PROGRESS REPORT OF

Donders Hearing & Implants

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Dear reader,

We are pleased to present the first progress report of Donders Hearing & Implants (DH&I). Donders Hearing & Implants is an interdisciplinary research platform that is firmly rooted within Theme 2 (Perception, Action & Control) of the Donders Institute for Brain, Cognition and Behaviour at the Radboud University Nijmegen.

The research activities are embedded in the Neurophysics Unit of the Donders Centre for Neuroscience (DCN) at the Faculty of Science. Our interdisciplinary group consist of audiologists and clinicians from the Otorhinolaryngology Department at the Radboud University Medical Center (Radboudumc), and of biophysicists and neuroscientists from the Biophysics Department at the Science Faculty (FNWI).

In collaboration with Hearing & Genes we explore the challenging research area of adults and children with genetic disorders who are in need of a hearing implant. It is our aim to bridge the gap between academic fundamental research of the human auditory system, and clinical applications in the field of hearing rehabilitation. It is our firm belief that bundling clinical and fundamental research, and sharing our expertise and resources, will improve the quality of care for hearing-impaired subjects, and lead to a better understanding of the mechanisms underlying hearing disorders. Our ambition is to provide the best possible clinical care, to understand the variety of mechanisms that are involved in hearing rehabilitation, and to contribute with our expertise to further improve auditory implant technologies and their objective evaluation.

With this progress report we present an overview of our recent work, and of our plans for the near future. This report does not intend to give a full overview of all DH&I research activities. We hope to share our enthusiasm for the potential of our work to the rehabilitation of the hearing impaired.

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In 1987, the first deaf adult patient received a cochlear implant in Nijmegen. The first child was implanted in 1992. At the end of 2013, 910 cochlear implants had been implanted in deaf adults, and 554 in deaf children. Cochlear implants have been developed for patients with profound hearing loss or total deafness. The actuator is an electrode array, typically 22
electrodes in a row, which is surgically placed in the deaf cochlea (in the scala tympani). An externally worn audioprocessor is coupled transcutaneously to an implanted receiver unit that drives the electrode array, see Figure 1. The electric current in the cochlea stimulates the remaining nerve endings, in such a way that the tonotopical organisation of the cochlea is used optimally.

Fitting of bone-conduction devices, like the Bone Anchored Hearing Aid (BAHA, Fig. 2), was started in Nijmegen in 1988. The first child was implanted with a percutaneous titanium temporal bone implant in the next year. At the end of 2013, 1521 patient had received a semi-implantable bone-conduction device, about 20% being children. It comprises an externally worn audioprocessor with vibrator (as actuator), coupled percutaneously to the skull by means of a titanium implant. Amplified acoustic signals are transferred into vibrations that are transmitted by the skull bone and stimulate the cochlea. This device was developed for patients with chronic draining ears or absent external ear canals and/or malfunctioning inoperable middle ears.

Implantable hearing aids or active middle ear implants (Fig. 2) are on the market since the mid-nineties. In the Nijmegen clinic, the first middle ear implantation was carried out in 1997. At the end of 2013, 102 adults have been implanted but, so far, no children. Primarily, this auditory implant was developed for cosmetic reasons. However, most widely applied is the semi-implantable version. In principle, this auditory implant is a conventional acoustic device with the telephone changed for a small vibrating actuator. That actuator is implanted in the middle ear, driving directly one of the middle ear ossicles or cochlear windows. In Nijmegen, middle ear implants were mainly applied in hearing impaired patients with co-morbid severe chronic external otitis.
Introduction

Because hearing impairment directly affects the ability to communicate with fellow human beings, it has a significant impact on someone’s social activities and on the perceived quality of life. For children, hearing impairment also affects their mental development, not only with respect to maturation and organization of their auditory system and language acquisition skills, but also on the development of their cognitive and socio-emotional abilities.

Hearing rehabilitation technology has improved spectacularly over the last decades, not only because of the introduction of fast digital sound processing systems, but also because of growing knowledge in the field of biomaterials. These improvements have led to better conventional hearing solutions with enhanced sensitivity and selectivity, and increased signal bandwidth. The technological advancements have also enabled the clinical application of (partly) implantable hearing devices, which have created new sound-amplification options for patients who suffer from previously untreatable hearing problems.

