Review Article

Technical devices for hearing-impaired individuals: cochlear implants and brain stem implants

developments of the last decade

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GMS Curr Top Otorhinolaryngol Head Neck Surg 2005;4:Doc04

Abstract

Over the past two decades, the fascinating possibilities of cochlear implants for congenitally deaf or deafened children and adults developed tremendously and created a rapidly developing interdisciplinary research field.

The main advancements of cochlear implantation in the past decade are marked by significant improvement of hearing and speech understanding in CI users. These improvements are attributed to the enhancement of speech coding strategies.

The Implantation of more (and increasingly younger) children as well as the possibilities of the restoration of binaural hearing abilities with cochlear implants reflect the high standards reached by this development. Despite this progress, modern cochlear implants do not yet enable normal speech understanding, not even for the best patients. In particular speech understanding in noise remains problematic [1]. Until the mid 1990ies research concentrated on unilateral implantation. Remarkable and effective improvements have been made with bilateral implantation since 1996. Nowadays an increasing numbers of patients enjoy these benefits.

Keywords: cochlear implant indications cochlear implant in children surgical technique speech understanding electrode carrier deep electrode insertion binaural hearing bilateral cochlear implantation

1. Introduction

One of the biggest steps forward in modern medicine is the possibility to replace a deaf ear, i.e. a sensory organ, with an implantable electronic prosthesis [2]. The development of cochlear implants (CI) has been the most important step for improving communication in congenitally deaf or deafened

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children, adolescents and adults in the last 200 years, if the foundation of the schools for the hearing impaired in Paris (1750) and Leipzig (1778) were taken as reference points.

Today, owing to cochlear implantation, congenitally deaf children or children with residual hearing can achieve almost normal auditory-verbal development.

In the early 1970ies cochlear implants typically allowed the auditory connection to the environment. With the technical possibilities of that time they were an enormous communicative remedy for many hearing-impaired individuals. Increasing knowledge of auditory physiological processes and the function of cochlear implants as well as their technical advancement now help many patients to reach open speech understanding which was considered impossible in earlier times [3], [4].

An important milestone significantly improving speech understanding in cochlear implant patients is certainly the CIS strategy (CIS = Continuous Interleaved Sampling) [3] published by Wilson in 1991 [5]. In clinical practice this strategy with high stimulation rates has helped many patients to improve their speech understanding [3], [6], [7], [8], [9], [10], [11], [12], [13]. Meanwhile, all cochlear implant manufacturers have implemented more or less modified and different "CIS strategies" in their implants [13].

Over the past two decades, influenced by innovative ear surgeons, the fascinating possibilities of cochlear implantation for congenitally deaf or deafened children and adults have created a rapidly developing interdisciplinary research field combining the efforts of specialized ear surgeons, engineers, physicists, technicians, audiologists, electro-physiologists, speech and language therapists, psychologists, teachers and, last but not least, CI users. This paper reviews, according to the wish of the president, Prof. Dr. Beleites, mainly recent developments of the past decade.

Progress in the area of cochlear implantation over the last decade is marked by the significant improvement of CI users' hearing and speech understanding. These high standards reached by this development are reflected by supplying more (and increasingly younger) children and the possibilities of binaural hearing with modern cochlear implants.

Improved speech understanding is attributed to advanced speech coding strategies [13], [1]. Despite this progress, modern cochlear implants do not yet enable normal speech understanding, not even in our best patients. Speech understanding particularly in noise remains more or less difficult [1].

Until the mid 1990ies research concentrated on unilateral implantation [14]. Remarkable, effective improvements have been made with bilateral implantation since 1996 [13], [1], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24].

2. Preliminary note: basic principles of cochlear implants

For the benefit of those who are not so familiar with the subject, this review begins with the basic principles of modern cochlear implants.

In most cases deafness is caused by cochlear disorders, e.g., loss or degeneration of sensory hair cells. Mechanical sound waves can no longer be converted into electrical stimulation.

A cochlear implant (CI) stimulates the auditory nerve directly electrically thus replacing the defective natural stimulus transmission of the sensory cells of the inner ear to the auditory nerve. The non-functional cochlea serves only as a place holder to keep the electrode in the most optimal position to the auditory nerve [3], [11]. The CI system takes over the functions of the middle and inner ear: Sound is picked up by the microphone, processed by the external speech processor and wirelessly transmitted via a coil to the implanted receiver. The speech processor codes the sound signal, e.g. speech or music, as a sequence of electrical pulses and relays those pulses to the stimulation electrodes in the cochlea (Figure 1 (Fig. 1)).

The electrode is inserted through the mastoid and the facial recess, passing the facial nerve, into the non-functioning cochlea. The electrode carrier has several electrode contacts which are positioned at different places in the cochlea to enable tonotopic stimulation of the auditory nerve. Fast series of pulses via several channels allow effective use of the temporal principle beside the tonotopic principle. This leads to natural sound and intelligible perception of the coded speech signals. Fast speech coding strategies, like the CIS strategy (CIS = Continuous Interleaved Sampling), are based on B.S. Wilson's [5] design. Important for the effectiveness of the implanted system is the pulse rate which should be at least 1500 Hz per channel. Another decisive factor seems to be that all pulses are newly calculated from the speech signal so that each pulse conveys new information. Compared to constantly newly calculated pulses, several repetitions of an identical pulse cause information loss [3].

Speech understanding depends on the way the auditory nerve is stimulated along the axis of the bony cochlea (modiolus). Since patients perceive usable and desired auditory sensations also with electrodes placed in the very tip of the cochlea, it seems plausible to assume that the entire length of the cochlea should be used if possible [11], [25]. Detailed investigations show that four to eight stimulation electrodes should be distributed as widely as possible along the cochlea to achieve good and stable speech results [3], [26], [27].

3. Development of pre-operative diagnosis and indications

The CI system codes information of incoming sound signals based on the speech coding strategy and converts those signals into bioelectrical pulses which electrically stimulate the auditory nerve. A CI is thus suitable for patients with insufficiently functioning cochleae. The auditory nerve itself must, however, not only be intact anatomically but also excitable to convey the coded information.

3.1 Preoperative diagnosis

Radiological diagnosis before implantation should include high-resolution petrosal bone computer tomography (CT) and, especially in children, magnetic resonance imaging (MRI). Information obtained with those imaging techniques is complementary [28], [29].

Functional magnetic resonance imaging (fMRI) can be used to display electrically evoked auditory sensations [30]. This method takes advantage of the different magnetic characteristics of oxygenated and deoxygenated blood (BOLD effect). Cortical metabolism increases during electrical stimulation, the activated area responds with a regionally increased blood flow. This causes a shift in the relation of oxygenated and deoxygenated haemoglobin. Images taken at two different points of time (in resting and stimulated state) are compared with statistical methods and the differences (depending on the stimulated areas) spatially matched.

Clinical application of this helpful tool is currently limited to individual cases due to long calculation times [30].

A promontory test before cochlear implantation is not used in general. Its prognostic value is uncertain. However, it has a high demonstrative value for patients and parents. When using an ear channel electrode instead of a promontory needle, it is non-invasive and not too much strain for the patient. It is an easy and fast method, particularly when combined with loudness scaling in analogy to the loudness scaling "Würzburger Hörfeld" [31].

3.2 Extending implantation criteria: cochlear implantation not only in patients with complete deafness but also in patients with residual hearing

Considering the positive results of cochlear implantation, a cochlear implant is not only indicated in cases of complete deafness. New implantation criteria also include "insufficient speech understanding" with correctly and optimally fitted hearing aids. Insufficient speech understanding is defined by the speech understanding levels achieved with modern cochlear implant systems [4], [32].

Beside many prognostic factors influencing the result of cochlear implantation, duration of deafness and residual hearing [33] are considered to be important. Patients with residual hearing may even be able to talk to strangers on the telephone after cochlear implantation and reach, on average, higher postoperative results (80% in the Freiburg Monosyllable Test); their benefit from a cochlear implant is higher-than-average. Particularly speech understanding tests in noise, which resemble everyday situations more closely, show more effective improvements for patients compared to earlier hearing aid use [7], [33], [34], [35], [36], [37]. Patients should be informed about the possibilities with modern cochlear implants as early as possible and should receive a cochlear implant before they are completely deaf.

Based on the good hearing results, cochlear implantation in adults is now even considered for individuals who no longer understand 30 - 40% of the words in the Freiburg Monosyllable Test at 70 dBSPL [3], [33], [34], [35], [36], [38].

Derived from these criteria, clinical practice indicates that cochlear implantation should be considered if a patient can no longer talk to strangers on the telephone even with optimally fitted hearing aids. Individual assessment of optimal supply with hearing aids requires a suitable trial period and hearing training if necessary.

3.3 Cochlear implantation in children

After cochlear implantation had been proven beneficial for adults and the surgical procedures had been found save, the next logical step was to implant (at first older) children. Before deciding on implanting a child it was and still is obligatory to use adequate hearing aids.

In view of the biologically important but temporarily limited time frames of auditory-verbal development, it became necessary to implant children at increasingly younger ages.

