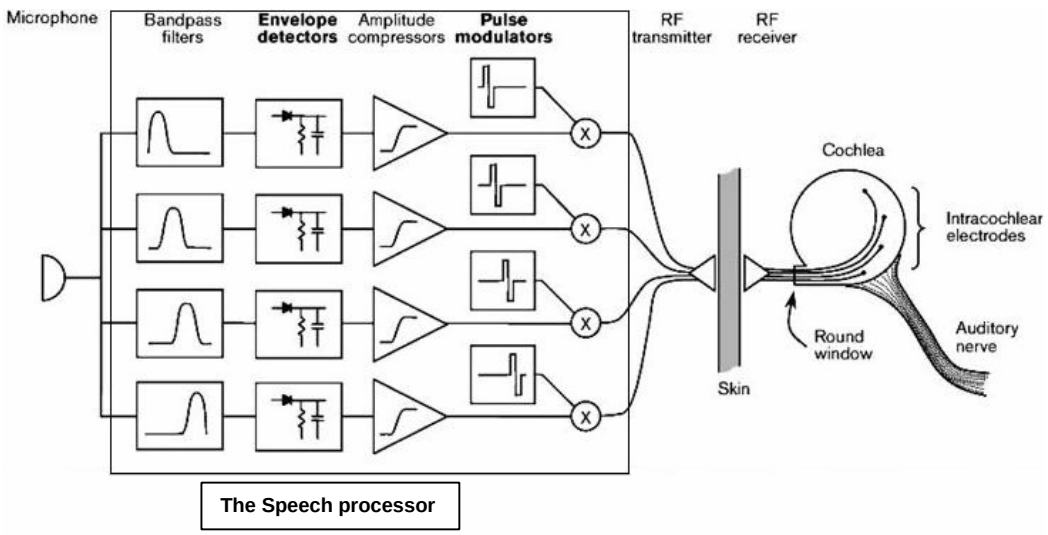



**Figure 2.7: Schematic representation of the speech processor of the CI system**

Figure adapted from Chivukula, Laulicht, Marcello, Patel, & Saphirstein (2006)

The dynamic range for an implant user is the perceptual range between threshold (or 'T' levels) and their maximum comfort (or 'C' level) for electrical stimulation. For a normally hearing person, their acoustic dynamic range is typically over 100 dB. However an implant user's dynamic range can be as small as 5 dB (Loizou, 1999). In

conversational speech, speech signals can fluctuate over a range of 30 dB. In consideration of this a non-linear compression function is used in CIs to ensure that the stimulation occurs within the patient's dynamic range for electrically evoked hearing. The electrical pulses, with amplitudes proportional to the input signal envelopes, are then delivered to the electrodes. That is, the electrical current presented to the active electrodes is controlled so that the amplitude of the current represents the intensity of the incoming acoustic signal, within the limitations of the implantee's dynamic range.

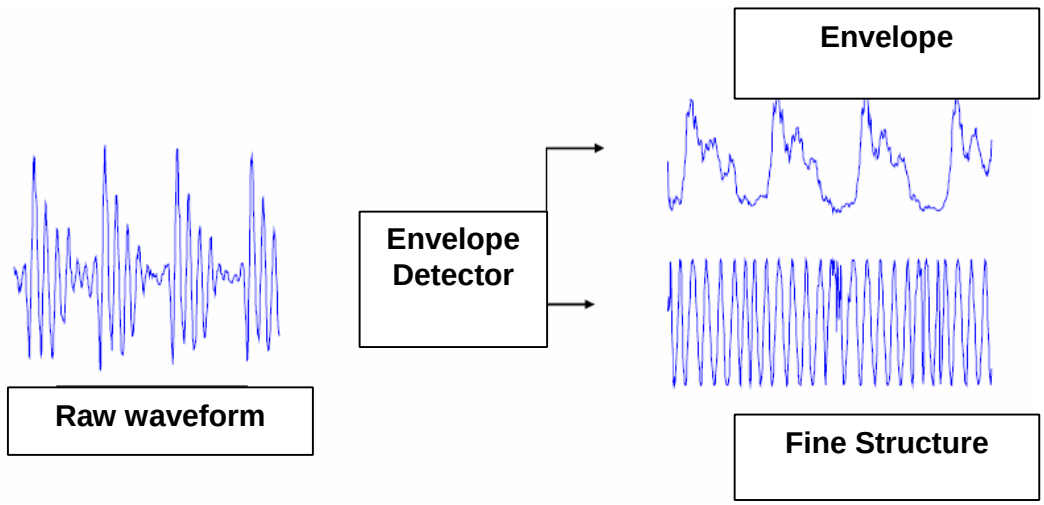



**Figure 2.8: The raw waveform and its envelope**

Envelope of a modulated signal like waveform is represented by the peaks of the signal

Figure adapted from Loizou (2006)

As mentioned previously, the input signal is sent to a bank of bandpass filters. The stimuli from the bands with low centre frequencies are directed to the apical electrodes

and the stimuli from the bands with high centre frequencies are directed to the basal electrodes. This mimics the tonotopic representation of frequencies in the cochlea.

**Table 2.1: Details of Implants and electrode arrays relevant to the thesis**

(A) Implant

| Implant | Intracochlear Electrodes | Extracochlear Electrodes | Channels of stimulation | Casing | Electrode arrays available | Maximum stimualtion rate (pulses/sec) |
|---|---|---|---|---|---|---|
| Nucleus CI 24 | 22 | 2 | 22 | Titanium | Straight<br>Contour Advance<br>Contour | 14400 |
| Nucleus Freedom | 22 | 2 | 22 | Titanium | Straight<br>Countour Advance | 32000 |
| MED-EL Pulsar CI 100 | 24 (arranged in 12 pairs) | 1 | 12 | Ceramic | Standard<br>Medium<br>Compressed | 50,704 |

(B) Electrode Arrays

| Electrode Array | Description | Length of Array | Number of electrodes | Distance between electrodes |
|---|---|---|---|---|
| Nucleus Straight Array | Longer length for lateral wall placement | 17mm | 22 | 0.45 mm |
| Nucleus Contour | Shorter length for perimodiolar position | 15mm | 22 | 0.1mm at apical end to 0.5 mm at basal end |
| Nucleus Contour Advance | Has 'soft tip' to aid smoother insertion | 15mm | 22 | 0.1mm at apical end to 0.5 mm at basal end |
| MED-EL Standard array | For deeper insertion | 31.7mm | 24 (arranged as 12 twin surfaces) | 2.4 mm |

The rate at which the electrical pulses are sent to the electrodes (i.e. stimulation rate) usually varies between 250 Hz to 4000 Hz, depending on the strategy being used. Increased stimulation rate provides the implant user with more temporal information about the incoming acoustic signal (Vandali et al., 2000). However this must be counterbalanced by the number of channels (providing spectral information) used for stimulation as each CI is limited by a due to the maximum total stimulation rate. For devices, and electrode arrays relevant to this thesis please see Table 2.1 A and B respectively.

## 2.5 Cochlear Implant Surgery

Just as CIs evolved from single-channel to multi-channel devices, the surgical procedure for implantation evolved as well. As multi-channel devices, aim to take advantage of the tonotopical organisation of the cochlea, the focus of the conventional/traditional surgery techniques for these devices was to achieve a full insertion of the electrode array in the scala tympani.

The following is a rudimentary outline of the fundamentals of conventional surgery. As it is beyond the scope of this thesis to discuss surgery in further depth, the reader is referred to Clarke, Franz, Pyman, & Webb (1991) for more detailed information.

a) The surgery is performed under general anaesthesia and full aseptic precautions. After the site of the implant placement is marked on the skin (Figure 2.9-1), an

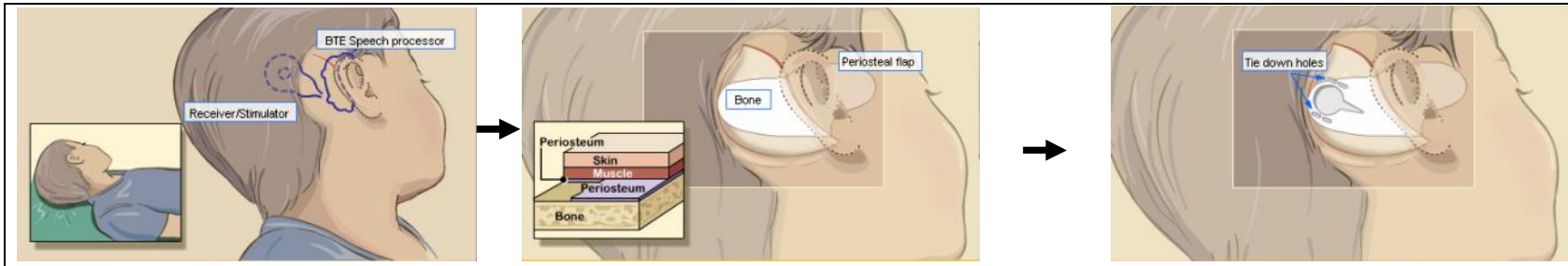
incision is made in the skin behind the ear and a “flap” of soft tissue and the periosteum is raised (Figure 2.9-2). This exposes the mastoid cortex and the temporal bone. Using a bone drill, a pocket is created in the bone for the placement of the receiver-stimulator package and the extra-cochlear electrode (Figure 2.9-3).

b) An intact canal wall mastoidectomy is carried out to expose the middle ear cavity. The facial and corda tympani nerves are identified and the bony facial recess is opened to allow the surgeon to identify the oval and round windows (Figure 2.9-4).

c) A cochleosteomy is then performed (Figure 2.9-4). This is a 2mm to 3mm wide hole drilled through the wall of the cochlea, antero-inferior to the round window membrane.

d) Once the scala tympani can be clearly visualised by the surgeon, the electrode array and the stylet, which holds the array in a straight position are guided through the cochleostomy. Once fully inserted, (i.e. all the intra-cochlear electrodes inside the cochlea, extending to the first one and a half basal turns), the stylet is withdrawn leaving the electrode array in the cochlea (Figure 2.9-5).

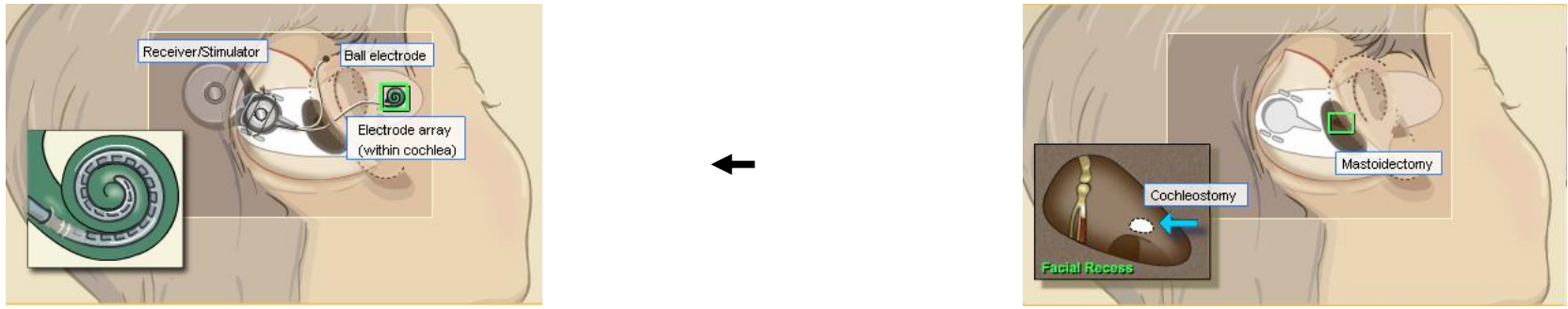
e) The cochlea and the surrounding area are then packed with soft tissue, the cochleostomy closed, and the receiver-stimulator is stabilised to the bone using sutures. The incision is finally closed with sutures and the head bandaged up.




**1** Placement of the receiver stimulator

**2** Post-aural incision of skin and periosteum

**3** Pocket for the receiver-stimulator




**5** Insertion of the electrode in the cochlea

**4** Opening of the mastoid and the cochlea

**Figure 2.9: Stages of CI Surgery**
Figure adapted from (Foundation, 2004)

## 2.6 Hearing - Hearing aid vs. Cochlear implant

As mentioned before in section 2.2, HAs as well as CIs are electronic devices that are used to compensate for severe to profound sensorineural hearing losses. However, the approach used to stimulate hearing by these devices differs. Hearing aids are instruments that work on ‘acoustic stimulation’ of the ear. That is, they present to the ear an amplified acoustic signal to the user. This amplified signal then stimulates hearing via the normal acoustic pathway with the hair cells of the inner ear performing the process of transduction from acoustic to electrical stimulus for the auditory nerve cells (section 2.1). In HAs, (Figure 2.10) sound received by the microphone is passed through the amplifier that has been programmed according to the hearing loss of the individual; the speaker then presents the amplified sound to the ear of the hearing aid user.

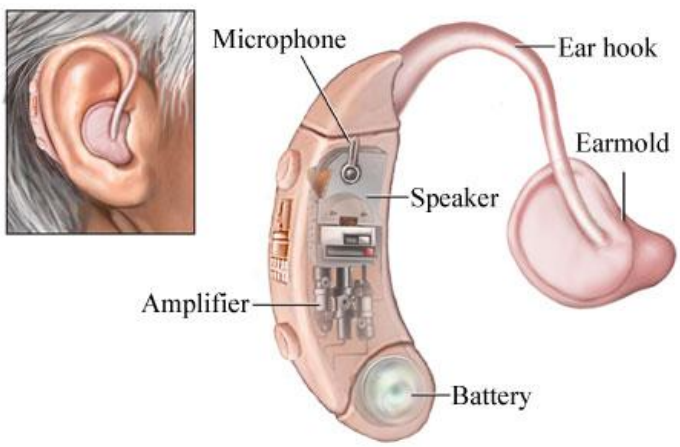



**Figure 2.10: Hearing aid**

Figure from http://health.yahoo.com/hearing-resources/hearing-aid/healthwise--zm6101.html

In contrast to HAs, CIs use ‘electrical stimulation’ of the ear (Figure 2.11). As explained Sections 2.5 and 2.6, the electrodes of the CI are inserted inside the cochlea to directly stimulate the spiral ganglion cells. This bypasses the transduction done by the inner hair cells of the cochlea. Electrical pulses, rather than amplified acoustic signals, are used to stimulate hearing.