The Nijmegen ENT clinic has become a leading clinic in the application of auditory implant technologies for over 25 years. We apply cochlear implants (CI), middle ear implants (MEI) and temporal bone implants (BI) to patients with a wide variety of hearing disorders. In a continuous search for the best amplification options, new technological developments were recognized as innovative treatments for specific hearing problems (e.g. CI for total deafness, MEI for chronic external otitis, and temporal BIs for chronic draining ears, atresia and single sided deafness). In children under the age of 3 years a bone-conduction device (BCD) cannot be used on a titanium BI because of the limited thickness of the temporal bone. The main research focus has been on the technology of temporal BIs in relation to the safety and stability of these titanium implants, on the effectiveness of BCDs
in objective terms (audibility, speech recognition, spatial hearing), in subjective terms (remaining disability, handicap) and in health technology studies.

We have recently started a number of academic research projects, in close collaboration with the department of Biophysics from the faculty of Science. The department has long-standing expertise in measuring monaural and binaural auditory processing through unique psychophysics in humans, and through psychophysics and neurophysiology in monkeys. It has advanced equipment to effectively test two-dimensional sound-localization behaviour in all directions through natural, objective responses (rapid gaze orienting), and it uses advanced psychophysical techniques and data analysis methods to objectively assess sound perception in humans. In May 2011, the clinical and academic research activities were bundled in a new joint research platform, called “Donders Hearing and Implants” (DH&I). The aim of this platform is to provide a long-standing fruitful collaboration, and to further extend the research activities on hearing impairment and hearing rehabilitation. By its increased research mass and its novel expertise we augment our possibilities to apply for external funding, and to thus initiate new projects using innovative technologies and objective analysis methods.

In what follows, we briefly describe the highlights of our current research projects. We summarize our current funding sources, and preview our near-future plans and long-term goals with DH&I. In Chapter I (Academic research) special attention is paid to binaural hearing, directional hearing and brain plasticity. Chapter II describes research projects investigating the effects of new sound-processing algorithms, the potential binaural benefits for bilateral application of devices, and the combination of different stimulation modes (acoustical, vibrational, electrical). In Chapter III (Behavioral research projects) we describe our efforts to optimize rehabilitation in deaf children with special attention for their academic and socio-emotional development.

Our aim is to continue our leading and pioneering position in the field of auditory implant technology, by extending our research efforts to the objective evaluation of auditory impairment and implant effectiveness, and by studying the potential neural mechanisms that underlie auditory rehabilitation and neural plasticity.
Academic research projects

Spatial hearing

For many years, directional hearing has been one of the main research topics in our laboratory. The laboratory comprises a sophisticated experimental setup in which we can present sounds from all possible directions (Fig. 3). We investigate sound localization in a completely dark, sound attenuated room. We are also able to investigate sound localization during whole body rotation (Fig. 4). The sound localization ability is measured in complete darkness with the magnetic search-coil technique (Fig. 5).
Our studies demonstrated considerable plasticity of the auditory system. In several high-impact research papers, we demonstrated that humans can relearn to re-acquire accurate sound localization abilities with new pinna geometries throughout life (Hofman et al., 1998). The adult human auditory system has the capacity for an ongoing spatial calibration. After modifying the outer ears (pinnae) of normal-hearing subjects with molds, which immediately deteriorates their localization ability dramatically because of disrupted spectral elevation cues, they reacquire an accurate performance within weeks (Fig. 6).

In line with these fundamental research findings, we recently demonstrated that also hearing-impaired listeners can learn to adapt their localization strategies under a wide variety of challenging hearing conditions. In several publications we have now demonstrated the increased localization abilities of patients with unilateral conductive hearing loss when fitted with a bone-conduction device.

We demonstrated that listeners with unilateral conductive hearing loss demonstrate improved directional hearing when they are listening with a bone-conduction device (Fig. 7). The data point towards the possibility that localization abilities increase because of restored access to binaural cues (Fig. 8).

An important factor affecting directional hearing with a bone-conduction device is the additional stimulation, through bone conduction, of the cochlea contralateral of the implanted side. This so called cross hearing is possible because of the limited transcranial attenuation...
of sound vibrations in the skull. We demonstrated that although cross-hearing might affect directional hearing, patients implanted with a middle ear implant did not outperform patients with a bone-conduction device on a sound localization test in our setup (Figure 9).