3.3.1 Age at implantation

From a physiological point of view very early implantation seems to be desirable [39], [40]: Particularly during the second babbling phase, starting at approx. 6 months of age, until about the end of the second year the synapses in the left temporal lobe multiply explosively allowing us to learn our mother tongue. Development of this speech competence naturally requires (*possibly long*) learning processes. Hearing experiences from the first day of life on are crucial for these learning processes [41].

Many publications have meanwhile investigated the results after cochlear implantation in children [3], [39], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73]. The chosen age limits of the groups are rather incidental due to the number of patients of each age group implanted in the course of time and the resulting data for analysis. Independent of the chosen age limits these investigations have proven the benefits of early implantation with regard to postoperative hearing abilities and auditory-verbal development of the tested children [42], [43], [45], [46], [49], [53], [58], [59]. The children's auditory and verbal performance was the better, the earlier they were supplied with CI [45]]. Early implanted children, i.e. children implanted before 24 months, not only scored higher in the tests on auditory-verbal development, they developed these abilities faster compared to children implanted later [45], [73]. Fortunately, all children benefit from cochlear implantation independent of their age at implantation compared to the use of hearing aids. To reach optimal results it is necessary, however, to aim at implantation before 24 months or, even better, before 12 months of age. Even though implantation before the age of 4 years seems to prevent irreversible alterations and deficits in the maturation of the auditory pathways, children of this age group do not reach the level of auditory-verbal development reached by earlier, i.e. younger, implanted children [73], [74].

Children should, therefore, be implanted and (re)habiliated at a very young age. An important step toward identifying hearing impairment or deafness in very young children to allow for early implantation has been made with the establishment of newborn hearing screening.

This way, parents can and must be informed about adequate therapy programmes within the first 24 months of their child's life. These first 24 months are crucial for the child's next seven or eight decades of further personal, professional and social development. Opportunities missed during this time cannot be compensated later [75].

While cochlear implantation in very young children was only rarely practiced in the USA [76], [77], physicians in Europe and particularly in Germany were more willing to offer cochlear implantation for younger children [9], [78], [42].

So far, only large centres in Europe and particularly in Germany have worked with children between four and twelve months of age, if, and only if, the diagnosis was certain or the reason for deafness was meningitis. Compared to the total number of implanted children, the percentage of so early implanted children is not as high as desirable for various reasons. According to Offeciers only 4.1% of all children implanted in Germany received their CI before the age of 18 months [79].

Our current observations of 48 children (15%) who received their CI under the age of 18 months (21 of those children were younger than 12 months when implanted in Würzburg) show that the efforts required of all specialists involved in CI supply to enable early implantation seem justified and desirable. These children's development, particularly in case of bilateral implantation, is measured against the development of normal hearing children [80], [24], [17]. Long-term observations of larger collectives are still missing because these children, who were between six and twelve months old, have only recently been implanted. Investigations of speech production of very early implanted children indicate the expected, early developing positive effects [73].

These observations raise the question of the optimal time or optimal time frame of cochlear implantation in children. Such considerations are not intended to initiate a competition among surgeons for the "youngest implanted child". The objective is rather to evaluate from a biological point of view when surgery can be performed to reach the best results while being of minimal risk.

3.3.2 Surgical aspects of CI surgery in children

Indication shall be based on each child's individual developmental status: The children should be able to control their heads to avoid blows to their heads. This reduces the risk of damaging the external and internal components of the CI.

From a surgical point of view it seems desirable to have a defined tension of the M. sternocleido-mastoideus at the tip of the mastoid which is associated with increasing head control. This tension is required for the development of the mastoid process [81]. This way the experienced surgeon finds enough space for an access to the cochlea even in a child's small mastoid to identify and preserve the delicate anatomic structures, especially the facial nerve (Figures 2 (Fig. 2) and 3 (Fig. 3)).

Surgery itself is planned by an interdisciplinary team including all the specialists involved in the support of the child, e.g. anaesthetists and paediatricians to guarantee optimal care for the anesthetized child before, during and after surgery. Intravenous access for example, can be challenging in infants. This shows that it is important to consider even obviously minor details carefully and in an interdisciplinary team when working with infants. Beside the special anatomic situation in children, their small respiratory pathways and relatively low blood volume have to be considered. An average-size, 6-month old infant weighing 8 kg has an average blood volume of only 640 ml (80 ml blood/kg body weight).

4. Surgical technique

The surgical technique of cochlear implantation is considered safe and without major complications [3], [67], [82], [83], [84].

Conservative surgery and atraumatic insertion of the electrode are self-evident and correct [32]. Lehnhardt coined the term "soft surgery" [84] for his surgical technique. This principle does not have any drawbacks, but Probst finds one disadvantage in the probably erroneous assumption that "soft surgery" will definitely preserve residual hearing and that this residual hearing may be used later [32].

4.1 Surgical risks

The literature describes up to 2.1% facial pareses, 0.6% of which are permanent [82], [85]. Fortunately, this risk has not been found in the more than 750 Würzburg patients implanted since 1994 (age at implantation 4 months to 86 years).

The fundamentals of safe cochlear implantation are reliable surgical techniques based on the principles and established rules of middle ear surgery [83]. The surgical technique varies only slightly in different clinics [3].

Already at primary implantation it has to be considered that cochlear implants are technical devices with limited lifetime which will eventually have to be replaced despite their high quality [86]. Based on observations with (rare) revision surgeries, we regard it as reasonable to sufficiently open the mastoid during initial surgery and to identify the facial nerve. A widely open facial recess allows the necessary view into the tympanum and the promontory with the cochleostomy.

4.2 Alternative surgical techniques

The detailed discussions of surgical techniques are complemented among others by the pros and cons of shaving, skin incision or cochlear implantation without mastoidectomy [87], [88], [89], [90], [91], [92].

The various surgical techniques available can be adapted to meet individual situations. Selection and application are at the surgeon's discretion. Individual techniques should not be seen too dogmatically because they are not too relevant for the overall results as they may seem to be when following the extensive discussions in the literature [3].

4.3 Cochlear implantation under local anaesthesia

The good results of cochlear implantation seem to justify surgery under local anaesthesia in patients with cardio-pulmonary problems [93].

5. Development of the electrode carrier

Another increasingly investigated branch concerns the electrode carrier of cochlear implant systems. Beside insertion trauma, design and possible insertion depth are subject of ongoing scientific discussion. Some aspects of this issue have not yet been completely solved [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108].

The electrode is an important part of the cochlear implant system: It provides the stimulation pulses and stimulates the auditory nerve. It has not yet been clarified which neural structures are stimulated inside the cochlea.

Depending on system design the electrode carriers have 8 to 24 single electrodes. Their arrangement on the electrode carrier varies for individual CI systems with regard to the length of the electrode section used for stimulation and the distance between single electrodes. A compromise between desired stimulation effects and undesirable artefacts caused, e.g., by interfering electrical fields of closely adjacent stimulation electrodes, is necessary. Given modern technical possibilities it seems to be impossible to arbitrarily increase the number of electrodes. Systems with e.g. 24 electrodes use only about 8 to 10 electrodes per stimulation cycle.

Modern technology seems to confirm an optimal number of eight to twelve electrodes [3], [26], [27], [109]. Good speech understanding in noise needs more channels compared to a situation in quiet, but even in noise 12 channels are considered more than adequate. Using e.g. 16 channels does not improve hearing [26], [27].

5.1 Deep electrode insertion

Probably based on the assumption that the bodies of the spiral ganglia are only distributed over 16 - 18 mm along the basal turn of the cochlea, an electrode insertion depth of 16 - 20 mm was generally considered sufficient. Helms showed already in 1994 that the electrodes can be routinely inserted about 30 mm up to the second turn of the cochlea (Figure 4 (Fig. 4), Figure 5 (Fig. 5)), however, the question of the benefit of this procedure, later called "deep electrode insertion" by Gstöttner [99], remained open for a long time. Patients with "deep insertion" had very good speech understanding [8].

This gives rise to the question if the many patients with deep insertion actually benefit from electrically stimulating the second turn of the cochlea. First studies [25], [110], [111] indicate that deep electrode insertion, i.e. more than 30 mm, and the associated electrical stimulation of the apical section of the cochlea contribute substantially to speech understanding in quiet and in noise. Less deep insertion showed no differences in speech understanding when comparing 22 mm to 25 mm insertion depth [112], which may, however, be due to the fact that the active area of the electrode used for stimulation was the same, i.e. 17 mm in both patient groups. Simulations of Dorman et al. [111] confirm the benefits of deep electrode insertion.

5.2 Perimodiolar electrode carrier

Another possible method to improve speech understanding is the placement of the electrode carrier closer to the modiolus. Certain neurone populations are expected to be stimulated more specifically, assuming that the closeness to the stimulated tissue enables more differentiated stimulation [113]. Preformed electrode carriers are used to reach this goal. They are inserted into the cochlea with special instruments and take their intended shape inside the cochlea after removing the insertion tools. Since the same preformed electrodes are used for all patients, individual characteristics in the anatomy of the cochlea cannot be accommodated (Figure 6 (Fig. 6)). Postoperative studies show that electrode placement is not always satisfactory. Displacement of the electrode carrier from the Scala tympani into the Scala vestibuli happens more frequently than expected. The hoped for improvement of speech understanding could not be demonstrated, although perimodiolar electrodes allow lower stimulation thresholds [104].

