Hearing Preservation CI Surgery and Hybrid Hearing

From Anatomical Aspects to Patient Satisfaction

ELSA ERIXON
Abstract

A common cause of profound deafness is hair cell dysfunction in the cochlea. Cochlear implants (CI) bypass the hair cells via an electrode and stimulate the cochlear nerve directly. Nowadays, it is possible to preserve residual hair cell function and hearing through flexible electrodes and a-traumatic CI surgery techniques; called hearing preservation CI surgery. This may suit partially deaf patients who can use natural low frequency hearing in combination with electric high frequency hearing; so-called hybrid hearing. The aim of this thesis was to elucidate the effectiveness of hearing preservation CI surgery. The thesis demonstrates human cochlear anatomy in relation to CI and evaluates hearing and patient satisfaction after hearing preservation CI surgery.

Analyses of human cochlear moulds belonging to the Uppsala collection showed large variations in dimensions and coiling characteristics of the cochlea. Each cochlea was individually shaped. The size and shape of the cochlea influences the position of the electrode. The diameter of the basal cochlear turn could predict insertion depth of the electrode, which is crucial for hearing preservation. The first 21 patients operated with hearing preservation CI surgery in Uppsala, showed preserved hearing.

Nine-teen partially deaf patients receiving implants intended for hybrid hearing, were evaluated concerning pure tone audiometry, monosyllables (MS) and hearing in noise test (HINT). They also responded to a questionnaire, consisting of the IOI-HA, EQ-5D VAS and nine questions about residual hearing. The questionnaire results indicated a high degree of patient satisfaction with improved speech perception in silence and noise. This was also reflected by improved results in MS and HINT. Hearing was preserved in all patients, but there was an ongoing deterioration of the residual hearing in the operated ear which surpassed the contralateral ear. There were no correlations between the amount of residual hearing and patient satisfaction or speech perception results. Electric stimulation provides a major contribution to speech comprehension in partially deaf patients. All the patients showed a high degree of satisfaction with their CI, regardless of varying hearing preservation.

Keywords: anatomic variations, human cochlea, cochlear implantation, EAS, electro-acoustic stimulation, residual hearing, partial deafness, IOI-HA, EQ-5D

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ISSN 1651-6206
urn:nbn:se:uu:diva-221536 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-221536)
To Mormor Gunnel 1914-2010
List of Papers

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals:


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Abbreviations

CI  cochlear implant
dB  decibel
EAS  electro-acoustic stimulation
EQ-5D™ VAS  EuroQol-5D Visual analogue scale
HA  hearing aid
HINT  hearing in noise test
HL  hearing level
Hz  Hertz
IOI-HA  International Outcome Inventory for Hearing Aids
LFH  low-frequency hearing
LF PTA  low-frequency pure tone average
MS  monosyllables
RW  round window
RWM  round window membrane
SD  standard deviation
SNR  signal-to-noise ratio
SPL  sound pressure level
Introduction

A human foetus can perceive sound as early as gestational week 19-20 (Hepper and Shahidullah 1994, Bibas et al. 2008), a time when myelination of the cochlear nerve is initiated (Locher et al.2014). In addition, at birth, the child may already recognise the voice and language of the mother (Mampe et al. 2009). Hearing is a major tool for communication, and humans “love” to communicate. The major disability of hearing impairment is social isolation. Seventeen percent of the Swedish population (age 16-100 years) have stated that they have “problems hearing in a conversation among several people” (SCB 2008). If the hearing loss is profound, hair cells in the cochlea are frequently damaged, and a conventional hearing aid may give limited benefit. A cochlear implant (CI) bypasses the sensory hair cells and stimulates directly the auditory neurons. This technique makes it possible for profoundly deaf patients to gain hearing and speech perception for oral communication.

When I started my work at the ENT department in August 2001, CI was still rare, magical and mysterious, and it caught my interest. Today, CI is routine in audiological medicine, and its indications have expanded to include patients with more residual hearing, but the magic is still present. CI makes sense. There is a time before and after for each patient receiving an implant. It is a gratification to share this event of decisive importance with the patient. If this thesis adds knowledge to the field, allowing some more patients to benefit from CI, it will be worth the effort.
Background

The ear and hearing

The human ear receives acoustic information and converts it to electric nerve impulses. The interpretation or “listening” function is executed at higher levels in the primary and secondary auditory cortex of the brain.

The cochlea is embedded in the temporal bone. Airborne vibrations, or sound, are transformed to mechanical impulses through the eardrum and middle ear ossicles and reach the cochlea via the oval window. The cochlea consists of three parallel fluid-filled corridors. The middle corridor, or scala media, is membraneous and delimited by the basilar membrane, lateral wall and Reissner’s membrane. This space is filled with so-called endolymph. The outer corridors are filled with perilymph. The organ of hearing (organ of Corti), with its sensory receptors or hair cells, is situated on the basilar membrane. The fluid pressure wave induced through the oval window initiates oscillating movements in the basilar membrane. The various physical properties of the basilar membrane underlie the primary filtering of the incoming sound wave. High frequencies provoke basilar membrane movements that are most pronounced in the base of the cochlea. Here, the basilar membrane is thicker and stiffer. Lower frequencies cause basilar membrane movements that are more pronounced apically in the cochlea. Incoming sound will generate a so-called *travelling wave* in the basilar membrane, as described by Georg von Bekesy, who was awarded the Nobel Prize in 1961. At the top of the cochlea, the scala vestibuli and tympani communicate, forming the so-called helicotrema. Frequencies below 20 Hz pass the helicotrema and give no recognisable stimulation of the organ of Corti. Fluids are non-compliant and movements of the inner ear fluids can only be generated through some kind of “release valve”. This function is served by the round window membrane (RWM).

The sensory receptor cells in the human inner ear number 15 400. There are 3 400 inner hair cells and 12 000 outer hair cells (Wright et al 1987, Spoendlin and Schrott 1990). The inner hair cells are widely connected to the CNS, while the outer hair cells have few afferent innervations that relay to the central auditory pathways. The hair cells are tonotopically arranged, which means that they are tuned to certain frequencies along the cochlear partition. Hair cells in the apex of the cochlea are tuned to low frequencies, and hair
cells in the basal part of the cochlea are tuned to high frequencies. This tuning is also expressed morphologically in dimensional differences in both hair cells and stereocilia. The inner hair cell stereocilia have a functional relationship to a specialisation of the tectorial membrane, known as Hensen’s stripe. Outer hair cells have stereocilia whose tips are embedded in the tectorial membrane. When the stereocilia move back and forth, ion channels open and close leading to sequential de- and repolarisation of the hair cells. This causes release of a transmitter substance that acts on surface receptors on the nerve terminals of the dendrites of the spiral ganglion cells. These neurons generate action potentials that are conveyed along the auditory nerve fibres to the central nervous system. There are approximately 35 000 spiral ganglion cells, which are associated mostly with the inner hair cells (95%). The cell bodies of the auditory nerve are located in Rosenthal’s canal in the modiolus of the cochlea. These primary auditory neurons convey electric signals to the secondary order cells located in the cochlear nucleus in the brain stem. The nerve signals are conducted via several synaptic relay stations in the brain stem before reaching the auditory cortex in the temporal lobe. This tonotopic arrangement is maintained in the brain cortex.

Among patients suffering from profound deafness, the inner ear is commonly injured, with loss of hair cell function and the normal mechano-transduction process. A conventional hearing aid (HA) only amplifies sound and may provide limited improvements in speech reception, depending on the extent of hair cell dysfunction.

A cochlear implant

A CI consists of an external and an internal part (Figure 1). A speech processor with a microphone is placed behind the ear. The processor receives acoustic information, which is band-pass filtered into different frequency-specific channels. The coded information from the sound processor is transmitted via radiofrequency through the skin to the receiver, which converts the information into electrical stimulus pulses. Through the electrodes inserted in the cochlea, these electrical impulses stimulate the spiral ganglion neurons and the auditory nerve, and the patient receives sound. Currently, it is possible to stimulate ganglion cells of the same cochlea simultaneously both through direct electrical and natural mechano-electric acoustic stimulation of the hair cells.
History

Anatomy

The human cochlea was originally described by Bartholomeus Eustachi in 1564, but the description was first published by Albinus in Leyden in 1744. In 1740, Antonio Valsalva published his studies of the ossicular chain and oval window. The Neapolitan anatomist Domenico Cotugno (1761) described the cochlear and vestibular aqueducts and found that the cochlea and vestibular organs were filled with liquid, not air, as was previously believed. He had discovered the perilymph. The endolymph and the inner ear membranous labyrinth were discovered by Antonio Scarpa (1789). Scarpa also published “Anatomical Observations on the Round Window” in 1772, in which he claimed that professor Fallopia was the discoverer of the round window (RW).

When compound microscopes and improved histological techniques were developed, it was possible for Alfonso Corti (1851) to disclose the organ of hearing that is named after him. Several inner ear cell types were named after their discoverers (including Claudius 1856, Deiters 1860, and Hensen 1863). Magnus Gustav Retzius performed comparative anatomical studies and described the membranous labyrinth in man in 1882. Retzius (1842-
1919) and Max Brödel (1870-1941) provided excellent anatomical inner ear drawings.

Towards the end of the 1950’s, electron microscopy techniques were introduced and provided new revelations about the structure of the inner ear. Scanning electron microscopy was found to be a particularly useful method to display the beautiful inner ear anatomy (Lim 1969, Engström 1972). Over the past thirty years, impressive new imaging techniques to visualise the human temporal bone, labyrinth and nerve structures have been developed. These techniques have, in many ways, revolutionised diagnostics and have led to many new discoveries about the inner ear and its pathology.

Cochlear implants

Alessandro Volta was the inventor of the electric battery. In the early 1800’s, he inserted a probe in each of his ear canals, connected the probes to a battery, and experienced a painful sensation that was followed by a bubbling sound (Asimov’s biographical encyclopedia of science and technology 1982). In 1930, Wever and Bray stimulated the cochlea in cats and recorded electrical potentials with waveforms resembling the stimulus (Wever and Bray, 1930). Some scientists believed that this potential could be replicated to restore hearing loss. In 1957, André Djournou (otolaryngologist) and Charles Eyriès (electrophysiologist) placed an electrode (with a coil leading to the temporal muscle) on the auditory nerve during a repeat operation on a patient who had lost both cochleae during prior surgery. This was the first direct electrical stimulation of the human auditory system (Djournou and Eyriès 1957). After implantation, the patient discriminated sound intensities but no pitch. Unfortunately, the device failed some weeks after implantation. They did another operation in a patient whose device failed as well; after this, they did not want to pursue further investigations.

Regardless, this publication, thanks to a patient, reached Dr William House in Los Angeles. It convinced him that auditory perception could be achieved by direct electrical stimulation. In 1961, he implanted his first patients with a single gold wire electrode that was inserted thorough the round window (House and Urban 1973, House 1976). He went on to develop the first commercially available CI, the House/3M cochlear implant. He collaborated with James Doyle, an electrical engineer, and later on with engineer Jack Urban. William House is often mentioned as the “father” of the CI.

In 1964, Blair Simmons at Stanford University implanted a six-channel single wire electrode into the modiolus of a deaf-blind volunteer and showed that perceived pitch varied with either a change in stimulating electrode or the rate of stimulation at a certain electrode (Simmons 1966). Still, speech understanding was worse than expected, so Simmons proceeded with studies in cats. Many other scientists wanted to perform more animal studies before going any further with CI. Furthermore, there was a great deal of scepticism...
about CI based on contemporary beliefs about hearing physiology, which claimed that CI could not possibly produce useful hearing.

In 1976, Dr Robert Bilger at the United States National Institutes of Health evaluated the performance of all thirteen patients who had been implanted in the United States to date. They all had single channel CI. The conclusion was that patients with the implant scored better at lip-reading, had better control of their own speaking voice, and had increased awareness of environmental sounds, providing a better quality of life. This is often called the Bilger report (Bilger and Black 1977), and it showed the world that CI was a promising technology. In 1984, the House/3M single channel device was the first CI approved by the United States Food and Drug Administration (FDA).

The five cochlear companies founded on research

A team at University of California, San Francisco (UCSF), led by Robin Michelson (otologist) and Michael Merzenich (neurophysiologist), discovered that different frequencies of stimulation at a single electrode in the cochlea only reached hearing up to 600 Hz, which was too limited for understanding speech (Merzenich et al. 1973, 1974). They developed a multichannel device with multiple sites of stimulation along the cochlea, making it possible to provide frequencies above 600 Hz. The research of the UCSF group together with that of the Research Triangle Institute in North Carolina resulted in the creation of Advanced Bionics, one of today’s five cochlear implant companies (Eshraghi et al. 2012).