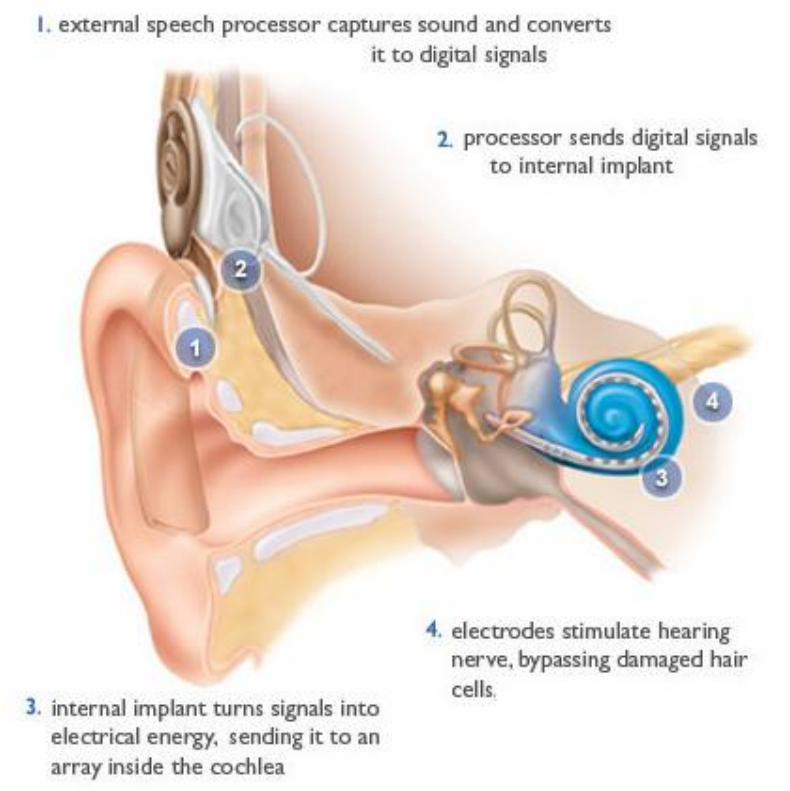



**Figure 2.11: Electrical stimulation by a Cochlear Implant**

Figure from http://www.theuniversityhospital.com/cochlearweb/cochlearabout/whatiscochlear.htm

## 2.7 Outcomes from cochlear implantation

The continual advancement in signal processing, as well as the improvement in the electrode and implant design has translated into improved speech perception outcomes by users of CIs particularly for quiet listening environments (Hamzavi, Baumgartner, Pok, Franz, & Gstoettner, 2003; Kiefer et al., 2004). Kiefer et al., (2004) compared the speech perception scores for 44 adults in the best-HA condition pre-operatively with the CI alone condition post-operatively. The stimuli used were the monosyllabic words, two-digit numbers and the 'Innsburk' sentence test, presented at 70 dB HL via a loudspeaker in a quiet listening condition. They found out that the speech perception scores were significantly better post-surgery with the CI as compared to pre-surgery with HA. Identification of numbers increased from 38% to 82% correct, and identification of monosyllabic words increased from 9% to 42 % correct. They further report that all except one of their participants performed better with the CI than with the HAs.

Hamzavi et al. (2003), compared speech understanding in noise between two groups of postlingually deafened adults. The first group (n=15) had severe-to-profound sensorineural hearing losses and were tested 3 years after being fitted with a HA. The second group (n=22) had been implanted with a Med-El Combi 40/40+ CI and were tested 1 year, 2 years, and 3 years post-surgery. The participants were tested using the Hochmaier, Shultz and Moser sentence test, for five different noise levels with signal-to-noise ratios (SNRs) varying between 0 dB to 15 dB. The study not only showed that the CI users' speech perception abilities improved over the 3 years post-implantation, but also that their speech perception results surpassed those of the HA group after 3

years of experience with their respective device. This suggests that for these subjects with a severe-to-profound hearing loss, the use of a CI provided greater benefit for perceiving speech when compared to HAs.

Whereas the above studies investigated speech perception in quiet, the results from studies of speech perception in noise suggest that CI and HA users often find this condition significantly more challenging. In situations that have background noise, the perception of speech becomes much more difficult as this requires the perception of fine-structure cues, in addition to the signal's envelope information (Fu, Shannon, & Wang, 1998). Current speech processing strategies discard the fine-structure information, only maintaining envelope information from the acoustic signal via envelope detectors as mentioned in Section 2.4 (Figure 2.8) As a result understanding speech in the presence of background noise is still an area that presents as a challenge for current users of CIs, regardless of the implant manufacturer, or speech processing strategy used as (Munson & Nelson, 2005; Stickney, Zeng, Litovsky, & Assmann, 2004; Yao, Turner, & Gantz, 2006).

## 2.8 Criteria for cochlear implantation

The audiological criteria that an individual must meet to be considered for a CI are constantly being re-examined. The underlying principle that determines these criteria is whether an individual is likely to achieve better outcomes with a CI than they currently obtain with HAs. When CIs were first implanted, individuals were only considered to be candidates if they had a total or profound bilateral hearing loss (Dowell et al., 1985).

However as technology and outcomes improved, the criteria gradually expanded to include individuals with lesser levels of hearing loss. It was one recommendation of the 1995 National Institutes of Health's Consensus Development Conference into CIs that, Cochlear implant candidacy should be extended to adults with severe hearing impairment and open-set sentence discrimination that is less than or equal to 30% in the best-aided condition (National Institute of Health Consensus Development Conference, 1995).

The previous trend of determining candidature for a CI based solely on audiometric thresholds has shifted to now primarily considering the individual's speech recognition ability in their best-aided condition pre-surgery. Flynn, Dowell, and Clark (1998) tested the speech perception performance of a group of adults with a severe (n=20) or severe-to-profound (n=14) hearing impairment who had used HAs for at least six months. They then compared these scores to a group of adults using CIs (n=63) whom were tested in a previous study by Skinner et al., (1994). Flynn et al. (1998) found that the CI users obtained higher mean open-set sentence perception scores than the group of adults with a severe-to-profound hearing loss who used HAs. From this the authors extrapolated that "Adults who obtain a moderate benefit (31%-60%) in open-set sentence perception from a Hearing aid could be considered for Cochlear Implant." (Flynn et al., 1998, p. 296).

Fraysse et al. (1998) compared the pre-operative speech perception scores for 20 postlingually deafened adults using HAs to their 6 month post-operative performance whilst using the CI in conjunction with a contralateral HA, where available. Both word

and sentence materials were assessed in an open-set format. Based on the results obtained, the authors concluded that the CI provided significant benefit for their participants, and recommended that speech perception scores ≤ 30% was an appropriate criteria for CI candidacy.

More recently, Dowell, Hollow and Winton (2004) retrospectively analysed post-operative speech perception outcomes for 262 postlingually deafened adults. They found that 75% of implant users scored above 70% for open-set sentence materials when tested with only their implant between 3 and 6 months post-surgery. Based on this, the authors recommended that the criteria for cochlear implantation be modified to include adults who scored up to 70% in the ear to be implanted, and up to 40% in their best-aided condition. They then retrospectively assessed the outcomes for those adults who met their modified criteria (n=45). The results from this subset of patients were consistent with the authors' hypothesis that postlingually deafened adults whose speech perception scores were up to 70% in the ear to be implanted had a 75% potential to obtain better speech perception scores in the implanted ear. The above-mentioned studies highlight how the criteria for a CI have expanded over time to include patients with better hearing thresholds.

The progressive improvement in technology of CIs is leading to improved outcomes. This is especially true for speech perception in quiet. Speech perception in noise is still proving to be a challenge as it is limited by the parameters associated with the current speech processing strategies. This improvement in the outcomes of current CI users has led to the expansion of the implantation criteria. That is, as CI outcomes improved,

more people would be able to benefit from an implant (as apposed to using HAs), and the implantation criteria has been adjusted accordingly. This has seen the number of people getting CIs continue to grow.

# 3 Electro-acoustic Stimulation

As discussed in the previous chapter, the expanding candidacy criteria for CIs has led to more people with better hearing thresholds getting CIs. This has introduced the concept of Electro-acoustic stimulation. This chapter looks at EAS and the potential benefits it provides. The importance of hearing preservation during surgery is also discussed in this chapter.

## 3.1 Overview of Electro-acoustic stimulation

The concept of of 'Electro-acoustic stimulation' (EAS) for CI users was first introduced by von Ilberg et al. (1999). This method of stimulation involves the simultaneous use of both acoustic and electric stimulation. Acoustic stimulation is enabled via HA(s) used to stimulate the surviving cochlear receptor cells, whereas electrical stimulation involves the direct stimulation of the auditory nerve via surgically implanted electrodes. EAS for CI users can be achieved by:

a) The use of a HA in the same ear as the implant (ipsilateral EAS);

b) The use of a HA in the ear opposite to the implant (contralateral EAS);

c) A combination of both (i.e. a CI in conjunction with bilateral HAs).

This mode of stimulation is suited to those with a steeply sloping hearing loss (i.e. a severe-to-profound high frequency hearing loss at frequencies ≥ 1000 Hz, but with significant levels of low frequency hearing remaining) (Figure 3.1). This type of stimulation is based on the premise that a HA can be used to amplify the remaining hearing at the low frequencies, with electrical stimulation providing higher frequency information

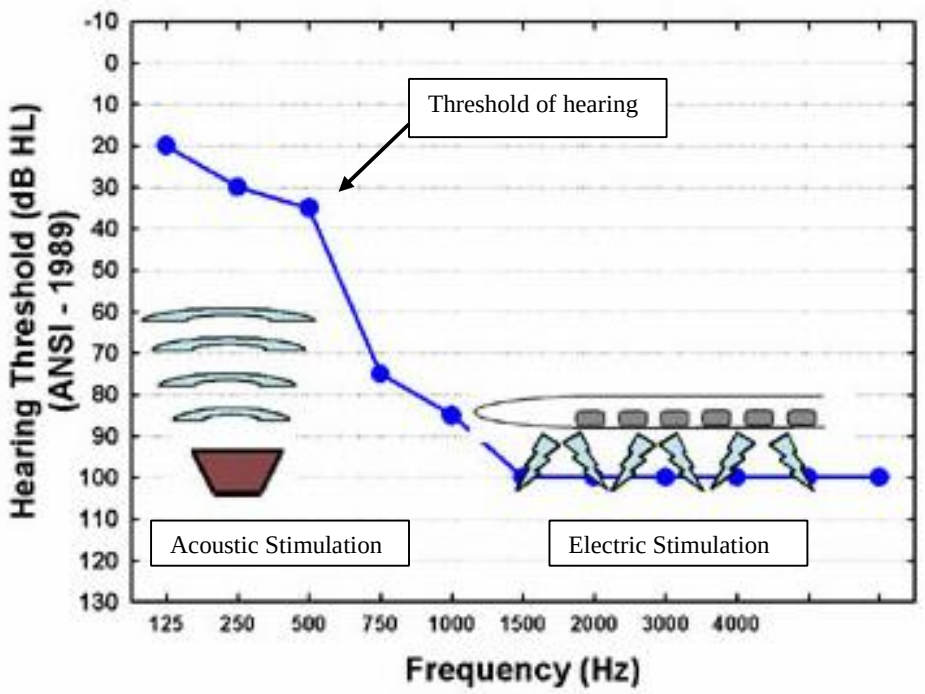



**Figure 3.1: Electro-acoustic stimulation**
Figure adapted from
www.audiologyonline.com/interview/interview_detail.asp?interview_id=284

## 3.2 Literature review of Electro-acoustic stimulation

In order to investigate whether the ear could integrate the acoustic and electric stimuli, Dorman et al. (2005), conducted a simulation study with normally hearing individuals. They report that all of the 12 participants who participated in their study performed significantly better in the EAS condition as compared to the 'acoustic-only' or the 'electric-only' conditions. In another simulation study Turner et al. (2006) compared speech perception ability in noise for 15 normally hearing participants. They found that the participants performed significantly better in the EAS simulation as compared to the CI simulation. Both of these studies indicate that the electrical and acoustic signals of simulated EAS can be successfully integrated by normal hearing individuals. In adopting EAS to CI users, Gantz & Turner (2003) reported that the preservation of acoustic hearing in their CI subjects provided improved consonant recognition results. These, and other similar studies (Fraysse et al., 2006; Gantz, Turner, Gfeller, & Lowder, 2005; Kiefer et al., 2004), collectively suggest that the human ear is able to integrate low frequency acoustic information with high frequency information presented electrically.

To evaluate the effectiveness of EAS, several studies have been conducted comparing outcomes for traditional CI recipients to those who use ipsilateral EAS (Fraysse et al., 2006; Kiefer et al., 2005; James et al., 2005;), as well as contralateral EAS (Dunn et al., 2005; Luntz et al., 2005; Mok et al., 2006). Kiefer et al. (2005) tested the speech perception performance of 13 adults who were implanted with a Med-El Combi 40+ CI using surgical techniques to preserve as much hearing as possible. All the participants had low frequency hearing of better than 60 dB below 1 kHz pre-surgery. Post-surgery,

assessments of the patient's speech perception abilities were made using monosyllabic words as well as sentences presented in both quiet and noise (SNR=10dB). Three listening conditions were evaluated: HA-alone, CI-alone, and ipsilateral EAS. Results for the word stimuli showed a significant improvement from the HA-alone to the CI-alone condition, with the further increase in scores from the CI-alone to the EAS condition approaching significance ($p = 0.059$). For the sentence stimuli, both in quiet and noise, scores in the EAS condition were significantly higher than for the CI-alone condition, with scores in the latter condition being significantly higher than those for the HA-alone condition. Further, a greater degree of improvement from the CI-alone to the EAS condition was noted for sentences presented in noise compared to sentences presented in quiet. This suggests that the benefit provided by EAS over using only the CI is particularly evident in noisy listening situations.