6. Cochlear implant and meningitis

Frequent application of a treatment, increasing patient numbers and associated long-term experiences principally increase the risk of observing undesirable side-effects or complications. Expanding indications and increasingly implanting young children have shifted the therapeutic focus to a patient group with frequent middle ear problems. Serous otitis media and acute otitis media are often observed during childhood. Complications like mastoiditis and otogenic meningitis may develop from an otitis media and are still life-threatening conditions. Even children without CI may develop meningitis: In Germany for instance as many as 250 children may contract pneumococci meningitis each year.

Unfortunately, several cases of meningitis after cochlear implantation have been observed, some leading to the patient's death. Fortunately, this risk has been seen in only very few patients.

The risk to contract otogenic meningitis after cochlear implantation is very low but meningitis may manifest itself also in children with cochlear implants. In these patients, meningitis can be causally related to the implant or occur independent of implantation.

Analysis of this problem [114], [115], [116], [117], [118], [119], [120], [121] showed that malformations of the inner ear and deafness caused by meningitis increase the risk of meningitis [115]. Some cochlear implant systems are more often connected with cases of meningitis than others [114]. Perimodiolar electrode carriers consisting of two components have been identified as possible reasons for increased implant-associated risks. The additional place holder is intended to press the electrodes as closely as possible to the modiolus. The risk of meningitis is higher for these electrodes than for other electrode carriers. As shown by histological investigations and in petrosal bone models, perimodiolar electrode carriers may cause intracochlear lesions [105], [106], [107].

A differentiated discussion of the problems of (otogenic) meningitis after cochlear implantation is given in Arnold et al.: Mastoiditis or meningitis after implantation must be treated surgically like any other inflammatory ear disease [115].

Particular attention must be paid to avoiding life-threatening complications. The risk of otogenic meningitis must be minimized before, during and after surgery to optimally prevent these dreaded complications. In addition to the smallest possible cochleostomy accommodating the electrode diameter, it is recommended to seal the electrode at the site of entry at the promontory with lint-free connective tissue similar to a stapes prosthesis. A thicker "stopper" on the electrode to plug the cochleostomy is also helpful [83].

Another important preventive measure is the inoculation against meningitis after consultation with the paediatrician. It offers a certain degree of protection, but not 100% [75].

Special care must be taken to consequently and early treat serous otitis media, acute otitis media or mastoiditis. In cases of dubious ear aches or fever patients should immediately be referred to an ENT specialist or, if the patient is a child, also to a paediatrician.

7. Modern speech coding strategies

The introduction of speech coding strategies with fast stimulation rates has significantly improved speech understanding in cochlear implant patients [13], [1], [122] and has meanwhile proven its value in clinical practice [8]. Initial objections against fast stimulation derived from animal experiments did not hold out against further verification [123], [124].

Meanwhile, all cochlear implant manufacturers have implemented a more or less fast CIS strategy or modification thereof in their systems [13]. The results also depend on the technical realization of the CIS strategy which has been solved by various manufacturers in different ways. Stimulation and actualisation rates differ for each manufacturer. Differences in the transmitted information content are due to the fact that not all systems calculate each stimulation pulse anew [3].

The mentioned differences of various designs [122] are not always easy to see. The companies' marketing strategies tend to show those differences in a distorting light and even the expert finds it difficult to detect them. Most physicians are overwhelmed with the task as are most patients. The patient's "selection" of a certain implant type is quite questionable and patients should not be left alone with this task unless they insist. Patient-targeted marketing strategies of CI manufacturers are quite dubious; however, as stated by Probst, tendencies into that direction cannot be overlooked [32].

Speech results of unselected patient collectives with established tests, such as the Freiburg Monosyllable Test, which are sufficiently difficult to differentiate patients, should be published. The distribution function at defined time intervals after implantation could show a patient's chances of reaching the best possible speech understanding with a certain speech coding strategy.

8. Speech processor fitting

Extending implantation criteria to include increasingly younger children leads to another aspect of cochlear implantation, i.e. speech processor fitting which is considered particularly difficult for congenitally deaf children and requires much experience [75].

It is not surprising that we look for objective methods in this area [32]. Beside stapedius reflex measurements we hope for additional objective intracochlear measurements of nerve potentials using the cochlear implant electrodes. Compound action potentials are considered an objective response of the neurones to the stimulation pulses emitted by the individual electrodes on the electrode carrier. Such intraoperative measurements should not be accepted without critical interpretation [32]. Mathematical correction factors are used to obtain information about the expected stimulation threshold during first fitting through intraoperative measurements. However, speech processor fittings obtained with objective methods are not yet equal to those determined with behavioural audiometry [125], [126], [127], [128].

9. Bilateral cochlear implantation

Having two ears which enable us to hear binaurally are the prerequisite to cope with many everyday hearing situations [129]. Directional hearing, spatial hearing and signal source separation are only possible with two ears. Binaural hearing supports speech understanding in noise and supplies adequate auditory quality.

First results with bilaterally implanted patients in the early 1990ies in Australia were not very encouraging [130]. A fusion of the auditory impression could be reached but speech understanding was not relevantly improved. In some tests speech understanding was even worse with two implants [130]. After these results the Australian workgroup did not pursue the approach of improving hearing with binaural cochlear implantation.

In 1996 the Würzburg workgroup under Univ.-Prof. Dr. Dr. J. Helms was the first worldwide to succeed in significantly improving speech understanding in quiet and in noise and restoring directional hearing in a bilaterally implanted patient 4 weeks after first fitting [14].

After verifying those first results in adults, children have consequentially been bilaterally implanted since 1998. The convincing results were brought to the attention of a broad scientific public in an announced discussion in 1999, hoping to make this technology available to more children [19].

Animal experiments support the neural-protective effect of electrical stimulation for the auditory nerve [131] and maturation of the auditory pathways. Although it was not yet clear when implanting the first children bilaterally if and how these children would benefit from the second implant, it seemed logical to assume binaural hearing to be good for the children based on the encouraging results in adults and in analogy to bilateral hearing aid supply. Bilaterally implanted patients benefit from sustained improvements of speech understanding in quiet and in noise (20% better speech understanding in quiet in the Freiburg Monosyllable Test, 30% better speech understanding in noise) [19], [20], [21], [24], [132], [133]. The effects and improvements of speech understanding in quiet and in noise seen in adults are also observed in children [24].

Major features of binaural hearing are spatial hearing, directional hearing and separation of signal sources. It was exciting to see if binaurally implanted children would develop spatial and directional hearing skills. In her dissertation C. Edelmann observed the first 13 bilaterally implanted children for a period of 3 years. She found directional hearing skills in children to develop at different rates. It took an average of 1.5 years for the children to develop directional hearing. Over the 3-year period not only directional hearing developed but the failure rate of judging direction decreased with increasing use of both ears. The results could be interpreted to indicate that the children not only learn to localize a sound source in space but also to more accurately localize this sound source.

Individuals with normal hearing achieve directional hearing using interaural time and level differences, deflection phenomena and sound reflections at the pinna. Bilateral CI users benefit - like normal hearing individuals - from interaural time and level differences [134]. As in normal hearing individuals, head shadow effect, squelch effect and binaural summation facilitate binaural hearing in CI users and contribute to their binaural performance [132], [133].

It is, without doubt, necessary to act immediately in cases of possible obliteration of both cochleae after meningitis, as it may be impossible to place the electrode inside the cochlea at a later time. Bilateral, simultaneous implantation should be considered unless medically contraindicated.

From a medical point of view it is not acceptable to refuse congenitally deaf children substantial improvement of their hearing situation for economical reasons as claimed by health insurance companies. Based on the low number of cochlear implantations performed in Germany it is ethically not justifiable to refuse affected individuals substantial improvement of their hearing abilities. The total costs of bilateral cochlear implantation are relatively low compared to, e.g., the high self-administration costs of health insurance companies. The gained economic benefit succeeds implantation costs by far, when children are given the opportunity to hear better thus having the chance to receive better vocational training and be integrated into the industry. From an economic point of view it is certainly much more reasonable to support bilateral implantation to enable working people to continue working (thus keeping them as tax and health insurance payers), rather than sending them into retirement at the expense of social insurance [11].

The question of bilateral implantation is probably most difficult to answer in the case of elderly patients with increased surgical and anaesthesia risk factors. Patients willing to take the risk and wanting bilateral implantation to improve their situation cannot be denied. Fears of health insurance companies and their medical services of a possible "implantation wave" at the cost of health insurance seem unfounded considering that only 15% of the adults implanted in Würzburg wanted a second implantat although being aware of the possible benefits.

With budgets remaining the same, budgetary constraints caused by specified contingents could lead to the problem that only half the future CI patients could be implanted if bilateral implantation became standard procedure. This scenario caused Laszig to ask if bilateral cochlear implantation was ethically acceptable [75]. Unfortunately, nobody asks the question if the specified budgets are ethically acceptable. The question of ethical acceptability of medical treatments does not only address the problem if, based on a certain budget, a certain number of patients should be implanted unilaterally or if half that number should be implanted bilaterally, but also points to another issue: Is it acceptable to refuse, e.g., children the development of the second auditory pathway and the benefits of binaural hearing which are necessary to cope with many everyday hearing situations [129], although we have scientific proof of the benefits [2], [3], [14], [20], [21], [22], [132], [133], [134], [135]?