In Vienna, Ervin Hochmair and Ingeborg Hochmair-Desoyer, electrical engineers, and Kurt Burian, head of the ENT clinic, developed and implanted their first multichannel implant in 1977. Their implant consisted of an internal receiver and an external sender, which eliminated the danger of previous versions, which used a percutaneous plug. In 1990, they founded MED-EL. Ingeborg Hochmair-Desoyer is still the chief executive officer.

Graham Clark and his group at the University of Melbourne also developed multichannel devices and were the first to show that CI patients were able to hear without lip-reading (Clark et al. 1981). In 1985, clinical trials proved this multichannel electrode far better than House/3M single electrode. Cochlear limited is derived from this research.

Neurelec is a cochlear implant company based on the research of Henri Chouard, a student of Eyriès, and Mac Leod during the 1970’s in Paris.

Fan-Gang Zeng, an electrical engineer, who did his post-doc at the House Ear Institute in California, founded Nurotron in 2006. The first implant appeared on the market in 2011. The headquarters are in Hangzhou, and the research and development centre is in California. It is a low-cost manufacturing company with the aim of providing cochlear implants to the Chinese people (Chaikof 2013).
Speech coding strategies
An important step in the evolution of CI was the progress in coding strategies that were developed through interleave strategies. Instead of simultaneous electric stimulation of the auditory neurons, these strategies made it possible to separate the signals in short delays along the various electrodes. This principle, known as continuous interleave sampling, or CIS, was initially presented by Professor Blake Wilson at Duke University in North Carolina at the Research Triangle Institute. This strategy was found to be extremely useful and improved speech perception greatly in most patients (Clark 1987, Wilson et al. 1991).

Hearing Preservation Surgery
Lehnhardt in 1993 described the soft surgery technique (Lehnhardt 1993). The goal of this technique was to preserve the inner ear structures, with sufficient excitatory neuronal structures for electrical stimulation. Initially, all patients receiving CI were completely deaf, but as the technique developed, patients with some residual hearing were also implanted. These patients were prepared to lose their residual hearing due to the surgery. CI was used in many patients, some of whom had residual hearing after implantation. Hodges et al. (1997) showed that approximately half of the patients receiving a CI had some measurable residual hearing after standard implantation. This gave Christoph von Ilberg et al. (1999) the idea of developing combined electro-acoustic hearing. Hearing and structure preservation is the underpinning of hybrid hearing.

   Initially, the electrode was introduced through the RW by House in 1961. The RW was later abandoned for the easier drilling of a cochleostomy to enter the scala tympani. A major disadvantage of cochleostomy is the bone dust generated in the scala tympani and the rupture of the inner ear membranes, resulting in loss of residual hearing. Another disadvantage is the unpredictable location of the scala tympani, due to variations in “hook” anatomy that can cause misplacement of the array. According to Aschen dorff et al. (2007) and Skinner et al. (2007), precise placement of electrode arrays into the scala tympani may be essential for good functional outcomes, including speech discrimination abilities, in patients irrespective of hearing maintenance. Inner ear trauma can also worsen the performance of CI due to fibrosis and new bone formation, which could impair blood supply and lead to a reduction in residual spiral ganglion cells. Preserving structures could allow patients to benefit from stem cell therapy in the future.

   As with the introduction of more flexible and thinner electrode arrays, surgeons have reintroduced the RW technique with a high degree of hearing preservation (Skarzynski et al. 2007, Lorens et al. 2008). Good outcomes have also been reported with a modified cochleostomy technique (Gstoettner
et al. 2004). Some studies indicate delayed hearing loss after surgery (Gstoettner et al. 2006 and Luetje et al. 2007), whereas other studies report stable hearing in the operated ear (Lenarz et al. 2009, Skarzynski et al. 2007). Nevertheless, the follow-up time after surgery is generally short, and there are several different ways to define preserved hearing.

In Uppsala today, we use the RW technique and perform hearing preservation surgery in most patients.

The main steps in hearing preservation surgery are:
- RW approach with wide exposure of the RWM (or modified cochleostomy)
- Thin and flexible electrode placement
- Slow insertion and stop if resistance
- No or limited suction near the RWM
- Corticosteroids
- Sealing of the RW membrane after insertion

Hybrid hearing
Von Ilberg et al. (1999) showed that it was possible to combine electrical stimulation in a CI device with acoustic stimulation from a HA (Figure 2). Initially, this technique was used for patients with pure tone thresholds of more than 60 dB in the low frequencies, but presently it is possible for partially deaf patients with normal low frequency hearing (LFH) to receive an implant. These patients do not need ipsilateral HA amplification in the low frequencies, simply complementary electrical hearing in the middle and high frequencies.

Hybrid hearing requires preserved LFH. Usually a shorter electrode is used, which is inserted around one turn. This minimises trauma to the low frequency region in the apical part of the cochlea.

Patients with residual hearing benefit considerably from CI alone compared with a conventional HA (Gantz et al. 2004, Cullen et al. 2004, Adunka et al. 2008, Dowell et al. 2004). The advantage of hybrid hearing over CI only has been demonstrated by von Ilberg et al. (1999), Helbig et al. (2008), Lorens et al. (2008) and Gstoettner et al. (2009). Music perception (Gfeller et al. 2006, 2007), as well as hearing in complex listening situations (Gifford et al. 2013), seems to improve with hybrid hearing compared with conventional CI. To date, only a few studies have investigated quality of life and subjective ratings in hybrid hearing patients (Santa Maria et al. 2013 and Lenarz et al. 2013).
Cochlear implants in Sweden

The first cochlear implant in Sweden was performed by Göran Bredberg in Stockholm in 1984. An extracochlear electrode was used. In 1990, Sten Harris in Lund performed the procedure in a child at the request of the parents. At that time, most Swedish professionals still believed that prelingually deaf children could not develop speech understanding with a cochlear implant. However, since 2008 national hearing screening for newborns is instituted and all profoundly deaf children are offered bilateral cochlear implants if possible.

In Uppsala, the first patient was implanted on May 2, 2001 by Helge Rask-Andersen, and the first child was implanted on October 28, 2002. The first hearing preservation surgery, using a modified electrode array through the round window, was performed on the 25th of November, 2008.

The place frequency position

Greenwood (1961) developed a place frequency function by integrating an exponential function fitted to a subset of frequency resolution-integration
estimates, (critical bandwidths). The function was based on data gathered by Békésy in the 1940s and Schuknecht in the 1950s, but is applicable to newer mechanical and physiological data (Greenwood 1990). Greenwood’s frequency-position function allows the estimation of the represented frequencies along the organ of Corti as a function of percentage length. This function has been used in most studies examining electrode position. The place frequency maps in the cochlea are of great interest in the development of electrode devices and the programming of CI, especially for hybrid hearing.

A disadvantage of this function is that the total length of the OC cannot be measured on patients in clinical practice. Instead, one has to convert the cochlear outer wall length to an approximate organ of Corti length. Kawano et al. (1996) performed estimations of the OC length and found that the ratio between the total OC and lateral wall lengths was 0.87. For one turn, the ratio was 0.9. From such data, a formula may be given to estimate the OC length at various positions of the cochlea. Another problem concerning the place frequency function and CI is that the CI stimulates the spiral ganglion cells rather than the organ of Corti. Stakhovskaya et al. (2007) demonstrated a correlation between the place frequency of the organ of Corti and that of the spiral ganglion.

### Prediction of cochlear length

An important aim of modern CI surgery today is to preserve hearing and auditory structures. Patients with partial deafness typically have usable hearing at 125-750 Hz and deafness for frequencies of 1000 Hz and higher. If residual low frequency hearing is assumed to be combined with electric hearing, identifying a planned position for the electrode in the cochlea is necessary.

Stakovskaya et al. (2007) correlated the frequencies along the organ of Corti with different angles of rotation from the posterior margin of the round window and found that at 360°, the mean frequency was 920 Hz, varying from 809 to 1063 Hz. According to these authors, the average, 1000 Hz, corresponded to the part of the cochlea closest to the centre of the vestibule.

Stakovskaya et al. (2007) found that the measurement of the basal turn diameter in preoperative images may allow not only the prediction of the length of the organ of Corti (R²=0.77) and that of the spiral ganglion (R²=0.88) but also the insertion depth necessary to reach specific angles of rotation and specific frequencies. Escudé et al. (2006) used the basal turn diameter and calculated the cochlear length using a spiral function.

A main message of the present thesis is that the human cochlear spiral is highly asymmetric and variable in its anatomy. Considering that the human cochlea is individually shaped and sized, the place-frequency map will vary, but the surgeons need to know (in mm) how far the electrode array should be...
inserted. For this reason, we need to predict the total cochlear length and the length of the intended insertion depth. However, the optimal insertion depth for different diseases, degrees of hearing loss and electrode arrays remains to be established.

Partial deafness

A partially deaf patient often exhibits profound hearing loss in the middle and high frequencies and normal hearing or moderate loss in the low frequency region (Figure 3). Speech prosody or melody may be audible, but there is limited speech perception. Many of these patients are good lip-readers, partly due to the speech “clues” obtained from the low frequencies. In quiet and with lip-reading, spoken language acquisition can be impressive, while in noisy surroundings speech perception is poor. Conventional hearing aids provide limited benefit as there is a restricted frequency interval that can be amplified. For the same reason, FM systems may give little support. The degree of disability in such individuals is often underestimated at school or work. In cases where the hearing loss is pre-lingual in nature, speech is also frequently affected due to restriction of consonant hearing. Furthermore, due to the low benefit from hearing aids, many partially deaf patients have lost contact with the audiology profession, which may exclude them from using modern equipment and techniques such as hybrid hearing.

Figure 3. Audiogram showing partial deafness
The team work of cochlear implants

Our CI team in Uppsala consists of an audiologist, an audiological physician, a surgeon, an engineer, a hearing therapist, a medical social worker, a speech-language therapist and a coordinator. Different hospitals have different teams, but it is important that a multi-disciplinary collaboration is established.

In a CI candidate, we evaluate hearing with and without hearing aids, lip reading ability, concomitant diseases and social perspectives. During a two-day evaluation, the patient meets the different professionals and an experienced CI patient. Three to four weeks after surgery, the patient is fitted (over 4 days), and listening training starts. We recommend that the patient uses the device all day. Five weeks after fitting, most patients are able to discriminate words without lip-reading. Patients who have been deaf since childhood or have been deaf for a long time may experience longer times for assimilation and speech recognition. During the first one to two years, the patients usually experience improved hearing followed by stabilisation.

We always try to identify best-aided conditions for each patient, which is usually when the patient uses the CI together with a hearing aid in the contralateral ear. In hybrid hearing patients, there is also the decision of whether to use an ipsilateral HA and at which frequency the processor should switch to acoustic stimulation (“the cut-off frequency”). Program testing and retrieving the best-aided condition, and integrating ipsi- and contralateral hearing can be complex and tiresome. The habituation process over time also adds to the complexity.

For hybrid hearing candidates, improvements in hearing with CI can be anticipated. The benefits of ipsilateral HA amplification are more difficult to predict and depend on preserved hearing and the ability to integrate the ipsilateral HA sound with the CI sound. Providing preoperative information, especially to hybrid candidates, is a challenge. A well-informed patient who is an active participant in his or her care is crucial for successful rehabilitation.

Patient-reported outcomes

Hearing impairment affects daily life in many ways. The effort to recognise and code speech is energy-consuming. Social isolation, as a consequence of impaired speech recognition and fatigue, are common.

As hearing loss has such a significant impact on everyday life the outcome of audiological testing, might give a limited understanding of a patient’s overall situation. Therefore, the use of different quality of life assessments is important. These can be generic and applicable in a wide variety of diseases, or disease- and disability-specific. Many generic instruments lack
proper sensitivity for analysing the effects of hearing loss (Bess 2000). Pa-
tient satisfaction surveys can be used both to evaluate the general health effects of an intervention or the patient’s opinion of the care given as part of their treatment. A major problem is the lack of clear definitions and distinc-
tions between the concepts “quality of life” and “patient satisfaction”.

In this thesis, we used “patient satisfaction” to describe the patients’ sub-
jective experience of the new hearing situation. An important goal was to assess the patient self-reported outcomes regarding hybrid hearing, as there have been only a few previous reports. We defined “quality of life” as a sub-
jective psychological general well-being (IOI-HA question no. 7).

It is a common experience that treatment with conventional CI has major benefits for patients, despite sometimes limited progress in audiological pa-
rameters. Thus, audiological test results may not provide sufficient informa-
tion about the effects of a treatment. This may also include patients with partial deafness.
The aims of the thesis:

• to demonstrate the variable anatomy of the human cochlea and its relation to hearing preservation CI surgery.

• to study if the diameter of the basal cochlear turn (diameter A) is correlated with the total cochlear length and could thereby be used to predict the insertion depth of the electrode.

• to evaluate the hearing preservation rate in the first 21 consecutive patients undergoing hearing preservation CI surgery.