James et al. (2005) tested 12 adults who had post-surgery thresholds better than 90 dB HL at 250 Hz and 500 Hz in the implanted ear, and were fitted with an in-the-ear HA in the same ear as the implant. Results indicated that the SNR thresholds (defined as: the SNR at which 50% of the words in the sentences were correctly identified) as for sentence recognition in noise improved by up to 3 dB for the ipsilateral EAS mode as compared with the CI-alone mode. Similarly Fraysse et al. (2006) compared 10 adults in the CI-alone mode to the ipsilateral EAS mode in their ability to perceive words presented in quiet as well as sentences presented in noise. They found that EAS provided benefit for speech recognition in noise equivalent to a 3 to 5 dB improvement in the SNR. The results of these studies suggest that ipsilateral EAS can provide additional benefit for speech perception in noise, when compared to using only the CI.

Similar outcomes have been reported for contralateral EAS. Luntz, Shpak, & Weiss (2005) investigated the ability of 12 patients (3 postlingually deafened adults and 9 prelingually deafened adults or older children) to identify sentences presented in background noise (SNR=10dB). The 12 subjects used a HA in the ear contralateral to the CI. The authors report an improvement in speech perception scores for the EAS mode as compared to the CI-only mode. Mok, Grayden, Dowell, & Lawrence (2006) investigated the use of contralateral EAS on speech perception in quiet and in noise for 14 adults. They report that of the 14 participants, 6 showed significant bimodal benefit for open-set sentences, and 5 obtained bimodal benefit for closed-set spondee words when compared to the HA-alone and CI-alone conditions. Dunn, Tyler, & Witt's (2007) study involving 12 adults report similar findings to the above studies regarding the benefit of contralateral EAS for speech perception in quiet as well as noise. Other reported benefits of EAS are improved sound quality (James et al., 2005), melody recognition (Gantz et al., 2005), and sound localisation (Ching, Incerti, & Hill, 2004; Ruffin et al., 2007; Tyler et al., 2002).

The overall finding of these studies show that both ipsilateral and contralateral EAS can provide significant benefit for speech perception in noise, and other complex listening situations when compared to using only a CI (Fraysse et al., 2006; James et al., 2005; Kiefer et al., 2004). As EAS is only applicable for patients with a steeply sloping hearing loss (or who have adequate residual hearing to benefit from a HA), the preservation of hearing in surgery becomes an important consideration.

## 3.3 Hearing preservation during CI surgery

With traditional surgical techniques, acoustic hearing levels in the ear receiving the implant are usually significantly diminished post-surgery (Gomaa, Rubinstein, Lowder, Tyler, & Gantz, 2003; Rizer, Arkis, Lippy, & Schuring, 1988). The loss of residual hearing from CI surgery can occur immediately during surgery as a result of electrode insertion trauma (EIT). This could damage the inner structures of the cochlea like the lateral wall, cochlear duct, basilar membrane, osseous lamina, and modiolus (Ronald & Wright, 2006), alternatively the loss may be delayed in nature e.g. due to inflammation or other pathways that lead to cell death (Balkany et al., 2006).

Pau et al. (2007) looked at the potential of acoustic trauma from noise exposure to the inner ear during the drilling procedure for a cochleostomy. They performed experiments on four human temporal bones and made quantitative measurements of the sound pressure level (SPL) while a cochleostomy for cochlear implantation was drilled. They found the levels in excess of 130 dB SPL were reached at the level of the round window, and subsequently concluded that the inner ear may be affected by very high levels of sound which could lead to potential hearing loss.

The various operative techniques that attempt to preserve residual hearing are:

1. To try to avoid acoustic trauma to the cochlea from excessive noise levels using low speed bone drills during the operative procedure (Pau et al., 2007);

2. Modified soft surgery – i.e. carefully placing the cochleostomy anterior and inferior to the round window membrane to avoid damage to the basilar membrane and the osseous spiral lamina. This is combined with not suctioning around the round window (James et al., 2006);

3. Using steroids to protect against injury to the cochlear structures at the cellular level (Kiefer et al., 2004);

4. The use of a shorter electrode array (Gantz & Turner, 2003), atraumatic electrodes such as the. perimodiolar electrode array (James et al., 2005) or partial insertion of a conventional long electrode array (Skarzynski, Lorens, Piotrowska, & Anderson, 2007);

5. Ensuring a small cochleostomy to prevent buckling of the electrode and the leak of perilymph (Roland, Gstottner, & Adunka, 2005);

6. Using of inhibitors of cell death pathways (Balkany et al., 2006) and;

7. The induction of localised cochlear hypothermia (Balkany et al., 2005).

# 4 Overview of the study - Rationale and Hypothesis

The constantly evolving CI technology, in conjunction with the current advances in implantation techniques, have made EAS a viable option for the future. As reviewed in Chapter 3, evidence suggests that EAS is able to provide significant benefit to the CI users, particularly for perceiving speech in noise. However, as EAS is only applicable to patients with sufficient levels of low-frequency residual hearing that can be amplified with a HA, the preservation of residual hearing during the implantation procedure is crucial. Up until 2007, no specific measures were employed by surgeons involved with the Southern Cochlear Implant Program (SCIP) to preserve residual hearing during the implantation procedure.

Studies have reported a significant relationship between pre-operative residual hearing levels and post-operative speech perception outcomes. For example, van Dijk et al. (1999) found a significant positive correlation between pre-surgery residual hearing levels and post-surgery speech perception scores for 37 postlingually deafened adults using a Nucleus CI. Similar results are cited by other studies (Gantz, Woodworth, Knutson, Abbas, & Tyler, 1993; Summerfield & Marshall, 1995). In view of research suggesting that greater levels of residual hearing may provide a better post-surgery outcomes for CI users, along with the benefits of EAS, the surgeons in the SCIP are

beginning to implement a few of the modified surgical techniques mentioned in the previous chapter. In order to effectively evaluate the success of the new techniques baseline measures are required for comparison.

Accordingly, the primary aim of this study is to measure baseline levels of residual hearing for patients implanted through the SCIP. These results would reflect the average amount of residual hearing remaining post-CI surgery when no specific techniques were implemented to preserve hearing during the implantation procedure. The results can then be used to evaluate the efficacy of any techniques employed to preserve hearing. This research may also be able to identify existing CI users in the SCIP who have the potential to benefit from EAS (i.e. those that presently use the CI only, but have enough residual hearing that could benefit from a HA).

It is hypothesised that: i ) Although post-surgery hearing thresholds will be significantly lower than pre-surgery levels, numerous patients will still have some degree of residual hearing remaining in their implanted ear; and ii) That participants with greater levels of residual hearing in the implanted ear will perform better on speech perception tests.

# 5 Methods

## 5.1 Participants

At the start of the study, there were 130 adult CI users registered with the SCIP. Consent letters were sent to these 130 adults informing them about the study. Fifty-five individuals (42%) provided consent for researchers to examine their audiological records at the SCIP, with 44 (33%) of these individuals fulfilling the inclusion criterion detailed below. Of these 44 individuals, 25 were included as part of the study. Nineteen individuals could not be included as testing sessions could not be scheduled at convenient times for various reasons such as the individuals living out of town. There were 6 males and 19 females with a mean age of 57.4 years (SD= 13.89). Their average experience with a CI was 28.12 months (SD=19.14). None of the participants were using a HA in their other ear. Additional details of the participants included in the study are given in Table 5.1.

The participant inclusion criteria were adults (18 years or older) having pre-surgery hearing thresholds of 100 dB HL or better at 250 Hz, 500 Hz and 1000 Hz in the implanted ear, and speaking English as their first language.

## Table 5.1 Details of the participants

**Hearing loss:** Years from diagnosis of hearing loss to implantation.
**HA Use:** Years of HA use prior to implantation.
**Implant:** CI24 M = Nucleus CI24 with the straight array; CI24R (CS) = Nucleus CI24R with contour electrode array; CI24R (CA) = Nucleus CI24R with contour advance electrode array; Freedom = Nucleus Freedom implant with contour advance electrode array; Pulsar ci100 = MED-EL Pulsar CI implant with standard electrode array
**Strategy:** ACE= Advance Combination Encoder; FSP= Fine Structure Processing

| Participant | Age | Sex | CI ear | Hearing loss (Years) | HA use (Years) | CI use (Months) | Implant | Speech Processor | Strategy |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 58 | M | Left | 38 | 38 | 28 | CI24R (CS) | ESPrit 3G | ACE |
| 2 | 61 | F | Right | 51 | 1.5 | 38 | CI24R (CA) | ESPrit 3G | ACE |
| 3 | 38 | M | Left | 38 | 35 | 14 | Freedom Implant | Freedom SP | ACE |
| 4 | 52 | F | Right | 21 | 21 | 35 | CI24R (CS) | ESPrit 3G | ACE |
| 5 | 74 | F | Right | 42 | 38 | 23 | Freedom Implant | Freedom SP | ACE |
| 6 | 69 | F | Left | 29 | 16 | 29 | CI24R (CA) | ESPrit 3G | ACE |
| 7 | 66 | M | Left | 16 | 16 | 37 | CI24R (CS) | ESPrit 3G | ACE |
| 8 | 44 | F | Right | N/A | N/A | 36 | CI24R (CS) | ESPrit 3G | ACE |
| 9 | 61 | F | Left | 25 | 6 | 48 | CI24R (CS) | ESPrit 3G | ACE |
| 10 | 51 | M | Left | 24 | 10 | 24 | Freedom Implant | Freedom SP | ACE |
| 11 | 54 | M | Left | 44 | 0 | 16 | Freedom Implant | Freedom SP | ACE |
| 12 | 72 | F | Right | 22 | 21 | 10 | Freedom Implant | Freedom SP | ACE |
| 13 | 45 | F | Right | 45 | 42 | 29 | CI24R (CA) | ESPrit 3G | ACE |
| 14 | 75 | F | Right | 34 | 27 | 24 | Freedom Implant | Freedom SP | ACE |
| 15 | 47 | F | Right | 41 | 37 | 44 | CI24R (CA) | ESPrit 3G | ACE |
| 16 | 38 | F | Right | 16 | 16 | 3 | Freedom Implant | Freedom SP | ACE |
| 17 | 67 | F | Left | 67 | 36 | 11 | Freedom Implant | Freedom SP | ACE |
| 18 | 77 | F | Right | 37 | 37 | 4 | PULSAR CI 100 | Opus 2 | FSP |
| 19 | 77 | M | Right | 77 | 45 | 23 | Freedom Implant | Freedom SP | ACE |
| 20 | 46 | F | Left | 44 | 42 | 26 | CI24R (CS) | ESPrit 3G | ACE |
| 21 | 68 | F | Right | 48 | 31 | 30 | CI24R (CA) | ESPrit 3G | ACE |
| 22 | 39 | M | Left | N/A | N/A | 18 | Freedom Implant | Freedom SP | ACE |
| 23 | 63 | F | Right | 32 | 28 | 12 | Freedom Implant | Freedom SP | ACE |
| 24 | 29 | F | Right | 15 | 11 | 42 | CI24R (CA) | ESPrit 3G | ACE |
| 25 | 64 | F | Right | N/A | N/A | 99 | CI24 M | Freedom SP | ACE |
| Mean | 57.4 | | | 36.64 | 25.20 | 28.12 | | | |

This level was chosen as it was assumed that individuals with pre-surgery hearing thresholds poorer than 100 dB HL would be highly unlikely to have assessable levels of residual acoustic hearing post-surgery as the limit of most commercially available audiometers extends to a maximum of 120 dB HL.

## 5.2 Equipment and Materials

Puretone Audiometry

Puretone audiometry was performed using the *Interacoustics AD229e* Diagnostic audiometer and TDH39 supra-aural headphones.

Speech perception

The Consonant-Nucleus-Consonant (CNC) words test (Peterson & Lehiste, 1962), and the Hearing-In-Noise Test (HINT) (Nilsson, Soli, & Sullivan, 1994) were used. The CNC words test consists of 10 lists, each containing 50 mono-syllabic words. The HINT test comprises 25 phonemically balanced lists of 10 sentences each, and are the speech perception tests currently used by the SCIP. The recording used was the same as is used by the SCIP and is of a female speaker from New Zealand.

Sound level measurements

Sound level measurements were performed using the *R Ion NA-24* Sound level meter, set on the instantaneous and fast mode.

## 5.3 Procedures

Ethical approval for this study was obtained from The University of Canterbury's Human Ethics Committee and all the procedures were in accordance with those guidelines. Participation in the study was voluntary and participants were free to withdraw from the study without penalty or impact on their other clinical assessments. Potential participants were sent an information sheet, consent form and a reply-paid return envelope requesting access to their audiological records held at the SCIP. The audiological records of the individuals who provided their consent were examined. Information on the duration of deafness, duration of implant use, type of implant, speech processing strategy, any complications during implantation surgery, duration of HA use prior to implantation, pre-surgery hearing thresholds, and speech perception test results (both pre-surgery and post-surgery) were recorded. Participants that met the inclusion criteria were then contacted to arrange a convenient time for testing.

Testing was conducted in a single testing session of approximately one hour duration, at the University of Canterbury's Speech and Hearing Clinic. All testing was undertaken in a sound treated room. In the session, participant's hearing thresholds were firstly assessed using puretone audiometry. Following this, their speech perception ability was assessed. More details on both of these assessments follows. For all of the tests, participants were provided with standardised written instructions explaining the procedures and response(s) required. Partcipants also had the opportunity to ask questions before the testing commenced. Prior to testing, the ambient noise level in the testing room was checked with a sound level meter to ensure that it was below 39 dB(A)

in accordance with the American National Standards Institute (ANSI) standards (Frank, 2000). The levels of presentation for the speech stimuli were also calibrated to be 65 dB(A) at the listener's ear.