We must also ask the question if it is acceptable to refuse patients who contributed to the social insurance system and who could stay in their jobs with two implants (thus continuing to pay their taxes and social insurance) bilateral implantation for budgetary reasons. Costs should be seen in an overall economic and social setting. The problem is, however, that implantation costs and subsequent relief affect different cost units [9], [74].

After initially very controversial discussions on bilateral cochlear implantation, bilateral cochlear implantation has meanwhile been accepted as standard procedure in Switzerland. A clear statement for bilateral cochlear implantation was offered at the "2nd Consensus Conference on Cochlear Implants" [136], [137].

10. Auditory Brainstem Implant (ABI)

Further development of cochlear implants and their universal acceptance also influenced the development of auditory brainstem implants. In 1979 the first one-channel brainstem implant was implanted via a translabyrinthine access at the House Ear Institute. In 1992 the first patients in Germany received brainstem implants. Laszig also used the translabyrinthine access for implantation [138], [139], [140].

Meanwhile, more than 200 patients have received an auditory brainstem implant (ABI) worldwide. The translabyrinthine access was favoured in the beginning, ABIs are now also implanted via a suboccipital access [139], [141].

Commercially available brainstem implants use the speech processor technology of cochlear implants. Clinical results remain behind auditory performance with cochlear implants, despite sophisticated speech processor technology. Identification of familiar sounds like a honking car or the door bell and improved lip-reading significantly improve the patients' situation compared to complete deafness [139]. The brainstem implant enhances the average patients' ability to lip-read so far that they can follow a conversation well without having to ask for repetitions. In sentence tests these patients reach a 60 - 80% discrimination score. Some patients achieve free word understanding and are even able to use the telephone [141]. Although most patients will not reach free speech understanding, their quality of life improves so much that they use their ABI daily [138], [141].

Auditory brainstem implants can be implanted without significant additional risks during tumour removal in patients with neurofibromatosis type 2 with bilateral acoustic neurinoma [141]. Side-effects caused by erroneous sensory stimulation when activating the electrodes are rare and disappear when deactivating these electrodes.

Increasing experience with auditory brainstem implants and associated safe and in large centres almost routine application has led to discussing auditory brainstem implants for use in children with auditory nerve aplasia and patients with cochlear ossification or traumatic auditory nerve deafness [142].

Postoperative fitting of the speech processor is much more complex than fitting a cochlear implant. Use of fast speech coding strategies in analogy to cochlear implants has prevailed in auditory brainstem implants as well. Specific speech coding strategies for stimulation via the cochlear nucleus have not yet been developed. Penetrating electrodes are expected to improve the situation. Although first, preliminary results were rather disappointing and the level of the still used surface electrodes has not been reached, modern brainstem implants effectively improve communication. Patients consider these implants a great help in their daily lives and they would not want to miss them. Several of our patients even achieved open speech understanding which indicates the potential developments possible with this method. Like cochlear implant users, patients with auditory brainstem implants will benefit from technological progress.

References

1. Wilson BS, Lawson DT, Müller JM, Tyler RS, Kiefer J. Cochlear implants: some likely next steps. Annu Rev Biomed Eng 2003; 5: 207-249
2. Vischer M, Kompris M, Seifert E, Häusler R. Das Cochlea-Implantat - Entwicklung von Gehör und Sprache mit einem künstlichen Innenohr. Therapeutische Umschau 2004; 61: 53-60
3. Helms J, Müller J. Die Auswahl eines Cochlea-Implants und die Ergebnisse der Implantation. Laryngo-Rhino-Otol 1999; 78: 12-13
4. Aschendorff A, Marangos N, Laszig R. Ergebnisse in der Rehabilitation erwachsener Cochlear-Implant-Patienten. Wien Med Wochenschr 1997; 147: 252-254
5. Wilson BS, Finley CC, Lawson DT, Wolford RD, Eddington DK, Rabinowitz WM. Better speech recognition with cochlear implants. Nature 1991; 352: 236-238
6. Gstoettner W, Adunka O, Hamzavi J, Baumgartner WD. Rehabilitation Horgeschädigter mit Cochlear-Implantaten - eine Übersicht. Wien Klin Wochenschr 2000; 112: 464-472
7. Hamzavi J, Franz P, Baumgartner WD, Gstoettner W. Hearing performance in noise of cochlear implant patients versus severely-profoundly hearing-impaired patients with hearing aids. Audiology 2001; 40: 26-31
8. Helms J, Müller J, Schön F, Moser L, Arnold W, Janssen T, Ramsden R, von Ilberg C, Kiefer J, Pfennigdorf T, Gstottner W, Baumgartner W, Ehrenberger K, Skarzynski H, Ribari O, Thumfart W, Stephan K, Mann W, Heinemann M, Zorowka P, Lippert KL, Zenner HP, Bohndord M, Huttenbrink K, Hochmair-Desoyer I. et al. Evaluation of performance with the COMBI40 cochlear implant in adults: a multicentric clinical study. ORL J Otorhinolaryngol Relat Spec 1997; 59: 23-35
9. Adams JS, Hasenstab MS, Pippin GW, Sismanis A. Telephone use and understanding in patients with cochlear implants. Ear Nose Throat J 2004; 83: 96-103
10. Profant M, Kabatova Z, Simko S, Simkova L. Clinical results with Nucleus 22 and Combi 40 device in postlingually deaf patients. Adv Otorhinolaryngol 1997; 52: 291-293
11. Helms J, Müller J, Schön F, Brill S. Cochlea-Implantation: Ergebnisse und Kosten, eine Übersicht. Laryngo-Rhino-Otol 2003; 82: 821-825
12. Kiefer J, Müller J, Pfenningdorff T, Schön F, Helms J, von-Ilberg C, Baumgartner WD, Gstoettner W, Ehrenberger K, Arnold W, Stephan K, Thumfart W, Baur S. Speech understanding in quiet and in noise with the CIS speech-coding strategy (MED EL Combi-40) compared to the MPEAK and SPEAK strategies (Nucleus). Adv Otorhinolaryngol 1997; 52: 286-290
13. Wilson BS. The future of cochlear implants. Br J Audiol 1997; 31: 205-225
14. Müller J. Erste Ergebnisse der Bilateralen Cochlear Implant Versorgung. European Archives of Oto Rhino Laryngology 255: 38
15. Au KK, Jin H, Hui Y, Wei L. Speech discrimination with bilateral cochlear implants in noisy conditions. Zhonghua Er Bi Yan Hou Ke Za Zhi 2001; 36: 433-435
16. Kong W, Yu L, Xu Y, Yue J, Xiong X, Zhu L, Duan J. Benefit of bilateral cochlear implantation on congenital prelingually deafened Chinese-speaking children. Lin Chuang Er Bi Yan Hou Ke Za Zhi 2003; 17: 577-579
17. Lesinski-Schiedat A et al. Bilateral Implantation in Young Children compared to Bimodally Fitted Children. Vortrag, 7th European Symposium Paediatric Cochlear Implantation, Geneva, Switzerland, May 2004.
18. Litovsky RY, Parkinson A, Arcaroli J, Peters R, Lake J, Johnstone P, Yu G. Bilateral cochlear implants in adults and children. Arch Otolaryngol Head Neck Surg 2004; 130: 648-655
19. Müller J. Angemeldete Diskussionsbemerkung. Dt. HNO-Kongress, Aachen 1999.
20. Müller J, Schön F, Helms J. Speech understanding in quiet and noise in bilateral users of the MED-EL COMBI 40/40+ cochlear implant system. Ear Hear 2002; 23: 198-206
21. Müller J. Cochlear-Implant-Versorgung heute. HNO 2002; 50: 793-796
22. Tyler RS, Gantz BJ, Rubinstein JT, Wilson BS, Parkinson AJ, Wolaver A, Preece JP, Witt S, Lowder MW. Three-month results with bilateral cochlear implants. Ear Hear 2002; 23 (1 Suppl): 80S-89S
23. Winkler F, Schön F, Peklo L, Müller J, Feinen C, Helms J. Würzburger Fragebogen zur Hörqualität bei CI-Kindern (WH-CIK). Laryngo-Rhino-Otol 2002; 81: 211-216
24. Kühn-Inacker H, Shehata-Dieler W, Müller J, Helms J. Bilateral cochlear implants: a way to optimize auditory perception abilities in deaf children?. Int J Pediatric Otorhinolaryngology 2004; 68: 1257-1266
25. Hochmair I, Arnold W, Nopp P, Jolly C, Müller J, Roland P. Deep electrode insertion in cochlear implants: apical morphology, electrodes and speech perception results. Acta Otolaryngol 2003; 123: 612-617
26. Brill SM, Gstoettner W, Helms J, von-Ilberg C, Baumgartner W, Müller J, Kiefer J. Optimization

of channel number and stimulation rate for the fast continuous interleaved sampling strategy in the COMBI 40+. Am J Otol 1997; 18 (6 Suppl): S104-106