In Nijmegen many young children receive a hearing implant. Ultimately we restore their hearing and succeed in providing them useful binaural cues. The ability to use binaural cues for the localization of sounds is difficult to measure at a young age. Our results are the first that demonstrate accurate sound-localization performance under open-loop conditions in a completely dark environment by children from 7 to 11 years of age. We demonstrated that children performed as well as young adults (age 20-35). Our experience with performing tests in children is now helpful to investigate the best hearing solution for different populations of patient with a young age.

Our ear keep growing throughout life, a side project performed in our laboratory is the study of the effect on ear size on sound localization. The results are published in the international literature and two articles on this project appeared in the Dutch quality newspaper NRC. Ear size (concha height) increased with advancing age. We hypothesized that larger ears might enable older adults to localize sounds in
elevation on the basis of lower frequencies, thus (partially) compensating their age-related high-frequency hearing loss. We found similar localization abilities in the horizontal plane for children (7–11 years), young adults (20–34 years), and older adults (63–80 years).

However, sound localization in the vertical plane was more variable. Subjects with larger ears could also judge the elevation of sound sources restricted to lower frequency content (see the Figure). Despite increasing ear size, sound localization in elevation deteriorated in older adults with high frequency hearing loss.

We conclude that the binaural localization cues are successfully used well into later stages of life, but that pinna growth cannot compensate for age-related high frequency hearing loss.

Our translational research has resulted in publications about the capacities of hearing impaired children and adults fitted with different types of hearing devices. We are currently investigating the advantage of sequentially bilateral cochlear implantation on sound localization abilities in deaf children. Furthermore, we are investigating how cross-stimulation affects the directional hearing abilities when listening with a BCD.
Auditory scene analysis

In everyday life, the auditory system is faced with the formidable challenge to attend and respond to behaviourally relevant sounds that are masked by a myriad of competing sound sources. The complexity becomes evident from the so-called ‘cocktail-party’ problem.

We investigate the neural mechanisms underlying segregation of auditory objects from complex backgrounds, and how hearing-impairment influences this. Results of this project have considerable practical value for improving current hearing-aids and speech-recognition systems that need to perform in noisy environments. Both hearing impairment and bottom-up auditory processing disorders jeopardize auditory perception (auditory scene analysis, ASA). In case of hearing loss, fitting of adequate state-of-the-art hearing aids helps with audibility but doesn’t lead to normal hearing. Furthermore, today’s hearing devices pre-process the incoming sounds which might be helpful for adults who are experienced with ASA, but not necessarily children, who are still developing their ASA capabilities. Problems with hearing and/or bottom-up auditory processing in children might deteriorate maturation and delay ASA development. Good ASA performance is essential for educational uptake, especially in the school environment, where children are exposed to a complex auditory scene. Children with hearing problems might not understand the teacher because they cannot focus on the teacher speaking, while ignoring other environmental sounds (such as produced by the other children).

Through psychophysical tests we determine the individual ASA capacities of children and adults, by parametrically assessing how co-varying spectral, temporal, spatial (see also the section about spatial hearing) and contextual cues influence ASA. For example, we ask subjects to detect changes in spectral and temporal fluctuations in rippled sounds in order to predict how they would perform when listening to any other sound with an arbitrarily complex acoustic pattern (naturalistic sounds, vocalizations and speech) in noisy environments. In another set of experiments, we aim to see how subjects are affected by spectrally-non-overlapping competing sound sources.
AUDITORY BRAIN PLASTICITY

At Donders Hearing & Implants, we use several techniques to provide an objective measure for the efficacy of cochlear implantation. Functional neuroimaging techniques allow for investigation of human central auditory processing and assessing human auditory cortical activity. We specifically look at how the visual system takes over auditory cortical areas in auditory-impaired subjects, and how this affects hearing performance after implantation. Unfortunately, several of the neuroimaging methods (magnetic-resonance imaging and magneto-encephalography) are severely limited in their usefulness in CI patients, as they are affected by and/or affect the metal, magnetic components of the CI. Therefore, we study neural reorganization of auditory cortical areas in prelingually deafened CI users by measuring metabolic changes in the brain through positron emission tomography (PET). This technique has the benefit of having a high spatial resolution, which allows us to accurately localize the activity in auditory, visual and multisensory areas of the brain before and after implantation. Comparing individual differences in localized activity with idiosyncratic hearing performance after implantation (as determined by psychophysical measures, see elsewhere), we aim to predict the effectiveness of implantation. PET has the disadvantage that it is invasive (an injection with a radioactive isotope is required). Therefore, we also combine two promising non-invasive neuroimaging techniques: electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS). Both techniques allow for measurements in a comfortable and