• to evaluate patient satisfaction in patients intended for hybrid hearing and its relationship to hybrid hearing.

• to relate hearing results in quiet and noise to subjective experiences and residual hearing.

• to evaluate if there is an ongoing deterioration of residual hearing in hybrid hearing patients.
Materials and Methods

Paper I and II

The Uppsala collection of human temporal bones.

The collection of material of unselected human temporal bones from autopsies was initiated by Dr Hermann Wilbrand and Professor Rask-Andersen in 1974. This collection was further enlarged thanks to several researchers at the Department of Radiology. The Uppsala collection consists of 80 micro-dissected temporal bones and 324 plastic moulds. Age and gender are not known. There are no reports indicating that the ears were affected by disease.

Preparation of the moulds

The applied method of casting temporal bone specimens was described by Wilbrand et al. (1974) and Wadin (1988). The temporal bone specimens were macerated and cleaned in KOH, boiled and treated with 2% hydrogen peroxide (H₂O₂) and trypsinised. The specimens were placed in a wax form with the orifices of the inner ear canals left open. The casting material, a polyester resin or silicone rubber material, was poured into the wax form. The specimens were placed in a low pressure chamber to optimise the penetration of the moulding material into the small bony channels of the macerated bones. After hardening, the bone was dissolved with hydrochloric acid. Haversian bone channels were also filled with resin to form an extensive network around the inner ear. This network was removed with a fine forceps in the polyester preparations or with scissors in the silicone material. In study I, we used 73 moulds, filled sufficiently to be used for dimensional estimations of the cochlea. In study II, we re-measured 51 completely filled moulds.

Measurement procedure

In paper I, the cochlear casts were photographed in standard views (Stenver and axial-pyramidal projections) with a millimetre scale in the picture parallel to the casts. Computer-aided planimetry was made on the photographs of
73 different cochleae. Calibrations were made before each measurement using the mm-scale inserted in each photo.

In paper II, each cochlear cast was photographed in Stenvers’ projection with an Olympus light microscope focusing on the round window and basal turn. Computer-aided planimetry was performed. Every distance was measured 3 times, and the average was calculated.

Reference points and measurements
We used the mid-point of the long diameter of the round window as a reference and starting point for measuring the length of the cochlea. This point was also recommended as the reference point by the consensus panel to find a cochlear coordinate system (Verbist et al. 2010a). A line is drawn from the starting point through the central axis of the cochlea to a distant point of the first turn. This line defines the basal turn diameter (diameter A) in study II. A turn is defined as the distance from the zero point to the point where this line bisects each cochlear turn (Figure 4). Another line was drawn perpendicular to diameter A through the axis of the modiolus dividing the cochlea into quadrants (Figure 5). Quadrants 1 to 4 constitute the first turn, 5 to 8 the second and 9 to 12 the third turn.

In paper I, we measured the outer wall length of each quadrant and the length of the maximal round window diameter. The maximal diameter and width of each turn of the cochlea were also estimated from the medial plane (Figure 6).

In paper II, we measured diameter A and re-measured the cochlear length. Diameter A and the various lengths of the cochlea were plotted in the Excel (Microsoft®) program and statistical regression analyses were conducted. A plot showing the residual and actual lengths of the first turn was also constructed.
Figure 4. Corrosion cast of a left human cochlea. Diameter A is defined as a line drawn from the midpoint of the round window (zero point) through the mid-portion of the modiolus to the opposite end of the outer cochlear wall. 1, end of first turn; 2 end of two turns; 3 end of total cochlear length.

Figure 5. Corrosion cast of a left human cochlea showing the reference points used for defining different quadrants. OW, oval window; RW, round window; FC, facial canal.
Figure 6. Corrosion cast of a left human cochlea. The reference points used for estimating the width and height of the various turns are shown. A, width first turn; B, width second turn; C, width third turn; D, height first turn; E, height second turn; F, height third turn. Total height = D+E+F

Papers III and IV

Patients

The patients in paper III are our first 21 consecutively operated patients using hearing preservation technique. Patient number 15 died of unrelated reason one month after surgery and was excluded, so the group we describe consists of 20 patients. Eleven patients fulfilled the MED-EL criteria for EAS (Sensorineural hearing loss with pure tone thresholds 125-750 Hz $\leq 65$ dB HL and 2000-8000Hz $\geq 85$ dB HL, monosyllabic score $\leq 60\%$ at 65 dB SPL in the best aided condition). Nine patients requested their residual hearing to be preserved, although the strategy employed was electric stimulation only.

In paper IV, the study group consisted of 19 patients intended for hybrid hearing. Two of them were children. From September 2008 to November 2011 the first twenty-four consecutive, partially deaf patients intended for hybrid hearing underwent hearing preservation surgery at our department. Preoperative candidacy criteria were an unaided pure tone threshold $\leq 65$ dB HL at frequencies $\leq 500$ Hz and $>80$ dB HL at frequencies $\geq 2000$ Hz in the ear intended for surgery and almost symmetrical hearing in their contra-
lateral ear (the better ear) The aided monosyllabic word score was less than 60% in each ear. In January 2013, when all patients had used their device for at least one year, they were asked to participate in the study. The study was approved by the Regional Ethical Review Board in Uppsala (2012/473). Nineteen patients provided written informed consent and responded to a questionnaire survey. Before surgery, the intention was to fit 7 patients with a cut-off frequency Opus 2 processor together with normal LFH and 12 patients with a Duet 2 processor (ipsilateral HA and CI).

Patient treatment
Patients were operated on between September 2008 and October 2011 by one surgeon. A flexible electrode that was 24 mm long (MED-EL FLEX\textsuperscript{EAS}) was used in all cases except for two patients. A 31 mm electrode (MED-EL FLEX\textsuperscript{SOFT}) was used in one patient in study III, and a custom-made electrode (20 mm) from MED-EL was used in one patient in study IV. All patients in the studies were treated according to the following clinical paradigm:

Audiometry
Patients were evaluated with a conventional pure tone audiogram. The audiograms were performed according to international standards. Speech discrimination tests with phonemically balanced monosyllabic words (MS) were performed, with and without HA, and uni- and bilaterally at a comfortable level (65-85 dB SPL) (\textit{Svensk Talaudiometri, C-A Tegnér AB: 1998}). The Hearing In Noise Test (HINT) a speech recognition test with everyday sentences in noise, was performed if there was sufficient hearing (Hällgren et al. 2006). At follow-up, we evaluated the pure tone audiogram and best aided MS and HINT scores

Radiology
Before surgery, every patient was evaluated radiologically using high-resolution computer tomography with axial and coronal projections. This included assessment of the 3\textsuperscript{rd} portion of the facial canal, its relationship to the RW niche of the cochlea, jugular bulb and pyramidal prominence. Peroperative radiology confirmed the electrode position in all cases. On the following date a plain X-ray (head rotated 30 to 45 degrees against the contra-lateral ear or Stenver projection) was taken.

Surgery
A RW approach was used with wide exposure of the lateral surface, visualising at least the anterior two-thirds of the membrane, including its fibrous ring. A vertical incision was made in the RWM near the anterior rim, and the electrode was inserted slowly (freehand) with 3 electrodes in steps that were interrupted by instillation of corticosteroids in the middle ear (Kenacort-T or
triamcinolone solution 40 mg/ml). Electrode introduction was halted at resistance. Except for the first three patients in study III and the first patient in study IV, the RWM was sealed gently with muscle and tissue glue around the electrode.

Fitting of Speech processor

One month after surgery, the middle ear was inspected for sanguineous effusion before audiometry and fitting. Postoperative audiograms are shown after the effusion was absorbed. The patients were fitted with a CI processor (Opus 2), and, if needed, most of the patients were fitted with the ipsi-lateral HA at the same time (Duet 2). The patients visited our clinic for four days during the first two weeks for adjustment and training and then at 5 weeks and 3, 6 and 12 months after fitting. This was followed by annual visits.

Measurements (paper III)

In study III, the insertion angle was estimated from postoperative radiographs. The insertion angle was defined as the angle between the apical electrode and a line drawn from the proximal rim of the RW (basal insertion of basilar membrane) across the central axis of the cochlea. This line was often parallel to the long diameter of the oval window. It defined one turn of the cochlea (360°; Figure 7). A line was also drawn along the lateral shaft of the superior semicircular canal to the mid-point of the long diameter of the oval window. This line was extended to the electrode array, where it defined the position of the RW on plain X-ray. All surgery was video recorded. For patients in study III, all niches were graphically delineated, and the percentage of visualisation of the RWM was assessed before and after drilling the niche.

![Figure 7. X-ray (Stenver projection) of FLEX 24 electrode array with corresponding reference lines and insertion angle. Ten electrodes are inside the cochlea. SSCC, superior semicircular canal; OW, oval window; RW round window](image)

30
Patient questionnaire survey (paper IV)

**International Outcome Inventory for Hearing Aids - Swedish (IOI-HA)**

We used the Swedish version, translated into Swedish in 2005 and provided by the International Collegium of Rehabilitative Audiology. The IOI-HA is a questionnaire targeting seven different domains with seven questions; (1) hearing aid use, (2) hearing aid benefit, (3) residual activity limitations, (4) satisfaction, (5) residual participation restriction, (6) impact on others, and (7) quality of life. Each item is scored from 1-5, and a higher score indicates more favourable outcome. The outcome measures can be divided into two subscales. Factor 1 is the sum of items 1, 2, 4 and 7, representing CI satisfaction, and factor 2 is the sum of items 3, 5 and 6, representing participation restriction (Kramer 2002, Stephens 2002, Öberg 2007). The questionnaire is validated and was initially developed for assessing HA outcome (Cox 2000, 2003). We exchanged “Present hearing aid(s)” with CI.

**EQ-5D™ visual analogue scale**

EQ-5D™ of the EuroQol Group is a standardised instrument to measure health outcome. It consists of two parts, of which we used the visual analogue scale (VAS), where the endpoints are labelled ‘Best imaginable health state’ (100 points) and ‘Worst imaginable health state’ (0 points).

**Formulae containing nine questions concerning the use of residual hearing**

This was added to scrutinise residual hearing and improve relevance to different listening situations, such as noise and music.

See appendix for the IOI-HA, the nine-question formula and the EQ-5D™ VAS.

**Statistics**

In paper III, MANOVA for repeated measurements was used to calculate the hearing loss (Statistica StatSoft®). In paper IV, group means and alterations in pure tone thresholds, MS, HINT and patient satisfaction scores were assessed. The parameters were plotted and correlations evaluated, using Excel (Microsoft®). Levels of significance (p values) were calculated using Wilcoxon’s matched Pairs Signed Rank Test.
Results

Paper I

There were large variations of dimensions and coiling characteristics. Each cochlea was found to be individually shaped like a “fingerprint”. The estimated mean number of turns of the human cochlea was found to be 2.6, with a range from 2.2 to 2.9 (929°, range 774 °-1037 °). The number of quadrants varied from slightly more than 8 to 12. For the estimated dimensions, see Table 1, Table 2 and Table 3.

Table 1. Cochlear length, Paper I

<table>
<thead>
<tr>
<th>Outer wall length (mm)</th>
<th>Mean</th>
<th>Range</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half diameter of the RW</td>
<td>1.1</td>
<td>0.3-1.6</td>
<td>0.21</td>
<td>65</td>
</tr>
<tr>
<td>First half of first turn</td>
<td>13.5</td>
<td>12.1-15.0</td>
<td>0.73</td>
<td>67</td>
</tr>
<tr>
<td>First turn (quadrant 1-4)</td>
<td>22.6</td>
<td>20.3-24.3</td>
<td>0.83</td>
<td>65</td>
</tr>
<tr>
<td>Second turn (quadrant 5-8)</td>
<td>12.4</td>
<td>10.7-13.3</td>
<td>0.63</td>
<td>63</td>
</tr>
<tr>
<td>Third turn (quadrant 9 to11(12)</td>
<td>6.1</td>
<td>1.5-8.2</td>
<td>1.40</td>
<td>58</td>
</tr>
<tr>
<td>Total length*</td>
<td>42.0</td>
<td>38.6-45.6</td>
<td>1.96</td>
<td>58</td>
</tr>
</tbody>
</table>

*The total length of the outer wall excluding the basal half of the round window (RW). SD, standard deviation. n, number of specimens

Table 2. Cochlear height. Paper I

<table>
<thead>
<tr>
<th>Height of the cochlea (mm)</th>
<th>Mean</th>
<th>Range</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>First turn</td>
<td>2.1</td>
<td>1.6-2.6</td>
<td>0.20</td>
<td>73</td>
</tr>
<tr>
<td>Second turn</td>
<td>1.2</td>
<td>0.8-1.6</td>
<td>0.17</td>
<td>67</td>
</tr>
<tr>
<td>Third turn</td>
<td>0.6</td>
<td>0.3-1.1</td>
<td>0.18</td>
<td>60</td>
</tr>
<tr>
<td>Total height</td>
<td>3.9</td>
<td>3.3-4.8</td>
<td>0.37</td>
<td>60</td>
</tr>
</tbody>
</table>

SD, standard deviation. n, number of specimens

Table 3. Cochlear width. Paper I

<table>
<thead>
<tr>
<th>Width of the various turns (mm)</th>
<th>Mean</th>
<th>Range</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>First turn</td>
<td>6.8 mm</td>
<td>5.6-8.2</td>
<td>0.46</td>
<td>71</td>
</tr>
<tr>
<td>Second turn</td>
<td>3.8 mm</td>
<td>3.3-4.3</td>
<td>0.25</td>
<td>68</td>
</tr>
<tr>
<td>Third turn</td>
<td>2.1 mm</td>
<td>0.6-3.6</td>
<td>0.52</td>
<td>60</td>
</tr>
</tbody>
</table>

SD, standard deviation. n, number of specimens
The length of the first turn represented approximately 53% of the total cochlear length, the second turn represented approximately 30%, and the third turn represented approximately 17% of the total cochlear length.