27. Garnham C, O'Driscoll M, Ramsden-And R, Saeed S. Speech understanding in noise with a Med-El COMBI 40+ cochlear implant using reduced channel sets. Ear Hear 2002; 23: 540-552
28. Czerny C, Gstoettner W, Adunka O, Hamzavi J, Baumgartner WD. Präoperative Bildgebung vor dem Einsetzen eines multikanalikulären Cochlear-Implantates mittels Computer- und Magnetresonanztomographie der Innenohrregion. Wien Klin Wochenschr 2000; 112: 481-486
29. Greess H, Baum U, Romer W, Tomandl B, Bautz W. CT und MRT des Felsenbeins. HNO 2002; 50: 906-919
30. Hofmann E, Preibisch C, Knaus C, Müller J, Kremser C, Teissl C. Noninvasive direct stimulation of the cochlear nerve for functional MR imaging of the auditory cortex. AJNR Am J Neuroradiol 1999; 20: 1970-1972
31. Müller J, Schön F. Lautheitsskalierung bei Cochlear-Implant-Patienten im Rahmen der präoperativen Austestung. Laryngo-Rhino-Otol 1994; 73: 128-131
32. Probst R. Cochlear Implants: Eine Erfolgsgeschichte und einige Fragen dazu. HNO 1998; 46: 4-6
33. van-Dijk JE, van-Olphen AF, Langereis MC, Mens LH, Brokx JP, Smoorenburg GF. Predictors of cochlear implant performance. Audiology 1999; 38: 109-116
34. Klenzner T, Stecker M, Marangos N, Laszig R. Zur Indikationserweiterung des "cochlear-implant". Freiburger Ergebnisse bei Patienten mit Resthörigkeit. HNO 1999; 47: 95-100
35. Müller-Deile J, Rudert H, Brademann G, Frese K. Cochlear-Implant-Versorgung bei nicht tauben Patienten?. Laryngo-Rhino-Otol 1998; 77: 136-143
36. Scholtz LU, Mueller J, Schoen F, Moser LM, Helms J. Fast stimulator cochlear implants in patients with residual hearing. Adv Otorhinolaryngol 2000; 57: 401-404
37. Hamzavi J, Pok SM, Gstoettner W, Baumgartner WD. Speech perception with a cochlear implant used in conjunction with a hearing aid in the opposite ear. Int J Audiol 2004; 43: 61-65
38. Laszig R, Klenzner T. Cochlear Implant bei Resthörigkeit. HNO 1997; 45: 740
39. Kral A, Hartmann R, Tillein J, Heid S, Klinke R. Hearing after congenital deafness: central auditory plasticity and sensory deprivation. Cereb Cortex 2002; 12: 797-807
40. Kral A, Hartmann R, Tillein J, Heid S, Klinke R. Delayed maturation and sensitive periods in the auditory cortex. Audiol Neurootol 2002; 6: 346-362
41. Klinke R. Sprachanbahnung über elektronische Ohren - so früh wie möglich. Dt Ärztblatt Jg 1998; 46: 3049-3052
42. Lenarz T, Lesinski-Schiedat A, von-der-Haar-Heise S, Illg A, Bertram B, Battmer RD. Cochlear implantation in children under the age of two: the MHH experience with the CLARION cochlear implant. Medizinische Hochschule Hannover. Ann Otol Rhinol Laryngol Suppl 1999; 177: 44-49
43. Sainz M, Skarzynski H, Allum JH, Helms J, Rivas A, Martin J, Zorowka PG, Phillips L, Delauney J, Brockmeyer SJ, Kompis M, Korolewa I, Albegger K, Zwirner P, Van-De-Heyning P, D'Haese P. Assessment of auditory skills in 140 cochlear implant children using the EARS protocol. ORL J Otorhinolaryngol Relat Spec 2003; 65: 91-96
44. Mack KF, Müller J, Helms J. Dimensions of the temporal bone in small children in relation to the cochlear implant - an analysis of CT scans. Adv Otorhinolaryngol 1997; 52: 57-59
45. Manrique M, Cervera-Paz FJ, Huarte A, Molina M. Advantages of cochlear implantation in prelingual deaf children before 2 years of age when compared with later implantation. Laryngoscope 2004; 114: 1462-1469
46. McConkey-Robbins A, Koch DB, Osberger MJ, Zimmerman-Phillips S, Kishon-Rabin L. Effect of age at cochlear implantation on auditory skill development in infants and toddlers. Arch Otolaryngol Head Neck Surg 2004; 130: 570-574
47. Miyamoto RT, Houston DM, Kirk KI, Perdew AE, Svirsky MA. Language development in deaf infants following cochlear implantation. Acta Otolaryngol 2003; 123: 241-244
48. Yang HM, Lin CY, Chen YJ, Wu JL. The auditory performance in children using cochlear implants: effects of mental function. Int J Pediatr Otorhinolaryngol 2004; 68: 1185-1188
49. Nikolopoulos TP, O'Donoghue GM, Archbold S. Age at implantation: its importance in pediatric cochlear implantation. Laryngoscope 1999; 109: 595-599
50. Nikolopoulos TP, Dyar D, Archbold S, O'Donoghue GM. Development of spoken language grammar following cochlear implantation in prelingually deaf children. Arch Otolaryngol Head Neck Surg 2004; 130: 629-633
51. Nikolopoulos TP, Gibbin KP, Dyar D. Predicting speech perception outcomes following cochlear implantation using Nottingham children's implant profile (NChIP). Int J Pediatr Otorhinolaryngol 2004; 68: 137-141
52. Niparko JK, Blankenhorn R. Cochlear implants in young children. Ment Retard Dev Disabil Res Rev 2003; 9: 267-275

53. Svirsky MA, Teoh SW, Neuburger H. Development of language and speech perception in congenitally, profoundly deaf children as a function of age at cochlear implantation. Audiol Neurootol 2004; 9: 224-233
54. Szagun G. Learning by ear: on the acquisition of case and gender marking by German-speaking children with normal hearing and with cochlear implants. J Child Lang 2004; 31: 1-30
55. Geers AE. Speech, language, and reading skills after early cochlear implantation. Arch Otolaryngol Head Neck Surg 2004; 130: 634-638
56. Geers AE, Nicholas JG, Sedey AL. Language skills of children with early cochlear implantation. Ear Hear 2003; 24 (1 Suppl): 46S-58S
57. Calmels MN, Saliba I, Wanna G, Cochard N, Fillaux J, Deguine O, Fraysse B. Speech perception and speech intelligibility in children after cochlear implantation. Int J Pediatr Otorhinolaryngol 2004; 68: 347-351
58. Sharma A, Tobey E, Dorman M, Bharadwaj S, Martin K, Gilley P, Kunkel F. Central auditory maturation and babbling development in infants with cochlear implants. Arch Otolaryngol Head Neck Surg 2004; 130: 511-516
59. Sharma A, Dorman M, Spahr A, Todd NW. Early cochlear implantation in children allows normal development of central auditory pathways. Ann Otol Rhinol Laryngol Suppl 2002; 189: 38-41
60. Sharma A, Dorman MF, Spahr AJ. A sensitive period for the development of the central auditory system in children with cochlear implants: implications for age of implantation. Ear Hear 2002; 23: 532-539
61. Sharma A, Tobey E, Dorman M, Bharadwaj S, Martin K, Gilley P, Kunkel F. Central auditory maturation and babbling development in infants with cochlear implants. Arch Otolaryngol Head Neck Surg 2004; 130: 511-516
62. Dowell RC, Dawson PW, Dettman SJ, Shepherd RK, Whitford LA, Seligman PM, Clark GM. Multichannel cochlear implantation in children: a summary of current work at the University of Melbourne. Am J Otol 1991; 12 Suppl: 137-143
63. Eisenberg LS, House WF. Initial experience with the cochlear implant in children. Ann Otol Rhinol Laryngol Suppl 1982; 91: 67-73
64. Hehar SS, Nikolopoulos TP, Gibbin KP, O'Donoghue GM. Surgery and functional outcomes in deaf children receiving cochlear implants before age 2 years. Arch Otolaryngol Head Neck Surg 2002; 128: 11-14
65. Zwolan TA, Ashbaugh CM, Alarfaj A, Kileny PR, Arts HA, El-Kashlan HK, Telian SA. Pediatric cochlear implant patient performance as a function of age at implantation. Otol Neurotol 2004; 25: 112-120
66. Schauwers K, Gillis S, Daemers K, De-Beukelaer C, Govaerts PJ. Cochlear implantation between 5 and 20 months of age: the onset of babbling and the audiologic outcome. Otol Neurotol 2004; 25: 263-270
67. Clark G. Cochlear implants in children: safety as well as speech and language. Int J Pediatr Otorhinolaryngol 2003; 67 (Suppl 1): S7-20
68. O'Neill C, O'Donoghue GM, Archbold SM, Nikolopoulos TP, Sach T. Variations in gains in auditory performance from pediatric cochlear implantation. Otol Neurotol 2002; 23: 44-48
69. Johnson IJ, Gibbin KP, O'Donoghue GM. Surgical aspects of cochlear implantation in young children: a review of 115 cases. Am J Otol 1997; 18 (6 Suppl): S69-70
70. Osberger MJ. Cochlear implantation in children under the age of two years: candidacy considerations. Otolaryngol Head Neck Surg. 1997; 117 (3 Pt 1): 145-149
71. Lehnhardt E, Gnadeberg D, Battmer RD, von Wallenberg E. Experience with the cochlear miniature speech processor in adults and children together with a comparison of unipolar and bipolar modes. ORL J Otorhinolaryngol Relat Spec 1992; 54 (6): 308-313
72. House WF, Eisenberg LS. The cochlear implant in preschool-aged children. Acta Otolaryngol 1983; 95 (5 - 6): 632-638
73. Govaerts PJ, De Beukelaer C, Daemers K, De Ceulaer G, Yperman M, Somers T, Schatteman I, Offeciers FE. Outcome of cochlear implantation at different ages from 0 to 6 years. Otol Neurotol 2002; 23 (6): 885-890
74. Schulze-Gattermann H, Illg A, Lesinski-Schiedat A, Schönermark M, Bertram B, Lenarz T. Kosten-Nutzen-Analyse der Cochlea-Implantation bei Kindern. Laryngo-Rhino-Otol. 2003; 82 (5): 322-329
75. Laszig R, Aschendorff A, Schipper J, Klenzner T. Aktuelle Entwicklung zum Kochleaimplantat. HNO 2004; Apr 52 (4): 357-362
76. NIH Consensus statement 1995. Cochlear Implants in Adults and Children. 15 - 17 May 1995; 13 (2): 1-30
77. Albegger KW. NIH-Konsensuskonferenz über Cochlea Implantate bei Erwachsenen und Kindern, 15. bis 17. Mai 1995. HNO 1996; 44 (3): 118