**Figure 10**

FNI S results

Average changes in oxy- (red) and deoxyhemoglobin (blue) concentrations after visual (V), auditory (A) and audiovisual (AV) stimulation. Stimulus presentation is represented by a grey patch. All measurements were performed at the right hemisphere.
natural environment. They can be utilized in infant and children studies, are portable, easy to handle, and have a relatively low cost. Importantly, these techniques are the only two that can readily measure cortical activity in CI patients. This allows us to study the rapid changes in auditory information processing, that are crucial for speech understanding and sound processing; to investigate functional networks and interhemispheric specializations of the auditory system of CI patients; and furthermore, to learn the processes underlying impaired binaural hearing and sound localization, which are deemed essential for normal-hearing sound perception in noisy environments.

With fNIRS, we measure how activity in the auditory cortex is influenced by auditory and visual speech (Fig. 10). Comparisons between normal-hearing subjects and postlingually deafened CI users indicate how the auditory-impaired process sounds differently.

Furthermore, we investigate auditory brain plasticity in bimodal listeners, listeners with a cochlear implant (CI) in one ear and a hearing aid in the other ear. Independent acoustic and electrical stimulation in each ear offers potentially complementary information that, when appropriately integrated in the brain, could allow for binaural spatial localization, as well as for improved speech understanding and sound-source identification in noisy environments. However, large individual differences in the efficacy of bimodal hearing have been reported. Factors causing these differences are largely unknown, but might include suboptimal fitting of both devices, technical limitations, and individual hearing- and neural-impairment differences. We apply rigorous psychophysical testing, assess the available perceptual acoustic cues for the individual hearing-impaired listener, and optimize these cues by adjusting bimodal device settings, parameters, and algorithms, on the basis of the listener’s responses.

Collaboration

This is in collaboration with the Advanced Bionics European Research Centre (ABERC), property of Sonova, holding company for Advanced Bionics (CI systems) and Phonak (hearing aids).
The cochlear implant is the most successful neural prosthesis. Because of the good performance of most patients the criteria for implantation have been relaxed over the years. The outcome of cochlear implantation depends on many factors. Perception of music, speech recognition in noise and spatial awareness, even in bilateral application, still falls behind that of normal-hearing subjects. One major reason for the limited profit for these implanted patients is a decreased frequency-specific stimulation of the auditory system.

An essential factor limiting the effectiveness of cochlear implants is the reduced channel separation due to the overlap of the electrical fields from each intra-cochlear electrode. As a result, the effective number of channels is estimated to be less than 12 for speech understanding in quiet and possibly even less than 6 for speech understanding in noise, even if 22 electrodes are available. Over the years, we have pioneered novel tripolar electrode configurations that use multiple stimulating electrodes inside the cochlea to “focus” stimulation at restricted populations of neurons and found some improvement of spectral resolution although speech understanding was not improved. One disadvantage of these “focused” configurations is that increased current levels are required to
achieve sufficient loudness, hampering a true application of tripolar stimulation. In a recent study, we attempted to gain a deeper understanding of the individual differences in the perceived loudness from tripolar stimulation. A model of excitation fed by highly accurate recordings of the intrascalar electrical field was correlated to loudness measures, which was successful in 6 out of the 10 subjects. These results suggest that advanced electrical field imaging, complemented with only a limited amount of psychophysical testing, enables estimation of the loudness of complex electrode configurations from earlier collected monopolar data.

Another pre-clinical research line to improve the electrode-neuron interface is the development of a cochlea-on-chip. In collaboration with the Biomaterials research group (Nijmegen) and University of Twente we aim to investigate which physical environment (surface on which neurons grow) provides the best conditions for an optimal connection between neurons and electrodes. The cochlea-on-chip is a novel method, based on lab-on-chip technology, to
Another possibility to activate dendrites of the cochlear nerve more selectively, might be to implant the cochlear nerve bundle directly with a penetrating electrode. We have conducted surgical and imaging research on this particular option (Fig. 12). Although it is still early days, it has been shown by our group that indeed the cochlear nerve may be approached surgically, without inflicting damage to the cochlea or labyrinth itself.

The COC consists of two channels separated by a membrane. A cochlear implant array is inserted at one side of the membrane. At the other side, recording-electrodes are positioned. Later on in the development of the cochlea-on-chip these recording-electrodes are replaced by auditory neurons. The membrane of the cochlea-on-chip was cultured with human bone.