Figure 8 shows different coiling characteristics. The shape of the first turn seemed to be influenced to a large extent by the “pattern” of coiling. The basal part of the first turn in some cochleae was straighter due to the coiling starting more distally. This seemed to result in a long first turn. Other cochleae coiled more proximally, resulting in a short basal part of the first turn (more compressed cochlea). There were also variations in the position of the central axis of the individual turn and some moulds showed a tilting of the turns. This made it difficult to define a central modiolar axis.

Figure 8. Plastic moulds showing the variational anatomy of the human cochlea.

Paper II

The mean and median length of diameter A was 9.3 mm (min 8.3, max 9.9 and SD 0.4 mm). The lengths of one turn, two turns and the total cochlear length are presented in Table 4. The range of the first turn was 3.5 mm (compared with its mean total length of 22.8 mm). The third turn had a mean length of 6.0 mm and a range of 6.2 mm (min 2.4, max 8.6, SD 1.1 mm).
Table 4. Cochlear outer wall length. Paper II

<table>
<thead>
<tr>
<th></th>
<th>Mean, mm</th>
<th>Range, mm</th>
<th>SD, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal turn</td>
<td>22.8</td>
<td>20.7 - 24.2</td>
<td>0.86</td>
</tr>
<tr>
<td>Two turns</td>
<td>35.1</td>
<td>32.5 - 37.2</td>
<td>1.28</td>
</tr>
<tr>
<td>Total length</td>
<td>41.2</td>
<td>37.6 - 44.9</td>
<td>1.86</td>
</tr>
</tbody>
</table>

Diameter A was found to be a significant predictor of the basal turn, two turns and total cochlear length (p<0.001, respectively). The correlation was strongest for the basal turn ($R^2=0.74$) and two turns ($R^2=0.70$) and less for the total length ($R^2=0.39$). Figure 9 shows the regression lines and equations. If two outliers were removed from the basal turn formula, $R^2$ increased to 0.78 with no change in the formula. Therefore, all values were maintained in the regression analysis. When two outliers were removed in the two turn formula, $R^2$ increased to 0.73 with a moderate change in the formula (2.73A+9.75).

$$y = 1.94x + 4.69$$
$$R^2 = 0.74$$

$$y = 2.82x + 8.79$$
$$R^2 = 0.70$$

$$y = 3.08x + 12.44$$
$$R^2 = 0.39$$

Figure 9. Graphs showing the relationship between diameter A and the basal turn length, two turn length and total cochlear length. The regression formula and $R^2$ are presented in each graph.

Diameter A was incorporated into the formula to calculate basal turns and residuals. The residuals were plotted against the length of the basal turn. The residual for the basal turn varied from -0.8 to +1.0, and if two outliers were removed, the variation was +/- 0.7 mm. When the formula was used to as-
sess the two turn dimensions, the residuals ranged from -1.2 to +1.8. The residuals for the total lengths ranged from -2.9 to +3.0 mm. Regression analyses for the total cochlear length and basal turn lengths showed the coefficient of determination to be 0.64.

Paper III
Hearing was preserved in all patients. Individual pure tone audiograms at one month (n=20), 7 months (n=13) and 13 months (n=11) are presented in Figure 10. Mean pure tone thresholds, one month after surgery, were elevated in the low frequency region (Figure 11). The mean low frequency (125, 250 and 500 Hz) pure tone average (LF PTA) shift was 14 dB in 20 patients (Median 14 dB, SD 12 dB). Statistically significant elevations of thresholds were found at the frequencies 125, 250, 500 and 1000 Hz. Patient no. 15 experienced hearing postoperatively, but died of unrelated reasons one month after surgery before postoperative audiogram, and was thereby excluded. In 13 patients followed up seven months after surgery, the mean LF PTA-shift was 13 dB (Median 13 dB, SD 11 dB). In eleven patients followed up at 13 months after surgery, the mean LF PTA-shift was 16 dB (Median 15.6 dB, SD 11 dB). Differences in LF PTA at one month and 13 months postoperatively were not statistically significant.

Neither insertion angle (300°-540°, mean 384°), insertion depth (17.5-28.5 mm, mean 21.1 mm) nor number of active electrodes showed a statistically significant correlation with the extent of hearing loss. The electrode configuration (based on postoperative X-rays) is shown for each subject in Figure 10. The place of the RW is marked with a line.

The anatomy of the RWM varied greatly. This included both window shape and surface angle relative to the facial recess approach. The percent of RWM exposed before drilling varied from approximately 0 to 40% to 50-90% after drilling. The percentage of RWM, for each subject, visualised by the surgeon before and after drilling the niche, is shown in Figure 10. The RWM was mostly ovoid and often saddle-like. All patients had extra membrane or fold positioned lateral to the RWM to some extent. Sometimes, this membrane or fold merged with the outer surface of the RWM, and crude elimination resulted in trauma and deterioration of parts of the RWM when extracted (no. 17). In two patients, the facial nerve was ante-positioned, partly obstructing the surgeon’s view of the RW niche (no. 6 and 20).
Figure 10. Audiograms, electrode configurations and percentage of round window membrane visualization.
No patients experienced new or aggravated tinnitus two months after surgery. Several patients had slight unsteadiness that started a few days after surgery and usually resolved within 1-2 weeks. One patient was hospitalised for a few days due to vertigo that started several days after surgery. One patient had severe unsteadiness that resolved after removing the most basal electrode stimulation.

General information about subjects’ surgeries, devices and fitting are presented in Table 5. Several patients preferred electric and acoustic stimulation at certain frequencies. Patients with thresholds around 50 dB HL at low frequencies (125-500 Hz) usually preferred full frequency CI and acoustic stimulation. If thresholds were less than 50 dB HL, a cut-off frequency was chosen; if the loss was more than 50 dB, patients did not use acoustic stimulation but preferred full frequency CI.
Table 5. Summary of patients operated with hearing preservation surgery. Paper III.

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Side</th>
<th>IA (°)</th>
<th>Electrode depth (mm)</th>
<th>No. of electrodes</th>
<th>Processor</th>
<th>Frequency range (Hz)</th>
<th>Criteria*</th>
<th>Contralateral ear</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>53</td>
<td>Left</td>
<td>360</td>
<td>19.5</td>
<td>11</td>
<td>Duet 2</td>
<td>100-8500 + AS</td>
<td>Yes</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>19</td>
<td>Left</td>
<td>360</td>
<td>19.5</td>
<td>9</td>
<td>Duet 2</td>
<td>550-8500 + AS</td>
<td>Yes</td>
<td>HA</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>87</td>
<td>Right</td>
<td>300</td>
<td>19.5</td>
<td>9</td>
<td>Duet 2</td>
<td>500-8500 + AS</td>
<td>Yes</td>
<td>HA</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>71</td>
<td>Right</td>
<td>400</td>
<td>22.5</td>
<td>12</td>
<td>Opus 2</td>
<td>100-8500</td>
<td>No</td>
<td>CI</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>50</td>
<td>Left</td>
<td>540</td>
<td>28.5</td>
<td>12</td>
<td>Opus 2</td>
<td>100-8500</td>
<td>No</td>
<td>CI</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>71</td>
<td>Left</td>
<td>360</td>
<td>18.5</td>
<td>10</td>
<td>Opus 2</td>
<td>100-8500</td>
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<tr>
<td>7</td>
<td>F</td>
<td>31</td>
<td>Left</td>
<td>380</td>
<td>19.5</td>
<td>10</td>
<td>Duet 2</td>
<td>100-8500 + natural</td>
<td>Yes</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>70</td>
<td>Left</td>
<td>315</td>
<td>20.5</td>
<td>10</td>
<td>Duet 2</td>
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<td>Yes</td>
<td>HA</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>50</td>
<td>Right</td>
<td>370</td>
<td>20.5</td>
<td>10</td>
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<td>HA</td>
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<td>10</td>
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<td>405</td>
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<td>11</td>
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<td>HA</td>
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<td>700-8500 + AS</td>
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<td>F</td>
<td>75</td>
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<td>540</td>
<td>20.5</td>
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<tr>
<td>Min.</td>
<td>9</td>
<td>F</td>
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<td>9</td>
<td>Duet 2</td>
<td>14 Opus</td>
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<td>11</td>
<td>M</td>
<td>87</td>
<td>540</td>
<td>28.5</td>
<td>12</td>
<td>6 Opus</td>
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<tr>
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<tr>
<td>SD</td>
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<td></td>
<td></td>
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<td>0.96</td>
<td></td>
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</tr>
</tbody>
</table>

All patients received the MED-EL SONATA FLEX<sup>®</sup> implant, except patient no. 5, who had SONATA FLEX<sup>®</sup> AS, acoustic stimulation representing acoustic amplification with hearing aid in the operated ear; CI, cochlear implant; Electrode depth, insertion length of the electrode as measured from the RW; F, female; HA, hearing aid in the contralateral ear; IA, insertion angle; M, male; No. of electrodes, number of active electrodes in the cochlea.

*Criteria, indicates whether or not the patient fulfilled the MED-EL electroacoustic stimulation (EAS) criteria.

Paper IV

The study group consisted of ten female and nine male patients, and the age at implantation ranged from 10 to 82 years. At the time of the patient survey, six patients used unamplified LFH and CI with cut-off frequency. Nine patients used amplified LFH and CI, and four patients used conventional full frequency CI (Table 6). There were no surgical complications and no persistent deterioration of tinnitus or dizziness, but one patient suffered a persistent loss of chorda tympani function.
Table 6. Age, sex, age of hearing loss, ear of surgery, date of activation, mode of fitting and usage of contra-lateral hearing aid. Paper IV.

<table>
<thead>
<tr>
<th>No</th>
<th>Age</th>
<th>Sex</th>
<th>Debut age</th>
<th>Ear</th>
<th>Date of activation</th>
<th>Frequency range (Hz)</th>
<th>HA contra</th>
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</tr>
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<td>L</td>
<td>Nov. 2009</td>
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<td>A</td>
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<td>3</td>
<td>82</td>
<td>F</td>
<td>50</td>
<td>R</td>
<td>Jan. 2010</td>
<td>100-8500</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>69</td>
<td>M</td>
<td>50</td>
<td>L</td>
<td>Jan. 2010</td>
<td>496-8500 + natural</td>
<td>S</td>
</tr>
<tr>
<td>5</td>
<td>48</td>
<td>M</td>
<td>10</td>
<td>L</td>
<td>April 2010</td>
<td>70-8500</td>
<td>S</td>
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<tr>
<td>6</td>
<td>68</td>
<td>F</td>
<td>40</td>
<td>L</td>
<td>May 2010</td>
<td>350-8500 + HA</td>
<td>A</td>
</tr>
<tr>
<td>7</td>
<td>70</td>
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<td>A</td>
</tr>
<tr>
<td>8</td>
<td>72</td>
<td>M</td>
<td>20</td>
<td>L</td>
<td>June 2010</td>
<td>250-8500 + HA</td>
<td>A</td>
</tr>
<tr>
<td>9</td>
<td>57</td>
<td>M</td>
<td>20</td>
<td>L</td>
<td>Aug. 2010</td>
<td>350-8500 + HA</td>
<td>A</td>
</tr>
<tr>
<td>10</td>
<td>73</td>
<td>F</td>
<td>50</td>
<td>L</td>
<td>Oct. 2010</td>
<td>393-8500 + HA</td>
<td>N</td>
</tr>
<tr>
<td>11</td>
<td>28</td>
<td>F</td>
<td>C</td>
<td>L</td>
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<td>350-8500 + HA</td>
<td>A</td>
</tr>
<tr>
<td>12</td>
<td>73</td>
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<td>L</td>
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<td>A</td>
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<tr>
<td>13</td>
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<td>F</td>
<td>C</td>
<td>R</td>
<td>March 2011</td>
<td>70-8500 + natural</td>
<td>A</td>
</tr>
<tr>
<td>14</td>
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<td>F</td>
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<td>R</td>
<td>April 2011</td>
<td>393-8500 + natural</td>
<td>N</td>
</tr>
<tr>
<td>15</td>
<td>53</td>
<td>F</td>
<td>20</td>
<td>R</td>
<td>May 2011</td>
<td>333-8500 + HA</td>
<td>S</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>F</td>
<td>C</td>
<td>R</td>
<td>May 2011</td>
<td>450-8500 + natural</td>
<td>S</td>
</tr>
<tr>
<td>17</td>
<td>67</td>
<td>M</td>
<td>20</td>
<td>R</td>
<td>June 2011</td>
<td>458-8500 + natural</td>
<td>A</td>
</tr>
<tr>
<td>18</td>
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<td>40</td>
<td>R</td>
<td>Nov. 2011</td>
<td>250-8500 + natural</td>
<td>A</td>
</tr>
<tr>
<td>19</td>
<td>69</td>
<td>F</td>
<td>40</td>
<td>R</td>
<td>Nov. 2011</td>
<td>100-8500</td>
<td>A</td>
</tr>
</tbody>
</table>

| Min | 10 | 9 | M | C | 8 | R | Oct. 2008 | 9 CI + HA | 3 | N |
| Max | 82 | 10 | F | 50 | 11 | L | Nov. 2011 | 6 CI + natural | 4 | S |