78. Lenarz T, Hartrampf R, Battmer RD, Bertram B, Lesinski A. Die Cochlear-Implant-Versorgung bei Kleinkindern. Laryngo-Rhino-Otol 1996; 75: 719-726
79. Offeciers E. The impact of changing selection criteria on the outcome of CI. Instructional Session, 5th Congress of EUFOS. Rhodes, GR: 2004
80. Kühn-Inacker H et al. Assessing Auditory Development in very Young Children using the Little EARS Questionnaire. Vortrag, 7th European Symposium Paediatric Cochlear Implantation. Geneva, Switzerland: May 2004
81. Fröber R. Jena, pers. Mitteilung. 11. Thüringer Kurs "Mikrochirurgie des Felsenbeines". Erfurt: März 2004
82. Fayad JN, Wanna GB, Micheletto JN, Parisier SC. Facial nerve paralysis following cochlear implant surgery. Laryngoscope 2003; 113 (8): 1344-1346
83. Helms J. OP-Manual. Bibliothek der Univ.-HNO-Klinik Würzburg 2004
84. Lehnhardt E. Intracochleäre Platzierung der Cochlea-Implant-Elektroden in soft surgery technique. HNO 1993; 41: 356-359
85. Kempf HG, Johann K, Weber BP, Lenarz T. Complications of cochlear implant surgery in children. Am J Otol 1997; 18 (6 Suppl): S62-63
86. Buchman CA, Higgins CA, Cullen R, Pillsbury HC. Revision cochlear implant surgery in adult patients with suspected device malfunction. Otol Neurotol 2004l; 25 (4): 504-510; discussion 510
87. Baumgartner W, Kronenberg J, Hamzavi J, Franz P. Der Suprameatale Zugang - eine Alternative Op-Technik zur Cochlea Implantation. Vortrag Deutsch-Östereichischer HNO-Kongress 2002. HNO-Informationen 2. Demeter Verlag April 2002, p. 88
88. Gibson WP, Harrison HC, Prowse C. A new incision for placement of cochlear implants. J Laryngol Otol 1995; 109 (9): 821-825
89. Kronenberg J, Migirov L, Baumgartner WD. The suprameatal approach in cochlear implant surgery: our experience with 80 patients. ORL J Otorhinolaryngol Relat Spec 2002; 64 (6): 403-405
90. Kronenberg J, Migirov L. The role of mastoidectomy in cochlear implant surgery. Acta Otolaryngol 2003; 123 (2): 219-222
91. James AL, Papsin BC. Device fixation and small incision access for pediatric cochlear implants. Int J Pediatr Otorhinolaryngol 2004; 68 (8): 1017-1022
92. Laszig R, Laubert A. Resorbierbare Intrakutannaht als Wundverschluss beim Cochlear Implant. Laryngo-Rhino-Otol 1995; 74 (8): 518
93. Scheich M, Müller J, Helms J. Cochlea Implantation in Lokalanästhesie. Bad Reichenhall: Vortrag Dt. HNO-Kongress 2004
94. Clark GM, Hallworth RJ, Zdanius K. A cochlear implant electrode. J Laryngol Otol 1975; 89 (8): 787-792
95. Cords SM, Reuter G, Issing PR, Sommer A, Kuzma J, Lenarz T. A silastic positioner for a modiolus-hugging position of intracochlear electrodes: electrophysiologic effects. Am J Otol 2000; 21 (2): 212-217
96. Brors D, Aletsee C, Schwager K, Mlynski R, Hansen S, Schafers M, Ryan A, Dazert S. Interaction of spiral ganglion neuron processes with alloplastic materials in vitro(1). Hear Res 2002; 167 (1 - 2): 110-121
97. De Ceulaer G, Johnson S, Yperman M, Daemers K, Offeciers FE, O'Donoghue GM, Govaerts PJ. Long-term evaluation of the effect of intracochlear steroid deposition on electrode impedance in cochlear implant patients. Otol Neurotol 2003; 24 (5): 769-774
98. Gstöttner W, Adunka O, Franz B. Perimodiolar electrodes in cochlear implants surgery. Acta Otolaryngologica 2001; 127: 216-219
99. Gstoettner W, Plenk H, Franz P, Hamzavi J, Baumgartner W, Czerny C, Ehrenberger K. Cochlear implant deep electrode insertion: extent of insertional trauma. Acta Otolaryngol 1997; 117 (2): 274-277
100. Husstedt HW, Aschendorff A, Richter B, Laszig R, Schumacher M. Nondestructive three-dimensional analysis of electrode to modiolus proximity. Otol Neurotol 2002; 23 (1): 49-52
101. Czerny C, Gstoettner W, Adunka O, Hamzavi J, Baumgartner WD. Postoperative Darstellung und Erfassung der Lage und Insertionstiefe von multikanalikulären Cochlear-Implantaten durch die hochauflösende Computertomographie und durch das Nativröntgen. Wien Klin Wochenschr 2000; 112 (11): 509-511
102. Aschendorff A, Kubalek R, Hochmuth A, Bink A, Kurtz C, Lohnstein P, Klenzner T, Laszig R. Imaging procedures in cochlear implant patients - evaluation of different radiological techniques. Acta Otolaryngol Suppl 2004; (552): 46-49
103. Johnsson LG, House WFJr, Linthicum FH. Otopathological findings in a patient with bilateral cochlear implants. Ann Otol Rhinol Laryngol Suppl 1982; 91 (2 Pt 3): 74-89
104. Klenzner T, Franz D, Reinhard A, Aschendorff A, Laszig R. Funktionelle Ergebnisse mit der