Puretone Audiometry

Participant's bilateral levels of acoustic hearing were assessed using puretone audiometry with supra-aural headphones. The unimplanted ear was tested first followed by the implanted ear. The order of testing across the frequencies was 1000, 1500, 2000, 3000, 4000, 6000, 8000, 750, 500 and 250 Hz. Participants were instructed to press a button each time they heard a 'beep'or' 'tone'. In a slight modification to the routine 'Modified Hughson-Westlake Ascending Procedure (Carhart & Jerger, 1959), 2 dB steps were used instead of the usual 5 dB steps. This allowed a greater degree of accuracy in examining the hearing thresholds of the participant post-surgery. Participants were asked to take off their CI for the testing (i.e. unaided threshold were obtained).

Speech Perception Testing:

Participants' speech perception ability was assessed using the CNC words and the HINT sentences tests. Testing was conducted in an 'auditory-alone' listening condition (i.e. without visual cues). Speech stimuli were presented at 65 dB(A), through a sound field

speaker placed one metre from the subject at 0 degree azimuth. This was the same presentation level used by the SCIP, and also corresponds to everyday conversational levels. Participants were asked to repeat back what they heard whilst using their CI. The speech stimuli were not repeated but the recording was paused between the sentences/words to give the subjects more time to respond if required. Participants were able to adjust the volume setting on their CI to their normal listening level before the test began. The tests were marked by the investigator during the session, using the standard marking guidelines as outlined in Nilsson et al. (1994) and Peterson & Lehiste (1962).

*CNC Words*: Each participant was tested using two lists of pre-recorded CNC words presented in quiet. The two lists were randomly selected from the 10 lists that comprise this test. A percentage words-correct score and a percentage phonemes-correct score was obtained for each list with the scores for the two lists being averaged to get the final score.

*HINT Sentences*: One list of pre-recorded HINT sentences was presented to each participant, in quiet, followed by one list presented with background noise (speech babble) using a SNR of +10 dB (i.e. speech signal 10 dB louder than the noise signal). Two lists were randomly selected from 12 of the 25 lists that comprise the HINT test. In order to ensure that a learning effect did not impact on the results, the 13 lists that were used by the SCIP in their rehabilitation sessions were not used to test the participants in this study. The number of words correctly repeated by the participant were totalled for each list and converted to a percentage-correct score.

# 6 Results

This chapter presents the results, along with the statistical analysis for the 25 participants, as well as further analyses from a subset of 13 participants that had measurable levels of acoustic residual hearing in the implanted ear post surgery. For all of the data analyses, 2-tailed statistical tests were used with a significance value of $p \leq 0.05$.

## 6.1 Hearing thresholds

The mean pre- and post-surgery thresholds for the 25 participants along with the average loss at each frequency is displayed in Figure 6.1. The individual thresholds of the participants showing pre- and post- surgery thresholds is included in the Appendix. The puretone average (PTA) was calculated by averaging the thresholds at 250, 500, 1000 & 2000 Hz. 250 Hz was included in the calculation of the PTA as residual hearing levels tend to be greater at the lower frequencies. Pre-surgery and post-surgery PTAs, along with the amount of hearing lost are listed in Table 6.1. The mean PTA pre-surgery was 89 dB HL (SD=12.46) and the mean post-surgery PTA was 117 dB HL (SD=7.09). The average loss across the four above-mentioned frequencies was 28 dB HL (SD=13.00). Of the 25 participants, 13 participants (52%) presented with measurable levels of acoustic hearing in their implanted ear (Measurable hearing being defined as recordable hearing at least one of these frequencies (250 Hz, 500 Hz and 1000 Hz).

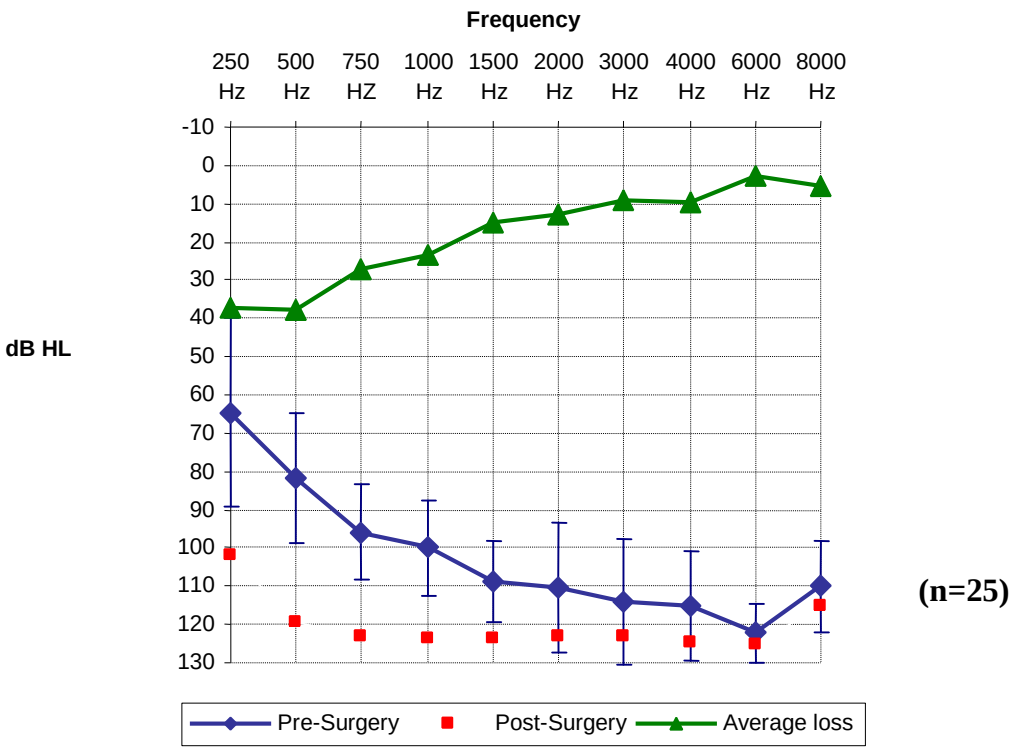



**Figure 6.1** **Mean puretone thresholds (implanted ear) pre-surgery, post-surgery and, average amount of hearing loss.**

(Error bars = 1SD)

Note: As the limits of the testing audiometer extended to a maximum of 110 dB HL at 250 and 8000 Hz, and 120 dB HL for frequencies between 500 to 6000 Hz, if no response was obtained at these limits the thresholds were recorded as 115 dB HL for 250 and 8000 Hz, and as 125 dB HL for 500 to 6000 Hz.

**Table 6.1** **Pure tone average (PTA) implanted ear - pre-surgery, post surgery, and the average loss.**

PTA = mean of 250, 500, 1000 & 2000 Hz

| **Participant** | **PTA (Pre-surgery)** (dB HL) | **PTA (Post-surgery)** (dB HL) | **Difference between pre- & post-surgery PTA** (dB HL) |
|---|---|---|---|
| 1 | 80 | 122 | 42 |
| 2* | 82 | 109 | 27 |
| 3 | 87 | 122 | 35 |
| 4 | 88 | 122 | 34 |
| 5 | 85 | 122 | 37 |
| 6* | 67 | 97 | 30 |
| 7 | 60 | 122 | 62 |
| 8* | 83 | 106 | 23 |
| 9 | 83 | 122 | 39 |
| 10 | 81 | 122 | 41 |
| 11* | 98 | 121 | 23 |
| 12 | 91 | 122 | 31 |
| 13* | 87 | 102 | 15 |
| 14* | 96 | 112 | 16 |
| 15* | 106 | 116 | 10 |
| 16* | 110 | 115 | 5 |
| 17 | 115 | 122 | 7 |
| 18* | 81 | 109 | 28 |
| 19* | 95 | 117 | 22 |
| 20* | 93 | 117 | 24 |
| 21 | 97 | 119 | 22 |
| 22* | 81 | 113 | 32 |
| 23 | 93 | 122 | 29 |
| 24* | 103 | 120 | 17 |
| 25 | 78 | 121 | 43 |
| Mean | 89 | 117 | 28 |

* Participants that had measurable residual acoustic hearing post-surgery.

## 6.2 Speech perception

Speech Perception in Quiet

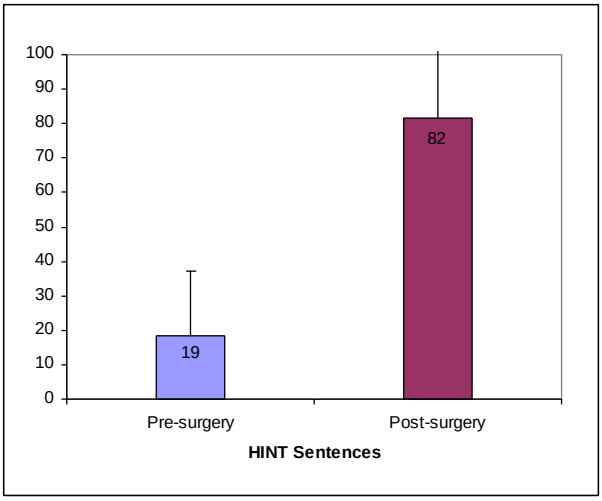
Figure 6.2 provides the mean pre- and post-surgery speech perception scores for HINT sentences, CNC words and CNC phonemes for the 25 participants.

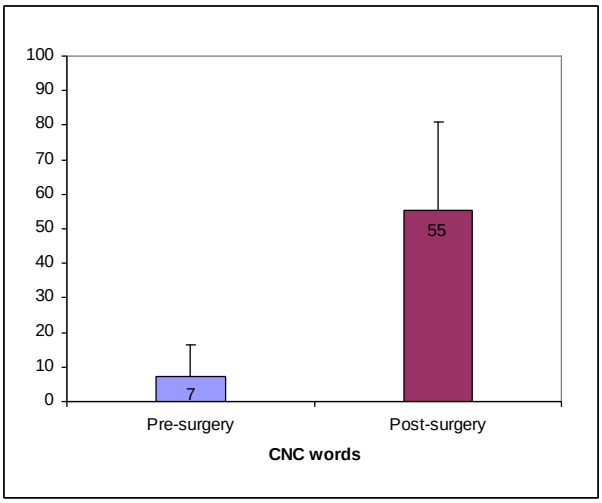
*HINT sentences*:

The mean score was 19% correct (SD=18.74) pre-surgery and 82% correct (SD=23.01) post-surgery. A paired t-test revealed that post-surgery scores were significantly better than pre-surgery scores ($p < 0.001$).

*CNC words*:

The mean pre-surgery words-correct score was 7% correct (SD=9.04) with the mean phonemes-correct score being 20% correct (SD=15.28). Post-surgery, the mean words-correct score was 55% (SD=25.41), with the mean phonemes-correct score being 72% correct (SD=21.37). Paired t-tests showed that the post-surgery scores were significantly better than the pre-surgery scores ($p< 0.001$ for both words-correct and phonemes-correct scores).



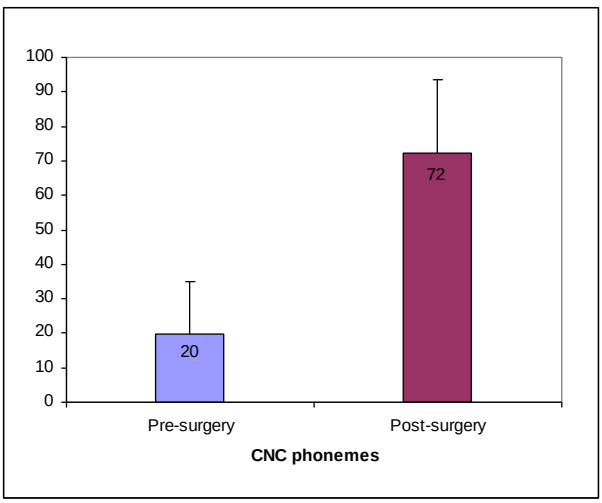




**Figure 6.2** **Pre-surgery vs. post-surgery mean speech perception scores in quiet for HINT sentences, CNC words, and CNC phonemes** (n=25). (Error bars = 1 SD)

Speech Perception in Noise

The mean post-surgery HINT sentence score when presented in noise was 50% correct (SD=30.32). Figure 6.3 illustrates the difference between post-surgery sentence scores when presented in quiet versus. noise. A paired t-test showed that the post-surgery scores for the quiet listening condition were significantly better than the noisy listening condition ($p<0.001$).

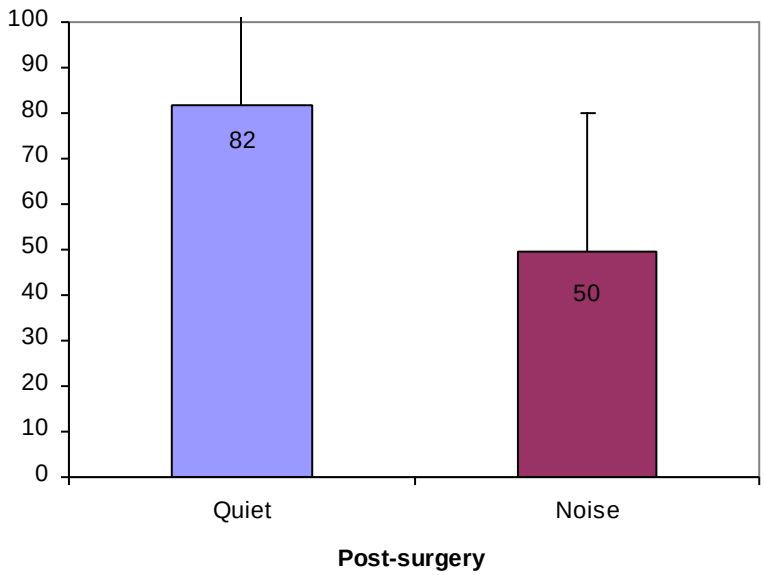



**Figure 6.3 Post-Surgery HINT sentence scores in quiet vs. noise**
(n=25)
(Error bars = 1SD)

## 6.3 Correlations

For all of the correlations below, non-parametric Spearman's rho were conducted in view of the small participant numbers, also that some of the data failed to pass the K-S test of normality. A significance level of $p < 0.05$ was used for all the correlations.