With this setup the influence of critical parameters, such as bone thickness and distance between cochlear implant and neurons, upon stimulation current spread, can be studied. Final aim of our study is the development of a more effective electrode-neuron interface. We aim to improve the electrode-neuron interface by developing cochlear implant electrodes which create a more effective (biological) connection with auditory neurons than presently used electrodes (Fig. 11).

Another possibility to activate dendrites of the cochlear nerve more selectively, might be to implant the cochlear nerve bundle directly with a penetrating electrode. We have conducted surgical and imaging research on this particular option (Fig. 12). Although it is still early days, it has been shown by our group that indeed the cochlear nerve may be approached surgically, without inflicting damage to the cochlea or labyrinth itself.

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Selected publications in the last 3 years:

In the past years, clinical research on the cochlear implants in adults was mostly related to questions that arose as a result of the widening the criteria for candidacy. Speech recognition in postlingually deafened CI users, tested after one year of CI use, has shown a dramatic improvement over the years, due to factors such as improved CI hardware and improved stimulation strategies. A statistical analysis showed that a significant improvement in speech recognition is likely for CI candidates with up to a 60% of speech recognition with conventional devices, compared to 40%, some 10 years ago (Fig. 14). As a result, candidates with considerable residual hearing now receive a CI, and research, aimed at the combined use of CI and a conventional hearing aid in the outer ear, is in progress. This mode of electrical-acoustical stimulation is called Bimodal Hearing.

In addition to residual hearing, other inclusion criteria have also changed, in specific for prelingually deafened adults (adult who were deaf...
before the acquisition of spoken language). CI candidacy of prelingually deafened adults has been debated as benefit is expected to be limited. A recent study in 24 of such subjects showed that indeed prelingually deafened adults shown less improvement in speech recognition compared to postlingually adults. However, we found that the gain in quality of life, although somewhat smaller than that found in postlingually deaf CI users, was substantial (Fig. 15). Remarkably, no relation was found with improvement in speech recognition in this population. However, prelingually deaf CI users also reported benefit regarding detection of environmental sounds which lead to increased sense of security. Benefit was found to develop gradually over an extended period post-operatively, as did quality of life. In addition, prelingually deafened adults typically produce speech that is difficult to understand by naïve listeners; the improved auditory feedback positively affected speech intelligibility. These results justify expanding the CI criteria with prelingually deafened adults. As described in the first chapter of this report, brain plasticity was also studied in this group of patients.

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SELECTED PUBLICATIONS IN THE LAST 3 YEARS:

A great deal of our research efforts in recent years has been focused on bilateral cochlear implantation in children. This was the consequence of the choice of our team to embark on an ambitious prospective cohort-control study in children who were implanted sequentially with cochlear implants. Reimbursement of a second cochlear implant for bilaterally deaf children has been subject to debate in the last five years in the Netherlands. Our work resulted in several articles, and the importance of this scientific work was acknowledged by the national board for health care provisionists and advising body for the Minister of Health, the CVZ, who has given a positive advice regarding the reimbursement of bilateral cochlear implants for children in 2012 and 2013.

Interesting results were obtained using objective measures. On a brainstem and cortical level, we could observe maturation of the auditory processing of the first and of the second cochlear implant,
with a reduction in latencies in time. Moreover, we observed that the latency of the second implant in fact caught up with that of the first to almost the same level. The morphology of the cortical wave generated by the second cochlear implant did however deteriorate with longer time intervals between the first and second implantation and the age at which the second implantation took place. (Fig. 16).

More and more evidence has been provided in the literature that indeed deaf children implanted bilaterally at an early age, simultaneous or with short intervals, leads to better results in speech recognition and sound localization (Fig. 17). Indication criteria for cochlear implantation for children have further changed in the last decade. Initially, deaf children with cognitive deficits or developmental delays were excluded. It was expected that for these children cochlear implantation might not always lead to significant speech understanding and language development, also these children have become candidates. Specific groups of children that fall into this category are children with CHARGE syndrome and children deafened as a result of a congenital CMV infection. Deaf children in need of a cochlear implant with CHARGE are rare but make up a special group owing to complicated anatomy of the temporal bone. We have gathered CT-scan data on all these children in The Netherlands in order to provide cochlear implant surgeons with a realistic set of surgical hurdles that may be encountered during the surgical procedure.