Nukleus® Contour™ Elektrode. Vortrag Deutsch-Östereichischer HNO-Kongress 2002. HNO-Informationen 2. Demeter Verlag April 2002, p. 147
105. Richter B, Aschendorff A, Lohnstein P, Husstedt H, Nagursky H, Laszig R. Clarion 1.2 standard electrode array with partial space-filling positioner: radiological and histological evaluation in human temporal bones. J Laryngol Otol 2002; 116 (7): 507-513
106. Richter B, Aschendorff A, Lohnstein P, Husstedt H, Nagursky H, Laszig R. The Nucleus Contour electrode array: a radiological and histological study. Laryngoscope 2001; 111 (3): 508-514
107. Richter B, Jaekel K, Aschendorff A, Marangos N, Laszig R. Cochlear structures after implantation of a perimodiolar electrode array. Laryngoscope 2001; 111 (5): 837-843
108. Paasche G, Gibson P, Averbeck T, Becker H, Lenarz T, Stover T. Technical report: modification of a cochlear implant electrode for drug delivery to the inner ear. Otol Neurotol 2003; 24 (2): 222-227
109. Dorman MF, Loizou PC, Rainey D. Speech intelligibility as a function of the number of channels of stimulation for signal processors using sine-wave and noise-band outputs. J Acoust Soc Am 1997; 102 (4): 2403-2411
110. Hodges AV, Villasuso E, Balkany T, Bird PA, Butts S, Lee D, Gomez O. Hearing results with deep insertion of cochlear implant electrodes. Am J Otol 1999; 20 (1): 53-55
111. Dorman MF, Loizou PC, Rainey D. Simulating the effect of cochlear-implant electrode insertion depth on speech understanding. J Acoust Soc Am 1997; 102 (5 Pt 1): 2993-2996
112. Adamczyk M, Bachor E, Bagus H, Fischer M. Cochlear Implantation - Zusammenhang zwischen Sprachentwicklung und Insertionstiefe der Elektrode bei Kindern. Laryngo Rhino Otol 2001; 80 (3): 123-126
113. Marrinan MS, Roland JTJr, Reitzen SD, Waltzman SB, Cohen LT, Cohen NL. Degree of modiolar coiling, electrical thresholds, and speech perception after cochlear implantation. Otol Neurotol 2004; 25 (3): 290-294
114. http://www. fda. org
115. Arnold W, Bredberg G, Gstoettner W, Helms J, Hildmann H, Kiratzidis T, Müller J, Ramsden RT, Roland P, Walterspiel JN. Meningitis following cochlear implantation: pathomechanisms, clinical symptoms, conservative and surgical treatments. ORL J Otorhinolaryngol Relat Spec 2002; 64 (6): 382-389
116. Callanan V, Poje C. Cochlear implantation and meningitis. Int J Pediatr Otorhinolaryngol 2004; 68 (5): 545-550
117. Centers for Disease Control and Prevention - CDC. Advisory Committee on Immunization Practices. Pneumococcal vaccination for cochlear implant candidates and recipients: updated recommendations of the Advisory Committee on Immunization Practices. MMWR Morb Mortal Wkly Rep 2003; 52 (31): 739-740
118. Cohen NL, Roland JTJr, Marrinan M. Meningitis in cochlear implant recipients: the North American experience. Otol Neurotol 2004; 25 (3): 275-281
119. Graveriau C, Roman S, Garrigues B, Triglia JM, Stein A. Pneumococcal meningitis in an immunocompetent adult with a cochlear implant. J Infect 2003; 46 (4): 248-249
120. Rose M, Hey C, Kujumdshiev S, Gall V, Schubert R, Zielen S. Immunogenicity of pneumococcal vaccination of patients with cochlear implants. J Infect Dis 2004; 190 (3): 551-557
121. Reefhuis J, Honein MA, Whitney CG, Chamany S, Mann EA, Biernath KR, Broder K, Manning S, Avashia S, Victor M, Costa P, Devine O, Graham A, Boyle C. Risk of bacterial meningitis in children with cochlear implants. N Engl J Med 2003; 349 (5): 435-445
122. Spahr AJ, Dorman MF. Performance of subjects fit with the Advanced Bionics CII and Nucleus 3G cochlear implant devices. Arch Otolaryngol Head Neck Surg 2004; 130 (5): 624-628
123. Tykocinski M, Shepherd RK, Clark GM. Reduction in excitability of the auditory nerve following electrical stimulation at high stimulus rates. Hear Res 1995; 88 (1 - 2): 124-142
124. Tykocinski M, Shepherd RK, Clark GM. Reduction in excitability of the auditory nerve following electrical stimulation at high stimulus rates. II. Comparison of fixed amplitude with amplitude modulated stimuli. Hear Res 1997; 112 (1 - 2): 147-157
125. Dillier N, Lai WK, Almqvist B, Frohne C, Müller-Deile J, Stecker M, von Wallenberg E. Measurement of the electrically evoked compound action potential via a neural response telemetry system. Ann Otol Rhinol Laryngol 2002; 111 (5 Pt 1): 407-414
126. Polak M, Hodges AV, King JE, Balkany TJ. Further prospective findings with compound action potentials from Nucleus 24 cochlear implants. Hear Res 2004; 188 (1 - 2): 104-116
127. Seyle K, Brown CJ. Speech perception using maps based on neural response telemetry measures. Ear Hear 2002; 23 (1 Suppl): 72S-79S
128. Thai-Van H, Chanal JM, Coudert C, Veuillet E, Truy E, Collet L. Relationship between NRT measurements and behavioral levels in children with the Nucleus 24 cochlear implant may change over time: preliminary report. Int J Pediatr Otorhinolaryngol 2001; 58 (2): 153-162

129. Blauert J. Räumliches Hören. Stuttgart: S. Hirzel Verlag 1974
130. van Hoesel RJM, Tong YC, Hollow RD, Clark GM. Psychophysical and speech perception studies: A case report on a binaural cochlear implant subject. Journal of the Acoustical Society of America 1992; 94: 3178-3189
131. Leake PA, Hradek GT, Snyder RL. Chronic electrical stimulation by a cochlear implant promotes survival of spiral ganglion neurons after neonatal deafness. J Comp Neurol 1999;412 (4): 543-562
132. Schleich P, Nopp P, D'Haese P. Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. Ear Hear 2004; 25 (3): 197-204
133. Nopp P, Schleich P, D'Haese P. Sound localization in bilateral users of MED-EL COMBI 40/40+ cochlear implants. Ear Hear 2004; 25 (3): 205-214
134. Schön F, Müller J, Helms J. Speech reception thresholds obtained in a symmetrical four-loudspeaker arrangement from bilateral users of MED-EL cochlear implants. Otol Neurotol 2002; 23 (5): 710-714
135. van Hoesel RJ. Exploring the benefits of bilateral cochlear implants. Audiol Neurootol 2004;9 (4): 234-246
136. Morera C et al. Consensus Statement, 2nd Consensus Conference on Auditory Implants. Valencia: Feb 2004. http://über www.hno.uni-wuerzburg.de
137. http://www.hno-wuerzburg.de
138. Laszig R, Sollmann WP, Marangos N, Charachon R, Ramsden R. Nucleus 20-channel and 21-channel auditory brain stem implants: first European experiences. Ann Otol Rhinol Laryngol 1995; 166 (Suppl): 28-30
139. Rosahl S, Lenarz T, Matthies C, Samii M, Sollmann W, Laszig R. Hirnstammimplantate zur Wiederherstellung des Hörvermögens: Entwicklung und Perspektiven. Deutsches Ärzteblatt 2004; 4: 101
140. Laszig R. European auditory brain stem prosthesis. Ann Otol Rhinol Laryngol 1997; 106: 884-885
141. Jackson KB, Mark G, Helms J, Mueller J, Behr R. An auditory brainstem implant system. Am J Audiol 2002; 11: 128-133
142. Colletti V, Fiorino F, Sacchetto L, Miorelli V, Carner M. Hearing habilitation with auditory brainstem implantation in two children with cochlear nerve aplasia. Int J Pediatr Otorhinolaryngol 2001; 60 (2): 99-111
143. Luxford WM, House WF, Hough JV, Tonokawa LL, Berliner KI, Martin E. Experiences with the Nucleus multichannel cochlear implant in three young children. Ann Otol Rhinol Laryngol Suppl 1988; 135: 14-16
144. Anderson I, Weichbold V, D'Haese PS, Szuchnik J, Quevedo MS, Martin J, Dieler WS, Phillips L. Cochlear implantation in children under the age of two - what do the outcomes show us?. Int J Pediatr Otorhinolaryngol 2004; 68: 425-431
145. Nevison B, Laszig R, Sollmann WP, Lenarz T, Sterkers O, Ramsden R, Fraysse B, Manrique M, Rask-Andersen H, Garcia-Ibanez E, Colletti V, von Wallenberg E. Results from a European clinical investigation of the Nucleus multichannel auditory brainstem implant. Ear Hear 2002; 23 (3): 170-183
146. Otto SR, Brackmann DE, Hitselberger WE, Shannon RV, Kuchta J. Multichannel auditory brainstem implant: update on performance in 61 patients. J Neurosurg 2002; 96: 1063-1071
147. de Balthasar C, Boex C, Cosendai G, Valentini G, Sigrist A, Pelizzone M. Channel interactions with high-rate biphasic electrical stimulation in cochlear implant subjects. Hear Res 2003; 182 (1 - 2): 77-87
148. Bierer JA, Middlebrooks JC. Cortical responses to cochlear implant stimulation: channel interactions. J Assoc Res Otolaryngol 2004; 5 (1): 32-48
149. Braunschweig T, Schelhorn-Neise P, Biedermann F, Weisser P. Untersuchungen zu Möglichkeiten einer physiologischen Anpassung von Cochlea-Implantaten. Laryngo-Rhino-Otol 2004; 83 (6): 387-390
150. Chatelin V, Kim EJ, Driscoll C, Larky J, Polite C, Price L, Lalwani AK. Cochlear implant outcomes in the elderly. Otol Neurotol 2004; 25 (3): 298-301
151. Cunningham CD3rd, Slattery WH3rd, Luxford WM. Postoperative infection in cochlear implant patients. Otolaryngol Head Neck Surg 2004; 131 (1): 109-14
152. Dahm MC, Shepherd RK, Clark GM. The postnatal growth of the temporal bone and its implications for cochlear implantation in children. Acta Otolaryngol Suppl 1993; 505: 1-39
153. Dettman SJ, D'Costa WA, Dowell RC, Winton EJ, Hill KL, Williams SS. Cochlear implants for children with significant residual hearing. Arch Otolaryngol Head Neck Surg 2004; 130 (5): 612-618
154. Fraysse B, Dillier N, Klenzner T, Laszig R, Manrique M, Morera-Perez C, Morgon AH, Müller-Deile J, Ramos-Macias A. Cochlear implants for adults obtaining marginal benefit from acoustic amplification: a European study. Am J Otol 1998; 19 (5): 591-597