Correlational analyses were performed between age at the time of implantation and the scores from the three speech perception tests post-surgery for all the 25 participants. Results of the analysis revealed no correlation between age at the time of implantation and any of the three speech perception scores. Correlational analyses between pre-surgery hearing thresholds in the implanted ear and post-surgery outcomes of speech perception for the three tests revealed no correlation. As mentioned previously, 13 of the participants presented with measurable acoustic hearing post-surgery (Table 6.1). The following correlations were then made using the data from this subgroup of 13 participants. As per the previous section, the PTA used for these analyses were derived by averaging the thresholds from the lower four frequencies (i.e. 250 Hz, 500 Hz , 1000 Hz and 2000 Hz).

Hearing Levels and Post-surgery Speech Perception

The analyses between pre-surgery hearing thresholds for the implanted ear and speech perception post-surgery did not reveal any significant correlation (Figure 6.4). The relationship between the acoustic residual hearing levels (post-surgery) in the implanted ear and speech perception scores is illustrated in Figure 6.5. No significant correlation

was found between these two variables. Similar analysis for the hearing levels (post-surgery) in the unimplanted ear and speech perception scores again revealed no significant correlation as illustrated in Figure 6.6.

In consideration of the fact that the residual hearing levels were greatest for the low frequencies, a correlational analysis was conducted to see if there was any relationship between post-surgery speech perception scores and the average of 250 Hz and 500 Hz thresholds. There was no significant relationship.

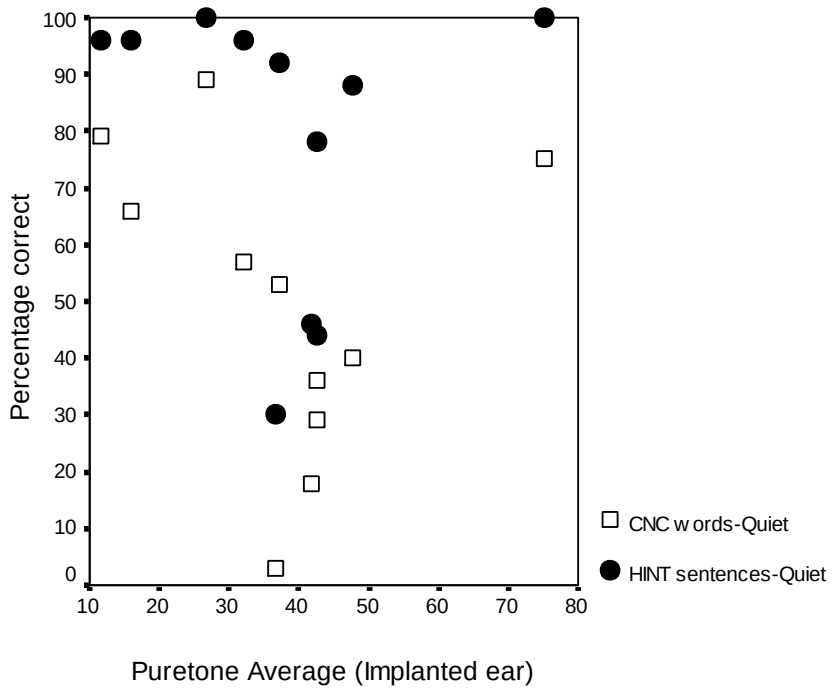



**Figure 6.4** **Relationship between pre-surgery PTA of the implanted ear and post-surgery Speech perception scores in quiet.**
(n = 13)
PTA = Average of 250, 500, 1000 and 2000 Hz

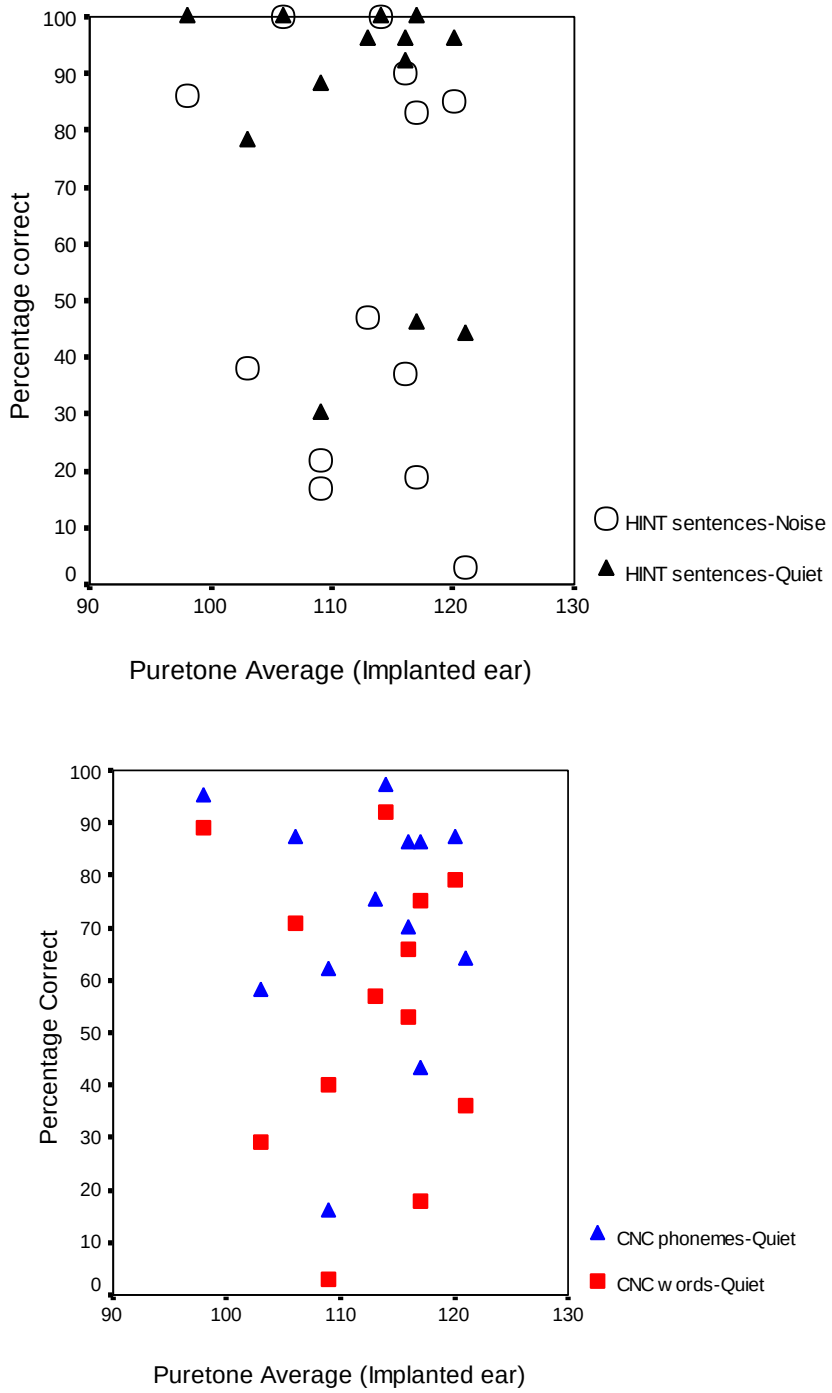
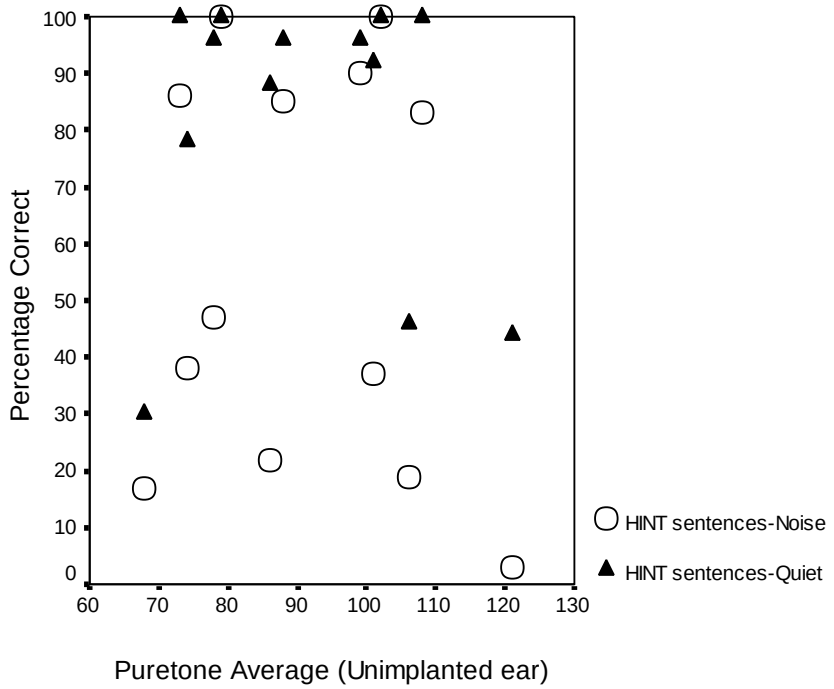



**Figure 6.5** **Relationship between post-surgery PTA of the implanted ear and post-surgery Speech perception scores.**
(n = 13)
PTA = Average of 250, 500, 1000 and 2000 Hz



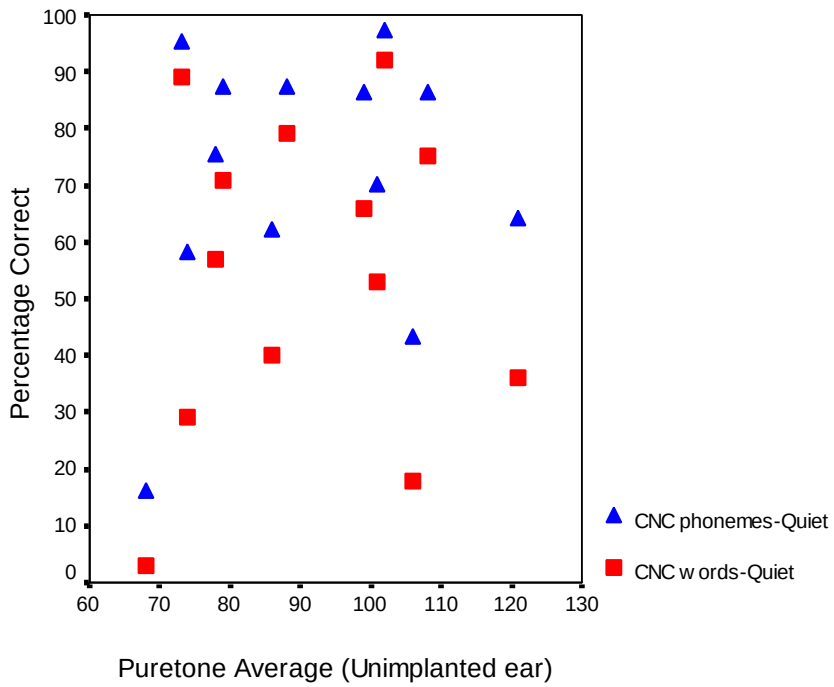




**Figure 6.6** **Relationship between post-surgery PTA of the unimplanted ear and post-surgery Speech perception scores.**
(n=13)
PTA= Average of 250, 500, 1000 and 2000 Hz

Subject factors and post-surgery speech perception scores

For the 13 participants with post-surgery residual hearing correlational analyses were also conducted to assess for the relationship between speech perception scores and the subject variables of i) Duration of hearing loss; ii) duration of HA use pre-implantation; and iii) experience with the CI (Figures 6.7, 6.8, 6.9 respectively). No significant correlation could be found for any of these three factors.