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FIGURE 17
Speech recognition-in-noise test

Results of the speech recognition-in-noise test in sequentially implanted children, 6, 12 and 24 months after the second cochlear implantation. Results of a reference group of unilaterally implanted children at 12 and 24 months is depicted. The speech stimulus is presented at the front and the noise stimulus at the first CI. Only at 24 months a second condition is added, where speech and noise are presented at the front.

SELECTED PUBLICATIONS IN THE LAST 3 YEARS:
Temporal bone-implants and bone-conduction devices

One of our research efforts focuses on stability, survival and tolerability of novel titanium temporal bone-implants (BIs) on which bone-conduction devices (BCDs) are fitted, see Figure 18.

We acquired long term results of novel implants, on earlier loading, and on implantation in different subgroups (children, adults, elderly, patients with mental retardation, patients with diabetes mellitus). We assessed more than 1,000 implants for percutaneous BCDs. This evaluation included skin reactions and implant survival, see Figure 19.

In an open, randomized, prospective multi-center clinical investigation, 77 adult patients were included. A new implant with in principle better properties for osseointegration (the Cochlear BI300 implant) and control implants were randomly assigned. Implant stability quotient (ISQ) values were recorded using resonance frequency analysis at the time of implantation and at 10 days, at 4, 6, 8, and 12 weeks, and at 6 months after surgery. Skin reactions were evaluated according to the Holgers classification. Sound processor fitting was performed from 6 weeks after implantation. The test implant showed better mean ISQ values than the control implants at the time of placement and over time. The level of osseointegration reached with the implants in adults as early as 6 weeks after implantation was sufficient to support the sound processor.

Because loading as early as 3 to 5 weeks did not negatively affect skin reactions or implant survival, full BCD installation can occur earlier than the conventional period of 6-12 weeks, without risk. Despite good results on osseo-
integration and limited skin reactions with percutaneous bone implants, there remains room for improvement. Especially in children, adverse events with percutaneous bone anchored hearing implants occur more frequently. A novel transcutaneous device was introduced where the traditional percutaneous implant was replaced by a coupling magnet, which has to be implanted just beneath the skin, see Figure 20. Transcutaneous bone implants, if powerful enough, can provide a solution that minimizes adverse events and implant loss. We compared a new transcutaneous device, the Sophono Alpha 1 (Fig. 20), with the percutaneous system. Both clinical results and audiologic data were gathered. The Sophono offers appealing clinical benefits of transcutaneous bone conduction hearing; however, the audiologic challenges of transcutaneous application remain, as the percutaneous Baha Divino exceeds the Sophono Alpha 1 device regarding gain and output.

Owing to its success and due to technological innovations, new sound processors for BCDs have been developed and new patient groups have been implanted. During recent years, studies focuses on the benefit of digital sound processing enabling better feedback suppression and wireless connections. Furthermore, we studied the application of these devices in patients with unilateral conductive hearing loss and with unilateral deafness. In the latter application, this works as a CROS device, routing signals from the deaf ear to the hearing ear. In patients with unilateral conductive hearing loss which were fitted with a BCD, the main outcome measure was binaural hearing, which was measured by a sound localization test. We demonstrated improved directional hearing abilities as compared to their unaided sound localization, as described in the first chapter of this progress report.

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Active middle ear implants

Initially, the driving force behind the development of active middle ear implants or implantable hearing aids was cosmetic, and semi-implantable commercial devices are on the market since the nineties, and they have been applied in the Nijmegen ENT clinic. Nowadays the active middle ear implants are used for patients with chronic draining ears who are not applicable for a BCD or CI. Typically, the middle ear ossicles are stimulated with an implanted actuator, driven transcutaneously by an externally worn sound processor. Direct stimulation of the ossicles might have an acoustical advantage as the non-linearly behaviour or the tympanic membrane for high frequencies is bypassed.

One of our research topics addresses the question whether middle ear implants are more effective to restore binaural hearing in unilateral aural atresia than bone conductors. Implantable bone conductors (the most effective bone conductors on the market) transform acoustical signals into vibrations. These vibrations are percutaneously transmitted to the skull and propagated by bone conduction. As a consequence both cochlea are stimulated with a somewhat higher effectiveness of the ipsilateral cochlea than the contralateral cochlea (about 5-10 dB). We demonstrate that in unilateral atresia, the so called cross-hearing seems not to hinder directional hearing abilities.

Another research topic is the development of a classification system for amplification options for conductive and mixed hearing loss.