Age; age (years) at activation of the processor. F; female. M; male. Debut age; age at approximate debut of hearing loss, and C is since birth or during early childhood. Ear; operated ear. L; left. R; right. Date of activation of the processor (usually 4 weeks after surgery). Frequency range; Frequency range of the processor in hertz at two-year follow up. HA; hearing aid. Natural; sufficient natural hearing in the operated ear such that HA amplification is not needed. HA contra; hearing aid at the contra-lateral ear at the time of the patient satisfaction survey. A; always. S; sometimes. N; never.
Table 7. Result summary paper IV.

<table>
<thead>
<tr>
<th>No</th>
<th>Frequency range (Hz)</th>
<th>VAS</th>
<th>IOI-HA</th>
<th>Silence</th>
<th>Noise</th>
<th>Music</th>
<th>Residual hearing</th>
<th>LF PTA dB</th>
<th>MS % (gain)</th>
<th>HINT dB (gain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>496-8500 + n</td>
<td>87</td>
<td>28</td>
<td>much better</td>
<td>same</td>
<td>not well</td>
<td>great benefit</td>
<td>37</td>
<td>68 (60)</td>
<td>4 (18)</td>
</tr>
<tr>
<td>13</td>
<td>70-85000 + n</td>
<td>27</td>
<td></td>
<td>much better</td>
<td>much better</td>
<td>very well</td>
<td>great benefit</td>
<td>-2</td>
<td>60 (2)</td>
<td>-1.6 (12)</td>
</tr>
<tr>
<td>14</td>
<td>393-8500 + n</td>
<td>80</td>
<td>33</td>
<td>much better</td>
<td>better</td>
<td>not well</td>
<td>beneficial</td>
<td>50</td>
<td>22 (18)</td>
<td>10.6</td>
</tr>
<tr>
<td>16</td>
<td>450-8500 + n</td>
<td>100</td>
<td>30</td>
<td>much better</td>
<td>much better</td>
<td>very well</td>
<td>beneficial</td>
<td>18</td>
<td>0.1 (11)</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>458-8500 + n</td>
<td>79</td>
<td>25</td>
<td>much better</td>
<td>same</td>
<td>well</td>
<td>great benefit</td>
<td>40</td>
<td>8.9 (11)</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>250-8500 + n</td>
<td>33</td>
<td></td>
<td>much better</td>
<td>much better</td>
<td>well</td>
<td>great benefit</td>
<td>45</td>
<td>12 (8)</td>
<td>5.4 (6)</td>
</tr>
<tr>
<td>1</td>
<td>100-8500 + HA</td>
<td>95</td>
<td>29</td>
<td>much better</td>
<td>much better</td>
<td>very well</td>
<td>great benefit</td>
<td>63</td>
<td>60 (36)</td>
<td>5.4</td>
</tr>
<tr>
<td>2</td>
<td>571-8500 + HA</td>
<td>27</td>
<td>30</td>
<td>much better</td>
<td>better</td>
<td>well</td>
<td>sometimes</td>
<td>48</td>
<td>64 (22)</td>
<td>0.5 (13)</td>
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<tr>
<td>6</td>
<td>350-8500 + HA</td>
<td>80</td>
<td>29</td>
<td>much better</td>
<td>same</td>
<td>well</td>
<td>great benefit</td>
<td>75</td>
<td>60 (60)</td>
<td>3.3</td>
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<tr>
<td>7</td>
<td>594-8500 + HA</td>
<td>85</td>
<td>34</td>
<td>much better</td>
<td>much better</td>
<td>very well</td>
<td>great benefit</td>
<td>35</td>
<td>80 (38)</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>594-8500 + HA</td>
<td>90</td>
<td>28</td>
<td>much better</td>
<td>much better</td>
<td>well</td>
<td>great benefit</td>
<td>57</td>
<td>76 (68)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>250-8500 + HA</td>
<td>80</td>
<td>29</td>
<td>much better</td>
<td>much better</td>
<td>not well</td>
<td>great benefit</td>
<td>60</td>
<td>68 (34)</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>393-8500 + HA</td>
<td>90</td>
<td>25</td>
<td>much better</td>
<td>better</td>
<td>not well</td>
<td>beneficial</td>
<td>52</td>
<td>44 (22)</td>
<td>4.9 (15)</td>
</tr>
<tr>
<td>11</td>
<td>350-8500 + HA</td>
<td>80</td>
<td>29</td>
<td>much better</td>
<td>same</td>
<td>well</td>
<td>great benefit</td>
<td>57</td>
<td>52 (4)</td>
<td>4.1 (8)</td>
</tr>
<tr>
<td>15</td>
<td>333-8500 + HA</td>
<td>85</td>
<td>29</td>
<td>much better</td>
<td>much better</td>
<td>well</td>
<td>beneficial</td>
<td>60</td>
<td>50 (38)</td>
<td>4 (9)</td>
</tr>
<tr>
<td>3</td>
<td>100-8500</td>
<td>48</td>
<td>22</td>
<td>better</td>
<td>same</td>
<td>not well</td>
<td>beneficial</td>
<td>50</td>
<td>60 (56)</td>
<td>5.2</td>
</tr>
<tr>
<td>5</td>
<td>70-8500</td>
<td>80</td>
<td>28</td>
<td>much better</td>
<td>same</td>
<td>not well</td>
<td>no benefit</td>
<td>67</td>
<td>48 (48)</td>
<td>6.1</td>
</tr>
<tr>
<td>12</td>
<td>100-8500</td>
<td>50</td>
<td>23</td>
<td>better</td>
<td>same</td>
<td>not well</td>
<td>no benefit</td>
<td>78</td>
<td>46 (34)</td>
<td>3.3</td>
</tr>
<tr>
<td>19</td>
<td>100-8500</td>
<td>90</td>
<td>35</td>
<td>much better</td>
<td>much better</td>
<td>not well</td>
<td>no benefit</td>
<td>65</td>
<td>20 (12)</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Frequency range at two-year follow up. n; natural unamplified hearing HA; hearing aid. VAS; EQ-5D™ visual analogue scale. IOI-HA total results. Silence, Noise; Response to questions (no. 5 and 6) about hearing in silence and noise. Music; How music sounds (no. 7). Residual hearing; Benefit of residual hearing (no. 9). LF PTA; low-frequency pure tone average (125 – 500 Hz) at one year. MS; Percentage of correct monosyllabic words in the best-aided condition in the operated ear at one year. The gain is in brackets. HINT; hearing in noise test binaurally in the best-aided condition at one year. Gain is in brackets, and a lack of brackets indicates that the HINT was not measured pre-operatively.
Patient satisfaction:

In IOI-HA, the mean score was 29 out of a possible 35 (SD 3.4, range 22-35). The individual results are shown in Table 7. All items, separated into the hybrid hearing and non-hybrid hearing groups, are presented in Table 8. The groups display nearly the same results for all the questions except number 5 (residual activity limitations), where the non-hybrid patients state more limits. This difference was not significant (p=0.71).

Table 8. Results of the International Outcome Inventory for Hearing Aids

<table>
<thead>
<tr>
<th></th>
<th>Natural LFH (6)</th>
<th>CI +HA (9)</th>
<th>Full CI (4)</th>
<th>All patients (19)</th>
</tr>
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<tbody>
<tr>
<td>1. Use</td>
<td>5.0 (±0.0)</td>
<td>4.8 (±0.7)</td>
<td>4.8 (±0.5)</td>
<td>4.8 (±0.5)</td>
</tr>
<tr>
<td>2. Benefit</td>
<td>4.5 (±0.8)</td>
<td>4.4 (±0.7)</td>
<td>4.3 (±0.5)</td>
<td>4.4 (±0.7)</td>
</tr>
<tr>
<td>3. RAL</td>
<td>3.2 (±1.5)</td>
<td>3.0 (±0.8)</td>
<td>3.0 (±1.7)</td>
<td>3.1 (±1.1)</td>
</tr>
<tr>
<td>4. Satisfaction</td>
<td>4.8 (±0.4)</td>
<td>5.0 (±0.0)</td>
<td>4.6 (±0.5)</td>
<td>4.9 (±0.3)</td>
</tr>
<tr>
<td>5. RPR</td>
<td>4.4 (±0.5)</td>
<td>3.6 (±0.7)</td>
<td>3.0 (±1.4)</td>
<td>3.7 (±1.0)</td>
</tr>
<tr>
<td>6. Impact on others</td>
<td>3.8 (±0.4)</td>
<td>4.0 (±0.9)</td>
<td>3.8 (±1.3)</td>
<td>3.9 (±0.8)</td>
</tr>
<tr>
<td>7. QoL</td>
<td>4.3 (±0.8)</td>
<td>4.7 (±0.5)</td>
<td>4.5 (±0.6)</td>
<td>4.5 (±0.6)</td>
</tr>
<tr>
<td>Factor 1</td>
<td>18.7 (±1.9)</td>
<td>18.9 (±1.3)</td>
<td>18.1 (±1.8)</td>
<td>18.7 (±1.5)</td>
</tr>
<tr>
<td>Factor 2</td>
<td>10.7 (±2.1)</td>
<td>10.2 (±1.6)</td>
<td>9.0 (±4.2)</td>
<td>10.1 (±2.4)</td>
</tr>
<tr>
<td>Global score</td>
<td>29.3 (±3.3)</td>
<td>29.1 (±2.3)</td>
<td>27.0 (±5.9)</td>
<td>28.8 (±3.4)</td>
</tr>
</tbody>
</table>

Mean scores (SD in brackets) for IOI-HA. The results are separated into patients with natural LFH (low-frequency hearing), CI+HA, patients with cochlear implant plus hearing aid amplified LFH and patients with full frequency CI. (Number of subjects in brackets.) The max score for each item is 5. Use, hearing aid use; Benefit, cochlear implant benefit; RAL, residual activity limitations; RPR, residual participation restriction; QoL, quality of life. Factor 1 is the sum of items 1, 2, 4 and 7 and represents CI satisfaction. Factor 2 is the sum of items 3, 5 and 6 and represents participation restrictions. The global score is the total score for the seven items.

The EQ-5D™ VAS was not answered by two patients (Table 7). The mean value of the seventeen responders was 78 (SD 18.9 range 27-100). The patients with natural LFH scored 87 (SD 9.7). The group with ipsilateral HA scored 79 (SD 20.2), and the non-hybrid group scored 67 (SD 21.2). The difference between the hybrid and non-hybrid patients was not significant (p=0.51).

According to the nine-question formula, eighteen patients were “very satisfied” with their CI, and one patient was “satisfied.” All the patients recommended CI to a person in the same situation as theirs. Seventeen patients used their CI more than 8 hours per day. One patient used it 4 to 8 hours per day, and one patient used it 1 to 4 hours per day. Table 7 shows the experience of hearing in silence, noise and music. One patient heard less than expected. Three patients heard “about the same”, seven heard “better”, and eight heard “much better” than what they expected.
When comparing the patients with useful LFH with the full-frequency stimulation group, there was a trend for higher scores in the former group. For hearing in noise, the hybrid-hearing patients scored 3.3 (SD 0.9) compared with 2.5 (SD 1.0). A similar difference was found for hearing in silence (4 (SD 0) compared with 3.5 (SD 0.6)). There were no differences in general satisfaction, time use, contra-lateral hearing aid use or expected hearing. Eleven of 15 hybrid-hearing patients claimed that music “sounds well or very well”. All the non-hybrid patients and four hybrid patients did not appreciate music. All the hybrid-hearing patients benefited from residual hearing. Ten out of 15 patients claimed a great benefit. Two out of four patients using full-frequency stimulation claimed no benefit for their residual hearing. One patient did not respond, and one patient with 50 dB LF PTA claimed a benefit.