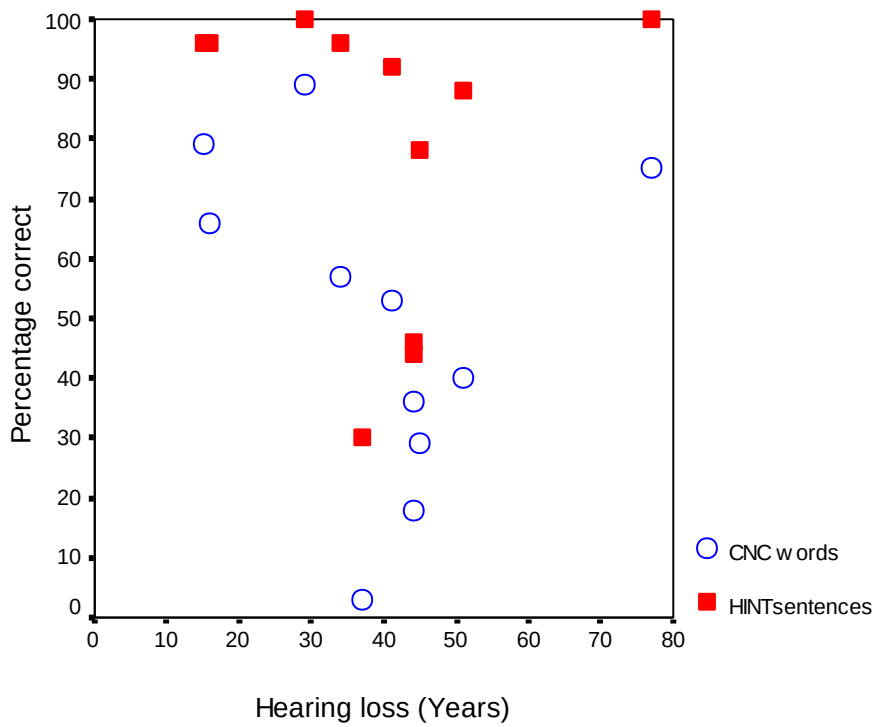



**Figure 6.7** **Relationship between duration of hearing loss and post-surgery speech perception scores in quiet.**
(n=13)

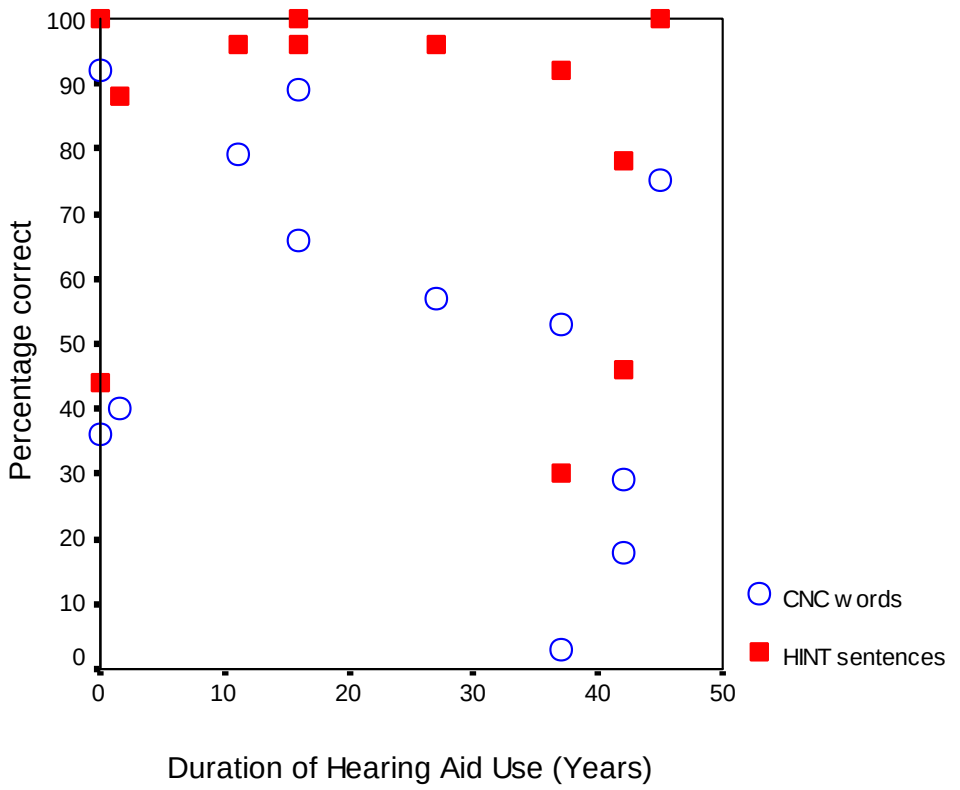



**Figure 6.8** **Relationship between duration of hearing aid use pre-implantation and post-surgery speech perception scores in quiet.**
(n=13)

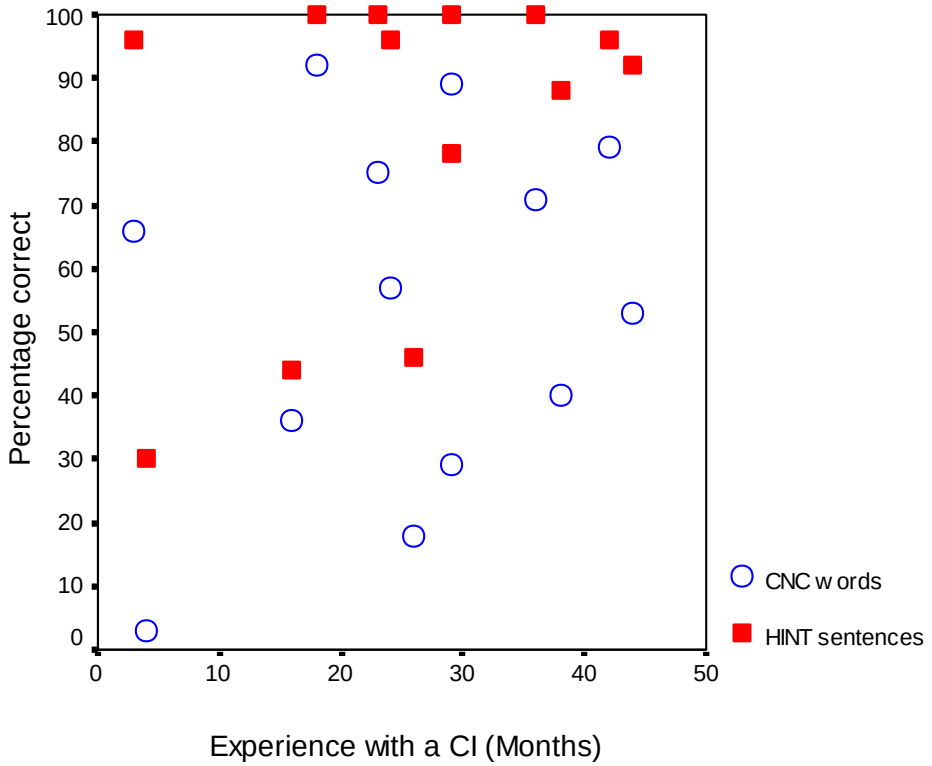



**Figure 6.9** **Relationship between time with CI and post-surgery speech perception scores in quiet.**
(n=13)

## 6.4 Hearing loss comparison – implanted vs. unimplanted ear

To assess if the change in amount of hearing (pre- to post-surgery) for the implanted ear was the same as the change in the unimplanted ear, a comparison of the hearing loss in the implanted ear was made to the hearing loss in the unimplanted ear. This was in order to account for the possibility of further hearing deterioration since the time of implantation(i.e. in the time after surgery as opposed to being a consequence of the surgery itself) Table 6.2 shows the pre- and post-surgery PTAs, as well as the average amount of hearing lost for both ears, for the 13 participants who had measurable levels of residual hearing post-implantation. The mean loss in the implanted ear was 21 dB HL (SD = 8.00), with the mean loss in the un-implanted ear was -1 dB HL (SD = 14.00) (Figure 6.10). A paired samples t-test indicated that the hearing loss in the unimplanted ear was significantly less than the hearing loss in the implanted ear ($p < 0.001$).

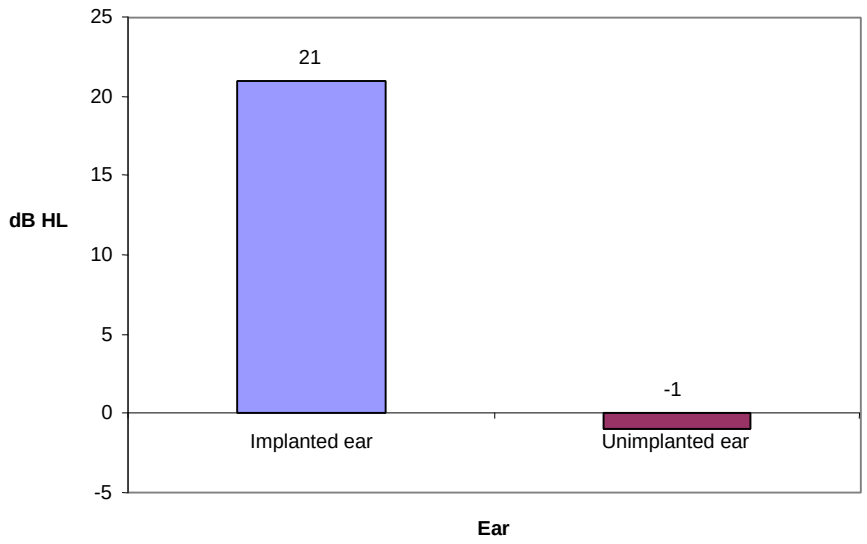



**Figure 6.10 Mean loss for the implanted and the un-implanted ear.**
Mean loss= post-surgery PTA- pre-surgery PTA averaged across 13 participants with measurable levels of residual hearing post-implantation

**Table 6.2 PTA and degree of hearing loss for the implanted and un-implanted ear.**

PTA = Average of 250, 500, 1000 and 2000 Hz

| | Implanted ear | | | | Un-implanted ear | | |
|---|---|---|---|---|---|---|---|
| Participant | Pre-surgery PTA (dB HL) | Post-surgery PTA (dB HL) | Average loss (dB HL) | (dB HL) | Pre-surgery PTA (dB HL) | Post-surgery PTA (dB HL) | Average loss (dB HL) |
| 2 | 82 | 109 | 27 | | 98 | 86 | -12 |
| 6 | 67 | 97 | 30 | | 75 | 72 | -3 |
| 8 | 83 | 106 | 23 | | 72 | 78 | 6 |
| 11 | 98 | 121 | 23 | | 122 | 120 | -2 |
| 13 | 87 | 102 | 15 | | 87 | 73 | -14 |
| 14 | 96 | 112 | 16 | | 77 | 78 | 1 |
| 15 | 106 | 116 | 10 | | 96 | 101 | 5 |
| 16 | 110 | 115 | 5 | | 113 | 99 | -14 |
| 18 | 81 | 109 | 28 | | 72 | 68 | -4 |
| 19 | 95 | 117 | 22 | | 113 | 108 | -5 |
| 20 | 93 | 117 | 24 | | 112 | 106 | -6 |
| 22 | 81 | 113 | 32 | | 60 | 101 | 41 |
| 24 | 103 | 120 | 17 | | 91 | 87 | -4 |

***** Negative values indicate that post-surgery hearing thresholds are better than pre-surgery thresholds (This will be discussed further in the next chapter).

# 7 Discussion

This chapter discusses the findings of this study, how they relate to the two hypotheses proposed, other relevant issues that the results brought up, possible limitations of the study, and suggestions for future research in the area.

## 7.1 Hypothesis 1: Hearing thresholds

The results of the study substantiate the first hypothesis; post-surgery hearing thresholds were significantly lower than pre-surgery levels, however numerous patients had some degree of residual hearing remaining in their implanted ear. Even in the absence of specific hearing preservation techniques being used when the participants in this study had their CI surgery, some of the participants still presented with measurable levels of post-surgery residual hearing. The mean post-surgery PTA hearing thresholds (i.e. average of 250, 500, 1000 & 2000 Hz) was found to be 117 dB HL, as compared to 89 dB HL pre-surgery. That is, there was a mean PTA loss of 28 dB pre-to post-surgery across the 25 participants. For the 13 of the 25 participants (52%) with measurable levels of acoustic hearing levels in their implanted ear post-surgery; the post-surgery, PTA was 118 dB HL.

These findings are in line with the findings of Hodges, Schloffman, & Balkany (1997) who looked at the pre- and post-surgery pure tone thresholds of 40 participants who had been implanted with a multi-channel CI. They reported that 21 (52%) of their participants had residual hearing for at least one of the frequencies assessed (500, 1000, 2000 Hz) both pre- and post-surgery, with the majority of participants having measurable hearing at all three frequencies tested.

In a similar study, Fraysse et al. (1998) looked at the effect of cochlear implantation on residual puretone thresholds for 20 post-lingually deafened adults. They obtained baseline pre-surgery audiograms for octave frequencies between 250 Hz to 8000 Hz and subsequently compared these to audiograms obtained 1 month after surgery. Similar to the current study, Fraysse et al. (1998) also report that although the implantation procedure resulted in a significant downward shift in hearing thresholds for the implant ear in the majority of subjects, report that 50% of their subjects displayed conservation of some residual hearing post-surgery.

Having established that cochlear implant surgery adversely affects hearing thresholds, it is worthwhile to consider the degree of hearing lost when conventional CI surgery techniques are used. In the above-mentioned study, Fraysse et al. (1998) report an average loss of 15 dB HL across the 3 frequencies tested (i.e. 500, 1000 and 2000 Hz) (116 dB HL pre-surgery; 131 dB HL post-surgery) for their study. In comparison, the PTA loss for our study was 28 dB HL (89 dB HL pre-surgery; 117 dB HL post-

surgery). The higher degree of loss, in comparison to that reported by Fraysse et al. (1998) could be attributed to a number of factors.

Firstly, Fraysse et al. (1998) calculated residual hearing as the average of 500, 1000 and 2000 Hz where as the current study used the average of 250, 500, 1000 and 2000 Hz. As the amount of residual hearing is likely to be greater in the lower frequencies pre-surgery, the greater amount of loss at the lowest frequency (250 Hz) would have a greater impact when calculating the average amount of hearing loss. Similarly, a second possible reason for the difference in the magnitude of the hearing loss may be that the participants in the current study had better pre-surgery hearing thresholds than those in of Fraysse et al's. (1998). That is the participants in the current study had more hearing to lose. Further, the testing limits of the audiometer must be considered; the higher mean threshold of Fraysse et al.'s study suggests that the ceiling effect would have had a greater impact on their study. If the PTA for the current study was calculated as the average loss at 500 Hz, 1000 Hz and 2000 Hz (as was the case in Fraysse et al's. (1998) study), the PTA loss would have been 12 dB HL (99 dB HL pre-surgery; 111 dB HL post-surgery). This degree of loss is consistent to that of Fraysse et al's. (1998) study. This suggests that the greater degree of loss at 250 Hz could account for the average-loss differences between the current study and Fraysse et al.'s (1998) study.

Several important considerations need to be accounted for when examining the mean levels of loss due to cochlear implantation found in this study. Firstly, the raw data seems to suggest that there is less loss at the higher frequencies than the lower frequencies. That is the mean loss at 250, 500, 1000, 2000, 4000, 8000 Hz was 37, 37

24, 13, 9 and 5 dB HL respectively. However, it should be noted that the initial degree of loss pre-surgery was greater at the higher frequencies, therefore not only did the participants have less residual hearing to lose at these higher frequencies, but there is also more likelihood that the limits of the audiometer would have been reached. Secondly, it is also possible that participants may have lost some or all of their residual hearing after cochlear implantation.