A classification was suggested based on a basic characteristic of implants, namely their maximum output, or, in other words, the loudest sounds that they can produce without distortion. When fitting today’s acoustic devices in patients with sensorineural hearing loss, the maximum output is not a problem; often it is too high what can easily be readjusted. Bone conduction is about 50 dB less effective than acoustical stimulation, asking for powerful amplifiers when bone conduction has to be used. Future research is aimed at the relation between such direct acoustical stimulation of the cochlea and electrical stimulation of the cochlea in patients with severe hearing loss.
Behavioural research projects

Development of deaf children with cochlear implants

Besides fundamental and clinical research a significant part of research is directed towards optimizing audiological care and educational infrastructure for children with a cochlear implant. More than 500 children receive advise and long term support by the Nijmegen CI team. Based on continuing evaluation guidance focus is determined. Over the years the focus has shifted from speech understanding and vocabulary, which were acquired at appropriate levels, towards more complex verbal skills, verbal reasoning, theory-of mind processes and development of personality.

There are currently a number of research areas:

1. The effect of CI in deaf children with special needs.
   An increasing number of children with special needs are considered candidates for CI. Limited research is yet available concerning the effects of CI on the development of this heterogenic group of children. It is difficult to define “profit” of CI for these children. For counseling candidacy and in order to determine areas of intervention more knowledge of long term outcomes is necessary. The present study aims to identify predictors for “profit”.

2. Effect bilateral implantation on verbal IQ of 50 hearing impaired children (age 4-8 years).
   Unilateral implantation has proven to provide a significant benefit in hearing impaired children with normal learning potential. Post implant speech perception and vocabulary are generally within the normal range of hearing children. These skills are mainly acquired in explicit, formal learning situations. Complex linguistic tasks and verbal reasoning skills, that are acquired in incidental (learning) situations, remain lagging behind.
Children with unilateral CI are less able to perceive speech in complex listening situations. Bilateral implantation enables the development of these listening skills significantly. These skills are expected to improve complex linguistic skills via incidental learning. Currently a retrospective study is performed to demonstrate the relation between speech perception in complex listening environments and complex linguistic skills (verbal cognition).

**3 Long term effect of cochlear implantation of wellbeing, personality and verbal skills.**

Starting with CI in deaf children in the Netherlands in 1990, now long term evaluations have been carried out. Where initially short term data about hearing and vocabulary have been collected to demonstrate effectiveness of the devices, later the focus shifted toward assessment of the educational attainments and wellbeing. Data concerning the performance of about 80 teenagers on the national educational curriculum, reading comprehension and psycho-social development will be presented.

Preliminary data on educational attainment are presented below (Fig. 22). These data were provided by the schools, with permission from the parents. The score is expressed by the levels, decreasing from A to E. Compared to deaf children with hearing aids, CI provided a beneficial auditory condition, especially for children in mainstream education. In addition, a large variability in developmental potential after implantation was observed. Ranging from resilient children, who show sufficient social interactions and school performance to vulnerable children with limited interactions.
Comparison of speech perception, vocabulary and verbal cognition of children with severe hearing impairment that use hearing aids or cochlear implant(s).

In ENT Nijmegen children with hearing impairments ranging from mild to profound are guided. Clinical evaluation includes speech perception (in quiet and in noise), language and cognitive (verbal and performance IQ) development. Despite the good prognosis for the majority of the hearing impaired children, the severely hearing impaired children with hearing aids tend to be the group of most concern. Remarkably, this group requires more support and obtains poorer results on language and cognitive outcomes than the profoundly hearing impaired children with (unilateral) CI. Clinical experience and preliminary research pilot outcomes confirm this.

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Selected Publications in the Last 3 Years:
William Demants og Hustra Ida Emilies Fond, Title project: Directional hearing through bone conduction, Postdoc for 2 years

Advanced Bionics, Title project: Bimodel and Hybrid Cochlear implant fitting, PhD for 3 years

Cochlear Benelux, Title project: Spacial Temporal Resolution Studies, Postdoc, 2 years 0.44 fte and 1 PhD for 3 years

MedEl Innsbruck, Active Middle Ear Implants in Patients with Aural Atresia

EU FP7 projects:

iCARE, Improved Children Auditory REhabilitation, 20 months postdoc (AR), 1 PhD (tba)

HealthPAC, Perception and Action in Health and Disease, 2 PhD (tba)