Hearing Preservation:

There was no incidence of a total loss of residual hearing in any of the patients; all the patients had hearing within audiometer limits (120 dB) in 125-500 Hz. We calculated the LF PTA at the frequencies 125, 250 and 500 Hz. Preoperatively, the mean LF PTA was 31 dB HL (SD 17, min -5 max 67) in the ear intended for surgery and 30 dB HL (SD 16, min 0, max 63) in the contralateral ear. The LF PTA for each patient before surgery and at follow-up is presented in Figure 12. The mean hearing loss at different frequencies is shown in Figure 13. The mean LF PTA loss at different times is presented in Table 9. There was a significant (p <0.05) hearing loss in the operated ear one month after surgery. There was an additional significant loss between the first and second year. The contralateral ear displayed no significant loss during the first year; only between the first and second year.

Eight patients had a three-year follow-up visit. For these patients the mean LF PTA loss in the operated ear was -29 dB (SD 19, max -8, min -58), and the loss in the contralateral ear was -9 dB (SD 7, max 2, min -17), three years after fitting. Two years after fitting, the mean LF PTA loss for these eight patients was -21 dB (SD 17, max 3, min -50) in the operated ear and -7 dB (SD 5, max 2, min -13) contralaterally. In these eight patients, there was a significant loss in the operated ear during the third year following surgery. A similar deterioration in hearing did not occur in the contralateral ear.

In the two children, hearing was well preserved. LF hearing was normal (<20 dB), up to 500 Hz and 750 Hz, respectively. After two years, the LF PTA loss was 7 dB and 22 dB, respectively. The child with 22 dB loss deteriorated 8 dB in her contra-lateral ear.
Figure 12. The low-frequency pure tone average (LF PTA; 125, 250 and 500 Hz) in decibels is presented for each patient preoperatively, one month post-operatively and one and two years after fitting. The three-year results for eight patients are presented.

Figure 13. The mean hearing loss for each frequency one month after surgery and one and two years after fitting and after three years for eight patients.
Table 9. Low-frequency hearing loss after surgery (125, 250 and 500 Hz) on the operated ear and contralateral ear.

<table>
<thead>
<tr>
<th>Time after surgery</th>
<th>Operated ear</th>
<th>Contralateral ear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean loss (dB)</td>
<td>Max (dB)</td>
</tr>
<tr>
<td>One month</td>
<td>-17</td>
<td>-40</td>
</tr>
<tr>
<td>One year</td>
<td>-19</td>
<td>-58</td>
</tr>
<tr>
<td>Two years</td>
<td>-24</td>
<td>-57</td>
</tr>
<tr>
<td>Three years (8 patients)</td>
<td>-29</td>
<td>-58</td>
</tr>
</tbody>
</table>

The difference in decibels in the low-frequency pure tone average (125, 250 and 500 Hz) before surgery and at the specified follow-up times is provided.

Speech recognition

Monosyllables

Before surgery, the patients displayed performances of 20% MS (SD 19, max 58, min 0) in the ear intended for surgery and 35% (SD 17, max 64, min 6) in the other ear at the best-aided conditions. The MS were presented at the mean 72 dB (SD 5, max 85, min 65). Binaurally, the patients displayed 39% MS (SD 17, max 70, min 10) at a mean of 70 dB (SD 4, max 80, min 65).

At the one-year follow-up (two patients missing), the patients displayed a 52% MS performance (SD 19, max 80, min 12) in the implanted ear at the best-aided condition. MS were presented at a mean of 69 dB (SD 3, max 75, min 65). Table 3 shows the individual results after one year. Binaurally, the patients (three missing) displayed a 63% MS performance (SD 16, max 88, min 34) at a mean level of 69 dB (SD 3, max 75, min 65).

At the two-year follow-up (one patient missing), the patients displayed 45% MS performance (SD 27, max 82, min 0) in the operated ear. The MS were presented at a mean level of 68 dB (SD 4.2, max 80, min 65). Binaurally, the patients (all patients) scored 58% MS (SD 17, max 90, min 22) at a mean of 67 dB (SD 3, max 75, min 65).

HINT

Nine patients could not perform the HINT test before surgery because of poor hearing. Ten patients presented a mean HINT result of a 15 dB signal to noise ratio (SNR) in a binaural best-aided listening situation (SD 4, max 10, min 22). In the ear intended for surgery (9 patients), the SNR was 16 dB (SD 6, max 21, min 3).

At the one-year follow-up (18 patients), the mean binaural SNR was 4.2 dB (SD 4, max -1.6, min 10.6), and in the operated ear (14 patients), the SNR was 6.0 dB (SD 5, max 17, min 0). The individual results after one-year are shown in Table 7. In nine patients presenting preoperative HINT scores, the binaural gain in the SNR was 11 dB after one year. A gain of 11
dB was scored in the operated ear in five patients measured monaurally. After two years, the HINT was assessed bilaterally in all the patients, with a mean SNR of 4.6 dB (SD 3.4, max -1.7, min 12.5), and in the operated ear (14 patients), the SNR was 5.8 dB (SD 3, max 11.5, min 0).

Correlations

There was a tendency for hybrid hearing patients to experience better hearing and be more satisfied, but the trend was not statistically significant in any of the questions. There were no correlations between residual hearing and the MS or HINT. The best scoring and the worse scoring patients on the MS and HINT were the hybrid-hearing patients. The patients’ conceptions of improved hearing in silence and noise were not correlated with the postoperative MS or HINT scores or with the MS or HINT gains. All the patients with a signal to noise ratio of less than 1 dB at HINT experienced better or much better hearing in noisy environments after implantation. All of these patients had hybrid hearing.
Discussion

Paper I

The most important finding in the first study is the vast variations in the cochlear anatomy. The varying anatomy has implications on the anatomical reference points and CI surgery.

We used the mid-point of the round window to define the various quadrants of the human cochlea. By definition, the cochlea starts at the cul-de-sac, where the basilar membrane and organ of Corti starts at the high frequency hook region near the postero-superior rim of the round window. Because this reference point was difficult to visualise from moulds, we used the RW mid-point instead. Due to asymmetry and individual variations in cochlear anatomy, general reference points are difficult to identify, and various authors have used different methods (Verbist et al. 2010a). Cochlear coiling and rotations of the cochlea vary among individuals. These anatomic peculiarities might explain the varying results obtained among different authors when assessing the size of the cochlea. When studying moulds, histological sections or x-rays of different reference points are pertinent, which make it even more difficult to compare different studies.

Kawano et al. (1996) investigated 6 human temporal bones and performed sectioning and computer-aided 3-dimensional reconstructions; they estimated the outer wall length to be 40.81 mm, which coincides with our data. We calculated the length of the bony outer wall of the human cochlea, which is longer than the estimated length of the organ of Corti (Ulehlova et al. 1987, Bredberg 1968).

Our estimated values of the width and height of the first turn are in accordance with those reported by Dimopoulos and Muren (1990). In 2007, Stakhovskaya et al. presented measurements of the cochlear width ranging from 6.9 to 8.2 mm, which is slightly larger than we found. The differences might be due to the different reference points used.

The estimated mean number of turns are in accordance with Kawano et al. (1996), who found the number of turns on average to be 2.69, with a range between 2.63 to 3. Cochleae with up to 3 turns were described by Tian et al. (2006). The relative lengths of the various turns are in accordance with Hardy (1938), who measured the organ of Corti in histological sections (first
turn was 58%, second turn 29% and third turn 13% of the total organ of Corti length).

The width of various turns differed greatly between individuals, and the cochlear height varied by as much as 1.4 mm, representing one third of the total height. The different diameters of the cochlear tube seem to have considerable surgical implications and might explain the difficulties experienced by surgeons in reaching full insertion, even in normal cochlea. The current study demonstrates the wide-ranging variations in the interrelationships of various turns. A tilting or “skewing” of the second turn could be seen, and a “displacement” of the second turn with its modiolar axis misaligned and shifted in parallel is possible. These conditions might influence the ease of introduction of the electrode array and explain difficulties in introducing long cochlear electrode arrays and warrant the need for minor manipulation to achieve full insertion in some instances.

The sampled cochleae were from unidentified autopsy materials. No information regarding the gender, age or disease was obtained. The intra-subject variability was not studied because only one cochlea from each cadaver was collected. The length of the modiolar wall could not be assessed, and the material only allowed for an estimation of the outer wall length. Escudé et al. (2006) found male cochleae to be statistically larger then female cochleae, but still this variation is much smaller than the interpersonal variations, and the longest cochlea could belong to a female. Hardy (1938) found the organ of Corti to be longer in men (0.83 mm) and found an inter-aural difference (0.74 mm). The right ear typically had longer organs of Corti. Stakovskaya et al. (2007) found no intersex differences in the length of the organ of Corti. Escudé et al (2006) found an inter-aural difference that was the same size as the error of measurement. The large variability between subjects overshadows any variability based on sex or the side of the head.

**Paper II**

Our calculations in 51 unselected cochlear moulds illustrate that a prediction of the lengths of the two first turns could be made from the diameter A. This prediction could not be made for the third turn because of its large anatomical variations and difficulties in defining a true end point. The diameter A is less predictive for the total cochlear length, which is unfortunate because the total cochlear length is needed to use Greenwoods’ equation (Greenwood 1961, 1990) Depending on the size of the cochlea, a fixed electrode length will end up at different insertion angles. Length measurements might be essential for anatomical reasons and hearing preservation, rather than for estimating the proper place stimulation in hybrid hearing.
Different reference points

Authors have used different reference points for measuring the basal turn diameter, and the results of the length measurements are summarised in Table 10. Similar to our study, Escudé et al. (2006), Martinez-Monedero et al. (2011) and Stakovskaya et al. (2007) used the midpoint of the round window as the starting point for the diameter crossing the modiolus. Dimopoulos and Muren (1990) used the anterior rim of the round window as a starting point, which explains the slightly shorter dimensions despite using the same collection for the analysis. Escudé et al. (2006) obtained similar results to ours using computer tomography. Martinez-Monedero et al. (2011) measured the diameter A using a 3D volume-rendered image in 64 adult cochleae. They noted a rather large variation in diameter A, which could be explained by difficulties in defining the exact reference points on the x-ray. Stkovskaya et al. (2007) measured the diameter of the organ of Corti, which could explain the shorter diameters.

Table 10. The mean length, range and standard deviation of diameter A in different studies.

<table>
<thead>
<tr>
<th>Diameter A</th>
<th>Present study</th>
<th>Escudé</th>
<th>Monedero</th>
<th>Stakhovskaya</th>
<th>Dimopoulos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (mm)</td>
<td>9.3</td>
<td>9.23</td>
<td>8.62</td>
<td>7.43*</td>
<td>8.58**</td>
</tr>
<tr>
<td>Range (mm)</td>
<td>8.3-9.9</td>
<td>7.4-10.3</td>
<td>6.9-8.2*</td>
<td>7.0-9.8**</td>
<td></td>
</tr>
<tr>
<td>SD (mm)</td>
<td>0.4</td>
<td>0.53</td>
<td>0.49</td>
<td>0.45**</td>
<td></td>
</tr>
</tbody>
</table>

* organ of Corti, ** anterior rim of RW as the starting point

There are numerous definitions of the zero degree point for the angular calculation. Figure 14 shows the different methods used to define the zero degree and basal turn. One definition is the basal end of the organ of Corti and scala tympani. Another definition is the posterior end of the round window, which largely coincides with the former definition. A line drawn from the round window across the mid-portion of the cochlea to the outer wall often traverses perpendicular to the superior semi-circular canal and could be used to define the cochlear turns. This line often, but not always, parallels a line drawn along the maximal diameter of the oval window. The asymmetry in gross morphology distorts these reference points, making the calculations difficult in several cases. We selected the midpoint of the RW as the zero degree, which is in accordance with the consensus panel (Verbist et al. 2010a), and using diameter A to separate the different turns is convenient (Figure 4).
Figure 14. Right inner ear mould demonstrating the reference points used to define the zero degree and degrees of the different turns among various authors. A, a line drawn from the mid-point of the round window to the mid-point of the modiolus. This reference line is used in papers I and II and by the consensus panel (Verbist et al. 2010a). B, a line drawn from the superior semi-circular canal through the centre of the vestibule. From this line, a perpendicular line is drawn through the centre of the modiolus, defining the “geometric 0-degree angle” (Cohen et al. 1996, Xu et al. 2000). According to Boëx et al. (2006), a zero reference point is used where a line drawn from the superior semi-circular canal through the centre of the vestibule crosses the electrode. This reference mostly corresponds to the mid-point of the round window. C, a line drawn from the most lateral point of the lateral semi-circular canal to the modiolus (Verbist et al. 2010b). According to Verbist et al. (2010b), there is a 34.6° angle formed between this orthogonal line and A (the mid-point of the round window). The dotted line represents the posterior aspect of the RW corresponding to the end of the organ of Corti. This line coincides with the zero point, according to Greenwood (1961, 1990). Stakovskaya et al. (2007) used a reference point located 1 mm from the basal end of the organ of Corti. The lines A-C bisect the cochlear turns at different points, explaining the various techniques used for defining the basal and second turns. The angular rotations differ, altering the reference points. LSCC; lateral semi-circular canal. SSCC; superior semi-circular canal. FN; facial nerve. *V; mid-point of the vestibulum. FN; facial nerve (displaced upwards).
The formula