One well documented reason for hearing loss in adults is presbycusis. Yao, Turner, & Gantz (2006) looked at this issue in relation to potential CI users. They investigated the stability of low frequency hearing thresholds in adults and children who are potential candidates for EAS. Their analysis of 28 adult patients' data indicated that there was an average of only 1.05 dB hearing deterioration per year in the low frequencies and that presbycusis accounted for approximately one third to one half of this decline. Other contributing factors were the original etiology of the hearing loss and exposure to noise. The cross-sectional approach to the current study means that participants were at different time frames post-implantation; therefore, it is possible that there has been a deterioration of their hearing thresholds in the time since their surgery. Should this be the case the post-surgery hearing levels recorded in this study could be worse than the level in the initial period post-surgery. Therefore a comparison between current hearing levels to pre-surgery levels may not be an accurate reflection of the deterioration resulting from the CI surgery itself, but rather a combination of the surgery along with further deterioration over the time since the implant. To account for this, we compared the pre- and post-surgery thresholds of the unimplanted ear with those of the implanted ear for the 13 participants that presented with measurable acoustic hearing. This

provides some indication as to the amount of deterioration of hearing that could be attributed to causes other than the CI surgery; as it would be reasonable to expect that post-surgery deterioration in hearing would affect both ears equally. Therefore if the degree of loss pre- to post-surgery in the implanted ear is greater than the degree of loss for the unimplanted ear, this intra aural difference could be attributed to the implantation procedure. Mean loss in the implanted ear was 21 dB HL with the mean loss in the unimplanted ear being -1 dB HL. This suggests that the loss in the implanted ear is due to the implantation procedure, and not further post-surgery deterioration. These results are also consistent with the findings of Fraysse et al.(1998).

Interestingly, as just mentioned, the mean loss for the unimplanted ear was -1dB HL. This result suggests that hearing levels in the unimplanted ear post-surgery actually improved in comparison to the pre-surgery levels. Although this is unlikely to actually e the case, one possible cause for this impression of better hearing could be less precise pre-surgery thresholds. The pre-surgery thresholds were recorded in 5 dB steps, where as the post-surgery thresholds were recorded in 2 dB steps and thus provide a more precise result. It is also possible that pre-surgery thresholds were not entirely accurate. The pre-surgery thresholds were taken from the audiological records at the SCIP. These pre-surgery assessments were conducted at various clinical settings, which may have had higher levels of ambient noise in the test environment. This could lead to a false elevation of thresholds. Due to the time span since implantation for some of the participants, the validity or nature of pre-surgery assessments could not be quantified / verified in some cases.

## 7.2 Hypothesis 2: Residual hearing and speech perception

The results of this study did not substantiate the second hypothesis that participants with greater levels of residual hearing in the implanted ear will perform better on speech perception tests. There was no significant correlation between levels of residual hearing in the implanted ear and any of the speech perception measures. These results are consistent with the findings of Gifford et al. (2007), and Turner, Reiss, & Gantz (2006).

Studies have reported a significant relationship between pre-operative residual hearing in the implanted ear and post-operative speech perception outcomes. For example, van Dijk et al. (1999) found a significant positive correlation between pre-surgery residual hearing levels and post-surgery speech perception scores for 37 postlingually deafened adults using a Nucleus CI. Similar results were cited by other studies (Gantz et al., 1993; Summerfield & Marshall, 1995). However, the results of this study did not find this relationship. Similarly, there was no correlation between post-surgery hearing levels for either ear and speech perception with the CI. It is likely that a ceiling effect would have impacted on the post-surgery speech perception scores in quiet for sentences. Nine (36%) of the participants achieved scores > 90% correct for sentence stimuli in quiet. However there was also no correlation between residual hearing levels and speech perception in quiet for words or sentence perception in noise for sentences which were not affected by a ceiling effect. One possible reason for this could be the high hearing thresholds of the participants of this study. That is there was insufficient range to provide sufficient scope to show correlation with the numbers of participants involved

in the study. Or it may be just possible that no association exists between these factors for the participants of this study.

It should also be highlighted that the participants in this study did not use a HA along with the CI during the process of testing. Therefore one reason for the lack of correlation between residual hearing levels in the unimplanted ear and speech perception could be that, with speech perception stimuli presented at 65 dB(A) it is unlikely that acoustic hearing would have contributed to the participants' speech scores as the participants' unaided thresholds (Appendix) were essentially above the presentation levels used in this study.

## 7.3 General discussion

It is worthwhile looking at these results from a broader perspective and in context with existing and future research.

### 7.3.1 Hearing conservation during surgery

The primary aim of this study was to obtain baseline measurements of levels of residual hearing in the adult cochlear implant users from the SCIP. This would allow comparative data for new surgical techniques implemented to try and improve residual hearing levels. Fraysse et al. (2006) report the results of hearing preservation following

implantation of a Nucleus 24 Contour Advance CI. Twelve of the 27 patients in their study had been implanted using a “soft-surgery protocol’ aimed to preserve hearing. For these 12 patients, thresholds were conserved within 20 dB of pre-surgery levels for 50% of patients at 125 Hz, 50% of patients at 250 Hz, and 33% of patients for 500 Hz. In comparison, in our study thresholds were conserved within 20 dB of pre-surgery level for 20% of patients at 250 Hz and 8% of patients at 500 Hz. James et al. (2006) found that 7 of 10 subjects implanted with a Nucleus 24 Contour Advance using soft-surgery and an advanced-off stylet technique had hearing preserved within 40 dB of pre-surgery levels.

Berrettini, Forli, & Passetti (2007) looked retrospectively at the conservation of residual hearing in three groups of patients implanted with a Nucleus CI using different electrode arrays and surgical techniques: i) Eight patients with CI 24 standard arrays using a classic round window cochleostomy; ii) Eleven patients with Contour electrode arrays using the soft-surgery technique; iii) Eleven patients with Contour Advance electrode array via modified anterior inferior cochleostomy. Their analysis aimed to assess which approach led to greater preservation of residual hearing; preservation of residual hearing was defined as hearing within 20 dB of pre-surgery thresholds at 250, 500 and 1000 Hz. They report that hearing was preserved in 81.8 % in group iii) as compared with 25% and 45.5% in group i) and ii) respectively. Balkany et al. (2006) report hearing preservation within 20 dB of pre-surgery thresholds in 89% of their 28 patients who were implanted with the Nucleus Freedom Contour Advance electrode using modified soft-surgery techniques. Di Nardo et al. (2007) report hearing preservation in 78% of their 37 patients, using minimally invasive approach designed to

reduce overall trauma to inner ear structures. Seven of these patients were implanted with Advanced Bionics implant, four with Med-El implant, 24 with the Nucleus implants and two with the MXM implant.

Other methods to preserve residual hearing are that have been used in humans are use of shorter electrodes (e.g. hybrid devices), performing a partial insertion of the standard electrode array, and the use of glucocorticoids locally during surgery. These were discussed in Chapter 3. Skarzynski, Lorens, Piotrowska, & Anderson (2007) report the results from 10 participants who were implanted with partially-inserted MED-EL COMBI 40 + electrode , using the round window approach. Hearing preservation was achieved in 9 of the 10 participants. Similar outcomes are reported by other studies using a range of methods like application of glucocorticoids locally during the CI surgery to reduce foreign body reaction to electrode array (Kiefer et al., 2004), or the use of a hybrid device using a short electrode array (Gantz & Turner, 2003; Luetje, Thedinger, Buckler, Dawson, & Lisbona, 2007). It is beyond the scope of the current thesis to detail these studies or techniques, and the reader is referred to the above-mentioned references for more information. In comparison, hearing preservation rate for the current study was 52%, with no specific techniques being used to preserve residual hearing.

### 7.3.2 Speech Perception

The SCIP candidacy criteria for cochlear implantation includes having pre-surgery speech perception scores less than 40% correct in the best-aided condition, and less than 60% correct in the ear to be implanted. Therefore, in order to evaluate if the current candidacy criteria for the SCIP is appropriate, (i.e. if implant recipients obtained significant improvement in speech perception outcomes post-surgery), this study also conducted speech perception tests with participants post-surgery (CI only). These results were subsequently compared to their pre-surgery speech perception scores. The participants showed significant improvement in their pre- to post-surgery speech perception scores in quiet (Sentences: pre- 19%; post- 82%. Words: pre- 7%; post- 55%). This suggests that the current SCIP criteria are enabling the majority of CI recipients to achieve significantly better speech perception in quiet. The speech perception results of this study are consistent with the findings of Kiefer et al. (2004), who report an improvement from 32% to 78% correct for open-set sentences, and an improvement from 7% to 56% for monosyllabic words in quiet. Various other studies report a similar improvement in speech perception post cochlear implantation (Fraysse et al., 2006; Hamzavi et al., 2003; James et al., 2006; Kiefer et al., 2004).

This significant improvement in speech perception outcomes (post-surgery) for the participants of our study indicates that the current speech criteria used by the SCIP to evaluate cochlear implant candidacy is not lenient. It may also be worthwhile considering expanding the implantation criteria, should resources, funding be available. For example, Dowell et al.'s (2004) study, the authors justified a criteria of sentence perception scores ≤ 70% (instead of 60%), in the best-aided condition. Expanding the criteria would allow more people with a significant sensorineural hearing loss to potentially benefit from a CI.

As mentioned in Chapter 2 although most current CI users achieve excellent speech perception in quiet listening conditions, understanding speech in the presence of background noise is still challenging for current users of CI users. This is regardless of the implant manufacturer, or speech processing strategy used (Fraysse et al., 2006; James et al., 2006; Munson & Nelson, 2005; Stickney et al., 2004; Yao et al., 2006). Fraysse et al. (2006) found the mean post-operative speech perception score in noise for open-set sentences to be 52% correct, and 60% correct for monosyllabic words in quiet. Similar results have been reported by James et al. (2006) where the mean post-operative sentence perception score in noise was 60% correct, with a  Words in quiet score of 56% correct. Understanding speech in background noise requires finer spectral resolution than is required for speech perception in quiet, along with temporal fine-structure information (Fu et al., 1998). With regard to spectral resolution, for a person using a cochlear implant this is governed by the number of channels which the input sound is divided into. For the Nucleus implants in this study, there are a maximum of 22 channels for stimulation. For the MED-EL implant up to 12 channels of stimulation are available. This is compared to the infinite number of non-linear auditory filters of a normally hearing cochlea with their continuous center frequencies. The crude spectral resolution of current day speech processing strategies makes it difficult for the CI user to understand speech in the presence of background noise (Friesen, Shannon, Baskent, & Wang, 2001). This is confounded by the fact that the current day speech processing strategies eliminate temporal fine structure information, preserving only the envelope information from the input signal. Although envelope information is sufficient for perceiving speech in quiet, it appears that fine structure information s necessary for

accurate speech perception in noise (Smith, Delgutte, & Oxenham, 2002). The results from the current study support these findings; sentence perception scores decreased significantly from 82% correct in quiet to 50% correct in noise.

Studies comparing speech understanding in noise of CI-alone and EAS (CI + HA) have shown a significant benefit for the EAS users (Fraysse et al., 2006; James et al., 2005; Kiefer et al., 2004). At present there are few patients in the SCIP who use a contralateral HA, irrespective of their residual hearing levels in the non-implanted ear. With the results of studies showing that a HA can assist in more-complex listening tasks, a HA may be a worthwhile consideration for these patients. For example of the participants in our study, participants 1, 2, 3, 4, 5, 6, 8, 12, 13, 14, 18, 23, and 24 may benefit from a HA for their non-implanted ear, based on this ears thresholds (Appendix).

### 7.3.3 Predictors of CI performance post-surgery

Although most CI users obtain significant benefit from their CI, there are still some patients who do not achieve satisfactory post-surgery outcomes. A number of studies have been conducted to try to identify predictive variables for post-surgery outcomes. Some studies have reported a negative correlation between the age of the individual at the time of implantation and their speech perception performance, with poorer outcomes recorded for those at an older age (Gantz et al., 1988; Waltzman, Fisher, Niparko, & Cohen, 1995). Dowell et al.'s (2004) study of 262 adults reported that younger patients showed better speech performance post-surgery than older patients. However there have

been other studies which have not found age to be a predictor of post-surgery performance (Green et al., 2007; Waltzman, Cohen, & Shapiro, 1993). In the current study there was no significant correlation between age at time of implantation of the CI user and the speech perception scores post-surgery.

Duration of hearing loss pre-surgery is another factor that has been found by some studies to be a predictor of performance post-surgery. Dowell et al. (2004), Gantz et al. (1993),Green et al. (2007) and Gomma et al. (2003) all found that patients with shorter durations of severe to profound hearing loss pre-surgery tended to have better post-surgery speech scores. In this study, clinical records did not specify the duration of severe to profound loss. Therefore, a correlation was calculated based on time from of diagnosis of hearing loss to the time of the implantation (i.e. duration of any hearing loss). There was no significant relationship between this factor and post-surgery speech perception scores. The lack of participant numbers and a ceiling effect in the post-surgery speech perception scores could have contributed to the lack of a correlation in this study.

Another predictive variable of CI outcomes specified in some studied is the duration of CI use. However, this study did not identify a correlation between time with the implant and speech perception scores. This may be in part due to the fact that 23 participants had had their CI for over 12 months, with 16 participants having greater than 24 months implant experience. Ruffin et al. (2007) evaluated the long-term performance of 31 adult Clarion CI users and found that there was no significant improvement in speech perception after 24 months experience with the implant. Hamzavi, Baumgartner, Pok,

Franz, & Gstoettner (2003) report that subjects made statistically significant improvements in speech perception in the first 12 months post-implant, with more-gradual improvements in the next 12 month period. These findings suggest that performance tends to plateau by about 12-24 months post-surgery for most implantees.