Could the formula for one turn length be used to predict the electrode insertion depth? If the surgeon wants to insert an electrode one turn, could the formula for one turn pertinently determine how many millimetres the electrode array should be inserted? The mean and median length for the first turn was 22.8 mm in the present study, with a range of 20.7 to 24.2 mm. A standard insertion of 23 mm would end near one turn. The formula predicts the length of one turn within -0.8 to +1 mm (variations of the residuals). The surgeons’ precision of insertion could be assumed to be approximately 1 mm. The uncertainty of the CT measurements and the definition of the correct measurement points must be considered. Plotting the residuals against basal turn length shows that the formula overestimated small cochleae and underestimated large cochleae. An easier and safer mode than using the formula for one turn might be to use the one turn graph and assess the value of the regression line corresponding to the measured diameter +/- 1 mm. We believe that the graph is helpful in finding extraordinarily small or large cochleae. The assessment of the diameter A might provide the surgeon with an immediate comprehension of the cochlear size, particularly whether the cochlea is “large” or “small”. In addition, the estimation of the first and second turn lengths could be performed.

Error of measurement I and II

The silicone and polyester resin materials had a shrinkage factor of 0.6-1%, which is regarded as negligible with respect to the measurement procedures. In study 1, the error of measurement was estimated by comparing the arithmetic mean of each quadrant length with the measured total length. This mean deviation was found to be approximately 0.08 mm. When comparing the results of studies I and II, for one and two turns, the difference between the two studies was not greater than 0.2 mm, and for the total length, the difference was approximately 1 mm. The reason for the discrepancy and the error of the measurements might be explained by the different techniques used for assessing the distal extreme point at the apex because it was measured by different authors. All the moulds were measured on a two-dimensional photo, which means that the first turn distance is correctly reproduced, but some apical focus is lost in the reproduced image, and an underestimation of the true length is made. If the cochlea is angled away from a Stenver plane, the basal turn length will be underestimated.
Paper III

The results showed that the introduction of thin flexible electrode arrays, approximately one turn, into the scala tympani through a well exposed RW in no instance eliminated hearing (suggesting preserved intra-cochlear ionic gradients and endocochlear potential). Our results seem to show that preserved hearing could be obtained at all frequencies. With the insertion of the 31 mm FLEX SOFT electrode, resistance was noted after one turn but because the goal was full insertion, the electrode was pushed to 540 degrees with preserved hearing (no. 5). There was no correlation between the insertion depths and hearing, but only two of our patients had insertions of more than 405° (no. 5 and 21 had insertion depths 540°). Both patients had an advanced flat loss SNHL before surgery and lost further hearing over several octave bands. Patient no. 21 had a 24 mm array inserted 10-11 electrodes, suggesting that the cochlea was relatively short. We still believe that an insertion more than 1.5 turns is likely to jeopardise residual hearing due to individual narrowing and asymmetry of the ST in the more apical regions.

The patients in study III were the first consecutive patients to receive hearing preservation surgery in Uppsala. This was not a homogeneous group, because we wanted to achieve hearing results and experiences concerning this new method for further patient counselling and recommendations. An important aim was to determine how sensitive the human inner ear is and how resistant the endocochlear potential is for RW perforations and array positioning in the scala tympani. All the consecutive cases were scrutinised, and because of their different auditory profiles, they are presented individually.

Because many of the patients had little high frequency hearing left, it was not possible to detect significant additional increases in the high frequency thresholds because of audiometer limits. The only way to assess structure preservation is through maintained hearing. Pure tone audiometry establishes sound thresholds and has limited value to assess the quality of the sound. Speech intelligibility gives us more information. Those patients who could discriminate words using headphones before surgery were tested after the surgery and had preserved discrimination in many cases after implantation. This was not routinely tested in every patient.

Air-conduction thresholds are presented, but in some patients bone-conduction thresholds were measured postoperatively showing the presence of an air-bone gap despite a normal eardrum. This indicated an induced conductive hearing loss. Whether or not this represents a “true” conductive or an “intra-cochlear” conductive loss remains to be elucidated. It is possible that an intra-cochlear electrode might influence the mechanical properties of the inner ear.
A shortcoming of this study was the definition of 360°. For uniformity, we should have used similar definitions as in study I and study II. Instead, the zero degree was defined at the proximal rim of the RW, which is often parallel to a line defining the long diameter of the oval window. This zero line in some patients corresponds to the geometric 0° angle (line B in \textbf{Figure 14}) used by Cohen et al. (1996) and Xu et al. (2000), but in some patients it does not. This shows the complexity in finding reproducible reference points because of varying anatomy. All the insertion angles in study III were measured in a standardised method, making comparisons possible.

Is 360° optimal if residual hearing is lost?

A deep insertion of the electrode array up to near the apex is thought to provide better low frequency CI hearing. The spiral ganglion in the modiolus only extends 1 ¾ turn of the cochlea. In the basal turn, ganglion cells are anatomically positioned near the corresponding hair cells in a tonotopic fashion. An electrode here could theoretically stimulate ganglion cells in a more frequency-specific manner. More apically, the ganglion cells are situated closer to each other in a 3-dimensional plane. A deeper insertion might not provide more discrete tonotopic stimulation, and this could restrict speech discrimination. Adunka et al. (2010) presented results from two matched groups of CI patients that were implanted either with a 20 mm or 31.5 mm device using similar speech processing strategies. They showed that the patients with shorter arrays with ipsilateral hearing preservation provided comparable speech perception performance to conventional full-length CI when electric stimulation was used alone. Preserved residual hearing provided an additional benefit over electrical stimulation alone. These results might challenge the view that more apical stimulation provides additional benefits for pitch perception and speech comprehension. A strategy of hearing preservation with insertion around 360° might be optimal. In study III, one patient used a CI with a long electrode on the contralateral ear with no obvious differences in the progress of the performance.

Paper IV

All our patients recommended a CI to a person in a similar situation as theirs, and this is a major sign of patient satisfaction. The overall benefits in high-frequency hearing seemed to overshadow the possible benefits of preserved LFH. Because only four patients lost the possibility of hybrid hearing, the cohort was too limited to assess the possible advantages of hybrid hearing. A control group lacking usable LFH in the ipsilateral ear could not be obtained because the majority of conventional CI patients have profound bilateral loss at all frequencies. Within subject comparisons were not possi-
ble because earplugs and ear defenders are estimated to mask only around 30 dB in the lower frequencies, which is not sufficient if the LFH is normal. Such comparisons would be time-consuming to routinely perform. Plugging of the operated ear was performed in a few patients to evaluate the LFH when considering full frequency CI stimulation or HA. Lenarz et al. (2013) performed within subject comparisons and showed that hybrid hearing was superior compared with non-hybrid hearing. Their patient satisfaction survey compared only hybrid hearing to preoperative HA hearing.

We separated the patients into three different groups according to their devices. We found it most useful to analyse the same groups in the patient survey. A disadvantage is that the patients with similar LFH might choose different fitting strategies including the ipsilateral HA. We compared the rate of satisfaction related to actual LFH and in different groups and found no correlations. Santa Maria et al. (2013) analysed a fairly small patient sample and similarly found no differences in patient satisfaction between EAS and non-EAS.

Our patients scored almost identical on the IOI-HA compared with patients suffering from otosclerosis receiving hearing aids (Redfors et al. 2013). The otosclerosis patients with mixed hearing loss were claimed to score better than the patients with only sensorineural hearing loss using a HA.

Our results indicate that music perception was better for the hybrid-hearing patients than for the non-hybrid patients. The contralateral hearing might also have contributed to the music experience, because patients with little LFH mostly had similar situations in the contralateral ear. The preoperative music experience differed. Some patients had normal hearing since birth, and others had limited high-frequency hearing memory. This raises a problem concerning relative patient satisfaction. Some patients were very satisfied by relatively small improvements, particularly if they had experienced a long-lasting period of profound hearing loss with limited hearing experiences. The duration of deafness varied greatly in the cohort. Fifteen patients (79%) scored their hearing as “better” or “much better” than they expected. This might be influenced by our pre-operative consultation, in which patients are generally offered low expectations to avoid major disappointment.

Despite ubiquitous hearing preservation after RW surgery, a deterioration of LFH in the operated ear was observed during the first years. The fact that the loss is more advanced in the operated ear suggests that the loss could have been induced by the electrode array. The explanation of the less severe hearing loss occurring in the non-operated ear might be related to the aetiology of hearing impairment.
There are several methods to present hearing loss in connection to hearing preservation surgery (Incerti et al. (2013)). Because all our patients had a skislope audiogram and because all the patients had measurable hearing at 125-500 Hz postoperatively, we found that our selected method was practical and easy to use every day in the clinic. Lenarz et al. (2013) characterised hearing preservation either as complete (≤10 dB) or partial (≤30 dB). In sixty-six patients, 43% had complete preservation, and 74% had partial preservation after one year. In the present investigation, 32% of our patients had complete preservation, and 95% had partial preservation after one month. At one year, the corresponding values were 21% and 89%, respectively; at two years, the values were 26% and 63%, respectively. The results indicate that the number of patients with completely preserved hearing was fewer in our study compared with the study by Lenarz et al. (2013), but the number of patients with partially preserved hearing was higher. A loss of 30 dB could be the difference between using acoustic complement and not using it.

In our material, we did not have a way to predict hearing deterioration instantly after surgery or later. A better understanding of the aetiology of hearing loss might contribute to making these predictions in the future. Because the loss of residual hearing could not be predicted, the progression of LFH loss should always be considered in patient consultations, but this should not contradict implantation because the patient will benefit from CI.

If the LF PTA amounts to 50 dB before surgery, it is likely that the patients will not use an ipsilateral HA. The patients who, due to more LFH loss, switched from the hybrid hearing strategy to full frequency programming did not complain, because they gained full frequency CI hearing and maintained LFH in the contralateral ear. They were pleased with the easier handling of the processor that does not obstruct the ear canal. The patients with initial unaided LFH who deteriorated after fitting abandoned the hybrid hearing strategy and used a full-frequency CI. One patient preferred full-frequency stimulation despite normal low frequency hearing, and another patient chose full-frequency CI stimulation with a HA in two years. These results indicate the remarkable potential of the “listening” brain and demonstrate the complexity of retrieving the best-aided condition. Because our patients have natural LFH in the contralateral ear, they likely suffer less from ipsilateral LFH loss. This needs to be taken into careful consideration before bi-lateral implantations for hybrid hearing. More studies are necessary before bilateral hybrid hearing is established.

One year after surgery, the patients displayed a mean 52% performance in the MS test in the operated ear. This is in accordance with earlier studies (Hamzavi et al. 2003, Skarzinsky et al. 2012, Lundin et al. 2013). The HINT results after one year were in accordance with Gifford et al. (2013). After two years, a slight reduction in the MS and HINT scores were seen. The
majority of the patients, when asked, experienced persistent or improved hearing.

In many patients, the speech test results were not consistent with the patients’ subjective experiences. Factors such as preoperative hearing ability, individual expectations and environmental needs might explain these inconsistencies. This shows the value of assessing the patient satisfaction score together with audiological tests to understand the bona fide hearing situation.

The two children included in this report are described separately because they seem to show the possibility for successful CI rehabilitation despite profound high frequency deafness since childhood. These children could receive early high-frequency CI hearing and improved hearing at a critical time of their life. The high frequency hearing seems to facilitate learning and cognitive development. Because both children had normal LFH preoperatively, they could benefit from hybrid hearing for many years despite deterioration of the residual hearing. This might be found to be important for their optimal educational situations and social development.
Conclusions

The human cochlea shows large variations in the dimensions and coiling characteristics, and the large variations influence the ability to insert an electrode.

The diameter of the basal cochlear turn (diameter A) shows a good correlation to the length of the first and second cochlear turn but to a lesser degree of correlation to the total cochlear length. Diameter A could be used to distinguish a small and a large cochlea and to suggest the insertion depth of the electrode.

The hearing preservation rate in the first 21 patients treated with hearing preservation CI surgery was successful, enabling us to implement this hearing preservation technique routinely.

Electric stimulation provides a major contribution to speech comprehension in partially deaf patients. All the patients were satisfied with their CI, regardless of varying hearing preservation.

The preservation of hearing constitutes an additional benefit that might improve hearing in noise and music perception. This effect has only a minor influence on overall patient satisfaction.

There was on-going deterioration of the residual hearing in the operated ear, which surpassed the contralateral ear. The gain reached in speech understanding widely exceeded the downside in losing some LFH.

Based on our findings we propose:

- Most people with partial deafness should be offered hybrid hearing.
- Evaluations of patient satisfaction should be used with conventional hearing tests to increase the knowledge of CI hearing.
- Diameter A should be assessed in all CI candidates, and the surgeon should be familiar with the varying cochlear anatomy.
The varying human cochlear anatomy is a challenge to the CI surgeon. More research is needed to design the optimal electrode fit for each individual cochlea.

Atraumatic CI surgery is important for all CI recipients. Besides preserving hearing, it might reduce the risk of further progressive damage to the hair cells and/or spiral ganglion neurons. It does not interfere with the future promise in drug, gene or stem cell therapy.

A new challenging field is the drug delivery to the inner ear to treat deafness. This field might open up new avenues for treating inner ear disorders. Recently, it was demonstrated that mammalian cochlear hair cells might be replaced by supporting cells through chemical induction. These novel revelations about the induction of hair cell regeneration from supporting cells might become a clinical reality in the future (Naomi et al. 2014). In Uppsala, we are now engaged in this type of research with American and European researchers within a framework of EU grant FP 7 with the acronym "Otos-tem".

A high rate of hearing preservation might expand the indications for CI surgery to include patients with severe tinnitus and even other types of inner ear diseases, and children and adults with less severe deafness.

In a nearer perspective, it is our hope that the collected information gathered from this thesis will help to council patients in their decisions regarding implantations and will provide patients with reasonable expectations of the outcome.
Hörseln är det viktigaste sinnet när det gäller mänsklig samvaro och kommunikation. Utanförskap och social isolering är ofta en följd av hörselned-sättning.

En vanlig orsak till grav hörselnedsättning är att hårcellerna i hörselnäckan är skadade så att snäckan inte kan omvandla inkommande ljud till nervimpulser. Ett snäckimplantat (cochleaimplantat, CI) ersätter hårcellerna och förmedlar elektriska impulser direkt till nervcellerna. Ett CI består av en elektrod som opereras in i snäckan och en yttre processor.


Det övergripande målet för denna avhandling är att demonstrera den vari- erande anatomins betydelse för hörselbevarande CI-kirurgi och att utvärdera hörselresultat och patientnöjdhet efter hörselbevarande CI-kirurgi

I arbete I och II använde vi Uppsalas samling av plastavgjutningar från mänskliga hörselnäckor. Dimensioner och anatomiska variationer studerades. Resultaten visar att varje snäcka är unik vad gäller form och storlek. Längden av snäckans yttervägg var i medeltal 42 mm (38,6-45,6 mm), höjden var i medeltal 3,9 mm (3,3-4,8 mm) och bredden var i medeltal 6,8 mm (5,6-8,2 mm). Det första varvets längd representerade i medeltal 53% av den totala längden. De stora individuella variationerna i snäckans anatomi har betydelse för den tekniska utvecklingen av CI-elektroder och för CI-kirurgens möjligt att bevara hörsel.

Vid val av elektrodängel är det viktigt att känna till snäckans storlek. Basala vindlingens diameter, diameter A, som sträcker sig från runda fönstrets mittpunkt, genom snäckans mitt, till motstående sida av snäckans första varv, är lätt att måta på en röntgenbild. Vi undersökte hur väl diameter A
korrelerar till snäckans längd. Vi fann att diameter A korrelerar väl med första varvets längd ($R^2=0.74$) men mindre väl med snäckans totala längd ($R^2=0.39$). Diameter A kan användas för att bilda sig en uppfattning om snäckans storlek inför kirurgi.


Resultaten innebär att även om hybridhörsel är att föredra så utgör tillskottet av elektrisk diskanthörsel den stora förbättringen för diskantdöva patienter. Att ge CI till diskantdöva ger en hög grad av patientnöjdhet och förbättrad taluppfattning oavsett nivå av bevarad bashörsel.
Först vill jag tacka

Alla patienter som har bidragit till avhandlingen!


Min biträdande handledare Konrad Konradsson som aldrig fick möjlighet att stötta mig med avhandlingen, men hann lära mig mycket annat.

Mina medförfattare Karin Wadin och Herman Högstorp som lade grunden till arbete I, och Susanne Köbler som invigde mig i de stora Excel-arken, hjälpte till med beräkningar och dessutom är en god vän!

Alla i CI teamet, utan teamets härliga samarbete hade patienterna aldrig nått de resultat vi ser i avhandlingen!

Karin Lundin och Fredrik Stillesjö, CI-ingenjörer. Karin, för din entusiasm, värdefulla synpunkter på avhandlingen och ditt stora tålamod med mina bristande tekniska kunnaper. Fredrik, för ditt genuina intresse för vad jag gör!

Jag vill och också tacka

Mina hörselkollegor Nadine Schart-Morén och Charlotta Kämpfe Nordström, utan er på jobbet hade det här aldrig gått. Eva Funseth Åhs, du kom med perfekt tajming! Vilken lyx det är att ni finns både på jobbet och privat.


Min kliniska handledare i ÖNH Monika Stenqvist-Asplund, du tog dig an mig när jag var ny på kliniken och förde in mig på forskningen genom att putta iväg mig med en poster till Riksstämman. Dessutom lärde du mig sådant om en klinik som inte kan läsas i böcker!

Alla arbetskamrater på alla sektioner på Öron- Näs och Halskliniken, med ett särskilt tack till alla på hörsel, för ni känns som ”hemma”.


Mats Holmström, min första chef som vågade anställa en nybliven mamma utan tidigare ÖNH-erfarenhet. Manochehr Amani min nuvarande chef som hjälpt mig skapa tid för detta avhandlingsarbete.

Alla mina vänner, som lett mina tankar bort från avhandlingen. Ni anar inte vad ni betyder!
Sist och mest vill jag tacka min familj.

Min mamma Alfhild och min pappa Torsten. Tack för den trygghet och kärlek ni ger mig och att ni alltid finns när ni behövs!

Mina Syskon Erik, Tomas och Agnes. Tack för allt roligt vi lekt och fortfarande leker!

Min svärfar Tage och min oändligt saknade svärmor Margaretha.

Sväger, svägerska och syskonbarn.

Mina älskade barn Hugo, Sara och Ivar. Ni är meningen med livet!

Min make Per. Tack för de 25 första åren vid min sida! Livet tillsammans är härligt. Älskar dig!


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SCBs levnadsvåndersökningar (ULF) 1984-2008.


## Appendix

**International Outcome Inventory for Hearing Aids – Swedish (IOI-HA)**
**Anpassad för Cochleaimplantat (CI)**

1. **Tänk på hur mycket du använder ditt CI under de senaste två veckorna.**
   **Hur många timmar använder du CI under en genomsnittlig dag?**
<table>
<thead>
<tr>
<th>Inte alls</th>
<th>Mindre än 1 timme per dag</th>
<th>1 till 4 timmar per dag</th>
<th>4 till 8 timmar per dag</th>
<th>mer än 8 timmar per dag</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
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<td>□</td>
</tr>
</tbody>
</table>

2. **Tänk på den situation där du mest önskade höra bättre innan du fick CI.**
   **Hur mycket har CI hjälpt i den situationen under de senaste två veckorna?**
<table>
<thead>
<tr>
<th>hjälpte inte alls</th>
<th>hjälpte lite</th>
<th>hjälpte någorlunda</th>
<th>hjälpte en hel del</th>
<th>hjälpte väldigt mycket</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

3. **Tänk igen på den situation där du mest önskade höra bättre.**
   **Hur mycket svårigheter har du FORTFARANDE i den situationen när du använder ditt CI?**
<table>
<thead>
<tr>
<th>stora svårigheter</th>
<th>en hel del svårigheter</th>
<th>måttliga svårigheter</th>
<th>lite svårigheter</th>
<th>inga svårigheter</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
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</tr>
</tbody>
</table>

4. **Tycker du att ditt CI är värt besväret om du tar hänsyn till allt?**
<table>
<thead>
<tr>
<th>inte alls värt besväret</th>
<th>lite värt besväret</th>
<th>någorlunda värt besväret</th>
<th>en hel del värt besväret</th>
<th>mycket väl värt besväret</th>
</tr>
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<tr>
<td>□</td>
<td>□</td>
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</tbody>
</table>

5. **Hur mycket har dina kvarstående hörselproblem försvarat vad du kunnat göra under de senaste två veckorna med ditt CI?**
<table>
<thead>
<tr>
<th>försvarat mycket</th>
<th>försvarat en hel del</th>
<th>försvarat måttligt</th>
<th>försvarat något</th>
<th>inte försvarat alls</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

6. **Hur mycket tror du att andra människor besvärades av dina svårigheter att höra under de senaste två veckorna?**
<table>
<thead>
<tr>
<th>besvärades väldigt mycket</th>
<th>besvärades en hel del</th>
<th>besvärades måttligt</th>
<th>besvärades lite</th>
<th>besvärades inte alls</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

7. **Hur mycket har ditt CI påverkat din livslådje om du tar hänsyn till allt?**
<table>
<thead>
<tr>
<th>försämrat</th>
<th>ingen ändring</th>
<th>förbättrat något</th>
<th>förbättrat en hel del</th>
<th>förbättrat väldigt mycket</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
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<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

Anpassad för CI november 2012 av Ela Erikson
Uppföljning av CI med hörselbevarande kirurgi:

Ringa in det svar som stämmer bäst!

1) Hur nöjd är du med ditt CI?
   - Inte alls nöjd
   - Litt nöjd
   - Nöjd
   - Mycket nöjd

2) Skulle du vilja rekommendera CI till någon i liknande situation som din?
   - Ja
   - Nej
   - Vet inte

3) Hur mycket använder du ditt CI?
   - 8 timmar eller mer per dag
   - 4-8 timmar per dag
   - 1-4 timmar per dag
   - Någon gång i veckan
   - Aldrig (Om du aldrig använder implantaatet behöver du inte svara på frågan på detta formulär)

4) När du använder ditt CI har du då hörapparat på andra örat?
   - Nej aldrig
   - Ja alltid
   - Ja ibland

När vi nu frågar hur du hör ska du tänka dig att du använder de hjälpmedel du oftast använder.
Till exempel CI på ett örat och ett hörapparat på andra örat.

5) Hur hör du med ditt CI i tyst miljö?
   - Jämför med hur du hörde före operationen!
     - Jag hör samma med CI än före operation
     - Jag hör ungefär lika som innan jag opererades
     - Jag hör bättre
     - Jag hör mycket bättre

6) Hur hör du med ditt CI i störmiljö (många som pratar, trafikbuller mm)?
   - Jämför med hur du hörde före operationen!
     - Jag hör sänkre med CI än före operation
     - Jag hör ungefär lika som innan jag opererades
     - Jag hör bättre
     - Jag hör mycket bättre

7) Hur låter musik med de hjälpmedel du har?
   - Jag lyssnar aldrig på musik
   - Jag kan lyssna men det låter inte bra
   - Musik låter bra
   - Musik låter mycket bra

8) Hör du så bra med CI som du före operationen hade förväntat dig att du skulle höra?
   - Jag hör sänkre än jag trodde att jag skulle höra
   - Jag hör ungefär som jag trodde att jag skulle höra
   - Jag hör bättre
   - Jag hör mycket bättre

9) Upplever du att du har nyttja av den bevarade hörseln på det opererade örat?
   - Ingen nyttja
   - Viss nyttja ibland
   - Nyttja
   - Stor nyttja

Här får du gärna skriva ned kommentarer och synpunkter:
Till hjälp för att avgöra hur bra eller dåligt ett hälsotillstånd är, finns den termometer-liknande skalan till höger. På denna har Ditt bästa tänkbbara hälsotillstånd markerats med 100 och Ditt sämsta tänkbbara hälsotillstånd med 0.

Vi vill att Du på denna skala markerar hur bra eller dåligt Ditt hälsotillstånd är, som Du själv bedömer det. Gör detta genom att dra en linje från nedanstående ruta till den punkt på skalan som markerar hur bra eller dåligt Ditt nuvarande hälsotillstånd är.
Acta Universitatis Upsaliensis

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Editor: The Dean of the Faculty of Medicine

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