## 7.4 Limitations, further research and clinical implications.

There are several limitations which should be considered when interpreting the results of this study, or if this study was to be replicated in future. Firstly, only 25 participants out of the 44 CI users from the SCIP who fulfilled the participant inclusion criteria were able to participate in the study. Many of the participants lived out of the city, and scheduling a time for them to attend a testing session at the University Clinic was often unfeasible. Some of the participants could not be contacted to arrange for a testing session, whilst others were not coming into the city during the time period of this study. A longer time frame or a follow-up study could have helped recruit a greater number of participants.

Secondly, pre-surgery testing was performed using 5 dB steps where as post-surgery testing was done using 2 dB steps. Using 2 dB steps in at least one pre-surgery test is recommended for future clinical assessment in order to provide greater accuracy when comparing to post-surgery thresholds. This will be particularly relevant when the surgeons want to assess the effectiveness of any modified surgical techniques or procedures. To allow for control over factors such as the progressive loss of hearing levels post-surgery, a longitudinal research design could be adopted where pre- and

post-surgery hearing tests are conducted at specific time intervals post-implantation for al the participants (e.g. 1 month, 3 months, 6 months, 12 months etc.).

Thirdly, none of the 13 participants that presented with residual hearing were currently using a HA in conjunction with the CI. A future study to evaluate the potential benefit that the HA may provide could be done using these participants with the results compared to this study.

The clinical implications of the results from the current research include that current, as well as future implantees through the SCIP who present with residual hearing should be encouraged to use a HA in their contralateral ear, along with their CI. This would allow them to maximise the benefits of both electric as well as low-frequency acoustic hearing. Additionally, the results from this study could be used to evaluate the efficacy of the new modified surgical techniques or strategies that the surgeons in the SCIP are beginning to implement. Should there be a further improvement in post-surgery outcomes, this could translate into expanding the candidacy criteria for a CI to include those persons with better hearing thresholds.

Finally, this study has demonstrated that like many overseas programs, cochlear implantation in New Zealand provides significant speech perception benefit for those with a significant sensorineural hearing loss. The mean open-set sentence perception improvement from 19% pre-surgery to 82% post-surgery is a clinically significant change. This along with the suggestion of potentially even better post-surgery outcomes in the future could be used to lobby the government for increased funding to the CI

program. This would not only be to address the current waiting list, but to enable more people who could potentially benefit from a CI to be afforded the opportunity to obtain one.

# 8 Summary and conclusion

This study found that even in the absence of specific hearing preservation techniques being used during implantation surgery for participants of this study, some of the participants still presented with measurable levels of post-surgery residual hearing. Thirteen of the 25 participants (52%) presented with measurable levels of acoustic hearing in their implanted ear. Further, 13 participants had aidable hearing in their contralateral ear. The speech perception results obtained from this study suggest that these implant recipients are obtaining significant improvement in speech perception outcomes post-surgery. The current SCIP candidacy criteria for cochlear implantation includes having pre-surgery speech perception scores less than 40% correct in the best-aided condition, and less than 60% correct in the ear to be implanted. The significant pre- to post-surgery improvement in speech perception outcomes for the participants of our study is a clear reflection that the current speech criteria for used by the SCIP to evaluate cochlear implant candidacy is not too lenient.

This thesis has also suggested that current, as well as future implantees through the SCIP who present with residual hearing in their contralateral ear should be encouraged to use a HA along with their CI. This would allow them to maximise the benefits of both electric as well as low-frequency acoustic hearing. Furthermore, should there be a future improvement in post-surgery outcomes resulting from the new modified surgical techniques or strategies that the surgeons in the SCIP are beginning to implement, this could translate into expanding the SCIP's candidacy criteria for a CI. However, this

would probably require additional funding in order to ensure that there are sufficient resources for increased patient numbers. The speech perception benefits demonstrated in this and many similar studies, along with the quality of life reported by a host of studies (Cohen, Labadie, Dietrich, & Haynes, 2004; Damen, Beynon, Krabbe, Mulder, & Mylanus, 2007; Mo, Lindbaek, Harris, & Rasmussen, 2004) should be communicated to the government and other funding bodies. With the continual improvements in CI outcomes, more hearing impaired people are, and will continue to benefit from a CI.

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# Appendix

## (A) Pre-surgery thresholds

### Implanted ear

| Participant | 250 Hz | 500 Hz | 750Hz | 1000 Hz | 1500Hz | 2000 Hz | 3000 Hz | 4000 Hz | 6000 Hz | 8000 Hz |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 60 | 80 | 90 | 95 | 90 | 85 | 80 | 95 | NR | NR |
| **2** | 60 | 70 | | 80 | 105 | 120 | NR | 115 | NR | NR |
| **3** | 65 | 75 | 85 | 100 | 105 | 110 | 120 | NR | NR | NR |
| **4** | 55 | 75 | 95 | 100 | 115 | NR | NR | NR | NR | NR |
| **5** | 60 | 70 | 85 | 105 | 110 | 105 | 120 | 115 | NR | NR |
| **6** | 30 | 35 | 95 | 100 | 105 | 105 | NR | NR | NR | 95 |
| **7** | 55 | 55 | | 65 | | 65 | 70 | 95 | 110 | NR |
| **8** | 20 | 90 | | 105VT | | 120 | | 115VT | | NR |
| **9** | 65 | 70 | | 90 | | 110 | NR | NR | NR | NR |
| **10** | 65 | 75 | 90 | 95 | 95 | 90 | 95 | 100 | NR | NR |
| **11** | 90 | 100 | | 95 | | 110 | 95 | 100 | | 90 |
| **12** | 70 | 80 | 85 | 90 | 110 | NR | NR | NR | NR | NR |
| **13** | 65 | 70 | 85 | 90 | 95 | NR | NR | NR | NR | NR |
| **14** | 50 | 105 | | 115 | | 115 | 115 | 115 | 110 | 105 |
| **15** | 100 | 100 | | 110 | 110 | 115 | NR | NR | NR | NR |
| **16** | 100 | 105 | 115 | 110 | 115 | NR | NR | NR | NR | NR |
| **17** | NR | 95 | NR | NR | NR | NR | NR | NR | NR | NR |
| **18** | 35 | 65 | 85 | 105 | 120 | 120 | 115 | NR | NR | NR |
| **19** | 70 | 85 | 95 | 100 | NR | NR | NR | NR | NR | NR |
| **20** | 95 | 95 | 95 | 95 | 90 | 90 | 90 | 90 | 95 | 95 |
| **21** | 75 | 95 | 105 | 105 | 110 | 115 | 115 | NR | NR | NR |
| **22** | 80 | 80 | | 90 | | 75 | | 75 | | 65 |
| **23** | 45 | 95 | 110 | 115 | 120 | 120 | 120 | NR | NR | NR |
| **24** | 75 | 100 | | 115 | 115 | NR | NR | NR | NR | NR |
| **25** | 15 | 80 | | 105 | 110 | 115 | 115 | 115 | NR | NR |

**NR**: No response at limits of audiometer; **VT**: Vibrotactile response; **Empty spaces**: No data available

**Unimplanted ear**

| Participant | 250 Hz | 500 Hz | 750Hz | 1000 Hz | 1500Hz | 2000 Hz | 3000 Hz | 4000 Hz | 6000 Hz | 8000 Hz |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 60 | 100 | NR | 100 | 110 | 115 | 120 | NR | NR | NR |
| **2** | 85 | 90 | | 95 | 120 | NR | NR | NR | NR | NR |
| **3** | 65 | 80 | 100 | 105 | 110 | 110 | 115 | NR | NR | NR |
| **4** | 85 | 85 | 90 | 95 | 100 | 105 | 110 | 110 | NR | NR |
| **5** | 50 | 60 | | 80 | 110 | 110 | 115 | 105 | NR | NR |
| **6** | 40 | 55 | 70 | 95 | 110 | 110 | 115 | NR | NR | NR |
| **7** | 60 | 60 | 75 | 80 | | 75 | 80 | 85 | 100 | 105 |
| **8** | 15 | 45 | 90 | 110 | | 120 | | NR | NR | NR |
| **9** | 50 | 55 | | 90 | | 110 | 90 | 100 | NR | NR |
| **10** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **11** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **12** | 65 | 75 | 75 | 80 | 90 | 105 | NR | 110 | NR | NR |
| **13** | 65 | 70 | 95 | 90 | 90 | NR | NR | NR | NR | NR |
| **14** | 20 | 70 | | 110 | | 110 | 110 | 115 | NR | NR |
| **15** | 85 | 90 | | 95 | 105 | 115 | NR | NR | NR | NR |
| **16** | NR | 105 | 110 | 110 | 110 | NR | NR | NR | NR | NR |
| **17** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **18** | 45 | 55 | 65 | 80 | 115 | 110 | 110 | NR | NR | NR |
| **19** | 110 | NR | 115 | 110 | 120 | 110 | 105 | 120 | NR | NR |
| **20** | 110 | 105 | 105 | 110 | NR | NR | NR | NR | NR | NR |
| **21** | 100 | 110 | 110 | 110 | 110 | 115 | NR | NR | NR | NR |
| **22** | 20 | 35 | 75 | 95 | | 90 | | 90 | 70 | 60 |
| **23** | 45 | 100 | 110 | 115 | 110 | 120 | 120 | NR | NR | NR |
| **24** | 65 | 90 | | 110 | 105 | 100 | 100 | 95 | 95 | 80 |
| **25** | 10 | 45 | | 105 | 105 | 115 | 115 | 110 | NR | NR |

**NR**: No response at limits of audiometer; **VT**: Vibrotactile response; **Empty spaces**: No data available

## (B) Post-surgery thresholds

### Implanted ear

| Participant | 250 Hz | 500 Hz | 750Hz | 1000 Hz | 1500Hz | 2000 Hz | 3000 Hz | 4000 Hz | 6000 Hz | 8000 Hz |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **2** | 78 | 108 | NR | NR | NR | NR | NR | NR | NR | NR |
| **3** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **4** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **5** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **6** | 70 | 98 | 110 | 110 | 113 | 113 | 108 | 114 | NR | NR |
| **7** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **8** | 50 | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **9** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **10** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **11** | 110 | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **12** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **13** | 90 | 97 | 108 | 110 | 118 | 114 | 118 | NR | NR | NR |
| **14** | 75 | NR | NR | NR | | NR | | NR | | NR |
| **15** | 107 | 115 | NR | NR | | 117VT | | NR | | NR |
| **16** | 109 | 110 | 119 | 118 | NR | NR | NR | NR | NR | NR |
| **17** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **18** | 76 | 110 | NR | NR | NR | NR | NR | NR | NR | NR |
| **19** | 94 | NR | NR | NR | NR | NR | 115 | NR | NR | NR |
| **20** | 104 | 115 | NR | NR | NR | NR | NR | NR | NR | NR |
| **21** | NR | NR | NR | NR | 113 | 113 | 119 | NR | NR | NR |
| **22** | 101 | 104VT | 115VT | NR | NR | NR | NR | NR | NR | NR |
| **23** | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **24** | 105VT | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| **25** | NR | NR | NR | NR | NR | 120VT | 119VT | NR | NR | NR |

**NR**: No response at limits of audiometer; **VT**: Vibrotactile response; **Empty spaces**: No data available

**Unimplanted ear**

| Participant | 250 Hz | 500 Hz | 750Hz | 1000 Hz | 1500Hz | 2000 Hz | 3000 Hz | 4000 Hz | 6000 Hz | 8000 Hz |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 60 | 99 | 98 | 100 | 110 | 115 | 115 | NR | NR | NR |
| 2 | 48 | 80 | 90 | 91 | 110 | NR | NR | NR | NR | NR |
| 3 | 54 | 75 | 83 | 95 | 94 | 99 | 109 | NR | NR | NR |
| 4 | 65 | 71 | 85 | 85 | 93 | 90 | 78 | 85 | 91 | 78 |
| 5 | 48 | 62 | 70 | 32 | 111 | 115 | 118 | NR | NR | NR |
| 6 | 38 | 52 | 60 | 90 | 110 | 110 | 108 | NR | NR | NR |
| 7 | 78 | 70 | 68 | 66 | 70 | 64 | 73 | 82 | 103 | 105 |
| 8 | 15 | 60 | 105 | 114 | NR | NR | NR | NR | NR | NR |
| 9 | 94 | 108 | 105 | 102 | 108 | 113 | NR | NR | NR | NR |
| 10 | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| 11 | 108 | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| 12 | 66 | 88 | 83 | 83 | 93 | 108 | NR | 108 | NR | NR |
| 13 | 65 | 65 | 90 | 84 | 77 | 80 | 116 | 114 | 105 | NR |
| 14 | 23 | 76 | 101 | 107 |  | 107 |  | NR |  | NR |
| 15 | 85 | 104 | 109 | 107 |  | 108 | NR | NR | NR | NR |
| 16 | 89 | 95 | 97 | 95 | 107 | 117 | NR | NR | NR | NR |
| 17 | NR | NR | NR | NR | NR | NR | NR | NR | NR | NR |
| 18 | 34 | 54 | 64 | 78 | 110 | 107 | 110 | NR | NR | NR |
| 19 | 90 | 110 | 100 | 107 | NR | NR | NR | NR | NR | NR |
| 20 | 93 | 104 | 106 | 108 | 120 | 120 | NR | NR | NR | NR |
| 21 | 101 | 110 | 108 | 106 | 108 | 108 | 120 | NR | NR | NR |
| 22 | 85 | 90VT | 100 | 107 | 115 | NR | NR | 119 | NR | NR |
| 23 | 36 | 88 | 93 | 98 | 104 | 115 | 120 | NR | NR | NR |
| 24 | 64 | 81 | 88 | 95VT | 105 | 111 | 114 | 119 | NR | NR |
| 25 | 75 | 95 | 100 | 101 | 114 | 114 | 115 | NR | NR | NR |

**NR**: No response at limits of audiometer; **VT**: Vibrotactile response; **Empty spaces**: No data available