155. Frijns JH, Klop WM, Bonnet RM, Briaire JJ. Optimizing the number of electrodes with high-rate stimulation of the clarion CII cochlear implant. Acta Otolaryngol 2003; 123 (2): 138-142
156. Gomaa NA, Rubinstein JT, Lowder MW, Tyler RS, Gantz BJ. Residual speech perception and cochlear implant performance in postlingually deafened adults. Ear Hear 2003; 24 (6): 539-544
157. Graham JM. Graham Fraser Memorial Lecture 2002. From frogs' legs to pieds-noirs and beyond: some aspects of cochlear implantation. J Laryngol Otol 2003; 117 (9): 675-85
158. Herzog M, Schön F, Müller J, Knaus C, Scholtz L, Helms J. Langzeitergebnisse nach Cochlear-Implant-Versorgung älterer Patienten. Laryngo-Rhino-Otol 2003; 82 (7): 490-493
159. House WF, Berliner KI, Eisenberg LS. Experiences with the cochlear implant in preschool children. Ann Otol Rhinol Laryngol 1983; 92 (6 Pt 1): 587-592
160. Ketten DR, Skinner MW, Wang G, Vannier MW, Gates GA, Neely JG. In vivo measures of cochlear length and insertion depth of nucleus cochlear implant electrode arrays. Ann Otol Rhinol Laryngol Suppl 1998; 175: 1-16
161. Klinke R, Hartmann R. Basic neurophysiology of cochlear-implants. Am J Otol 1997; 18 (6 Suppl): S7-10
162. Klinke R, Hartmann R, Heid S, Tillein J, Kral A. Plastic changes in the auditory cortex of congenitally deaf cats following cochlear implantation. Audiol Neurootol 2001; 6 (4): 203-206
163. Koelsch S, Wittfoth M, Wolf A, Müller J, Hahne A. Music perception in cochlear implant users: an event-related potential study. Clin Neurophysiol 2004; 115 (4): 966-972
164. Kreft HA, Donaldson GS, Nelson DA. Effects of pulse rate on threshold and dynamic range in Clarion cochlear-implant users. J Acoust Soc Am 2004; 115 (5 Pt 1): 1885-1888
165. Kubo T, Yamamoto K, Iwaki T, Matsukawa M, Doi K, Tamura M. Significance of auditory evoked responses (EABR and P300) in cochlear implant subjects. Acta Otolaryngol 2001; 121 (2): 257-261
166. Loizou PC, Dorman MF, Tu Z, Fitzke J. Recognition of sentences in noise by normal-hearing listeners using simulations of speak-type cochlear implant signal processors. Ann Otol Rhinol Laryngol Suppl 2000; 185: 67-68
167. Nadol JBJr, Shiao JY, Burgess BJ, Ketten DR, Eddington DK, Gantz BJ, Kos I, Montandon P, Coker NJ, Roland JTJr, Shallop JK. Histopathology of cochlear implants in humans. Ann Otol Rhinol Laryngol 2001; 110 (9): 883-891
168. Nadol JBJr, Eddington DK. Histologic evaluation of the tissue seal and biologic response around cochlear implant electrodes in the human. Otol Neurotol 2004; 25 (3): 257-262
169. Pasanisi E, Bacciu A, Vincenti V, Guida M, Barbot A, Berghenti MT, Bacciu S. Speech recognition in elderly cochlear implant recipients. Clin Otolaryngol 2003; 28 (2): 154-157
170. Rubinstein JT, Hong R. Signal coding in cochlear implants: exploiting stochastic effects of electrical stimulation. Ann Otol Rhinol Laryngol Suppl 2003; 191: 14-19
171. Ruh S, Battmer RD, Strauss-Schier A, Lenarz T. Cochlear Implant bei resthörigen Patienten. Laryngo Rhino Otol 1997; 76 (6): 347-350
172. Skinner MW. Optimizing cochlear implant speech performance. Ann Otol Rhinol Laryngol Suppl 2003; 191: 4-13
173. Tykocinski M, Cohen LT, Pyman BC, Roland TJr, Treaba C, Palamara J, Dahm MC, Shepherd RK, Xu J, Cowan RS, Cohen NL, Clark GM. Comparison of electrode position in the human cochlea using various perimodiolar electrode arrays. Am J Otol 2000; 21 (2): 205-211
174. Vlahovic S, Sindija B. The influence of potentially limiting factors on paediatric outcomes following cochlear implantation. Int J Pediatr Otorhinolaryngol 2004; 68 (9): 1167-1174
175. http://www.fda.ord
176. http://www.cochlear.com
177. http://www.medel.com
178. http://www.cochlearimplants.com
179. Wilson BS, Finley CC, Lawson DT, Zerbi M. Temporal representations with cochlear implants. Am J Otol 1997; 18 (6 Suppl): S30-34
180. Wilson BS. pers. Mitteilung. Würzburg: Wullstein Symposium 2001
181. Witte RJ, Lane JI, Driscoll CL, Lundy LB, Bernstein MA, Kotsenas AL, Kocharian A. Pediatric and adult cochlear implantation. Radiographics 2003; 23 (5): 1185-1200
182. Zeng FG. Trends in cochlear implants. Trends Amplif 2004; 8 (1): 1-34

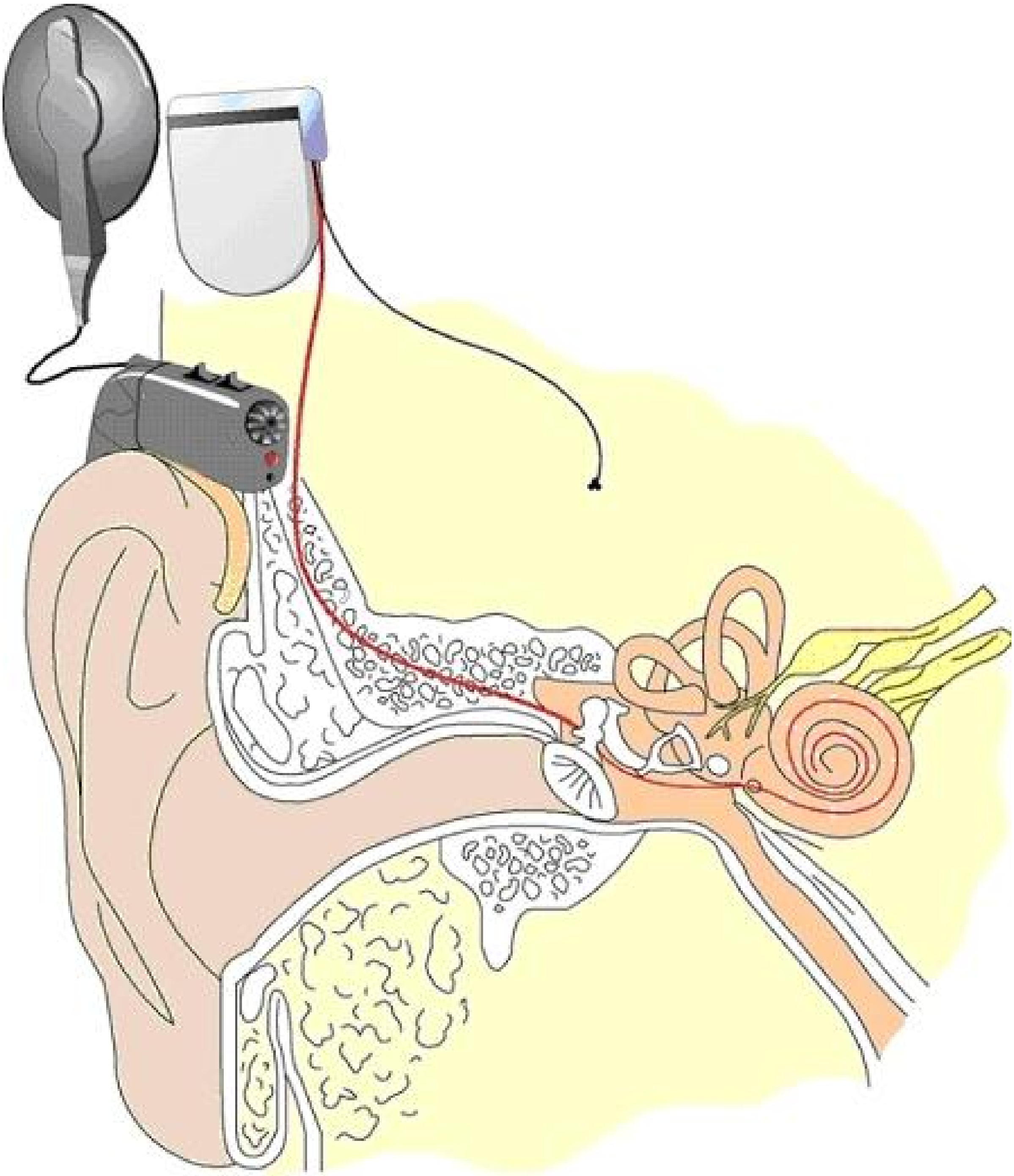

Figure 1: Function of a cochlear implant system:

Sound is picked up by a microphone (1), processed by the external speech processor (2) and wirelessly transmitted by a transmitter (3) to an implantable receiver (4). The electrical signal, coding e.g. speech or music as a defined sequence of electrical pulses, is then relayed to an electrode (5). The electrode is inserted through the mastoid, the facial recess, past the facial nerve through the middle ear into the non-functional cochlea (6). The electrode carrier stimulates the auditory nerve. The brain decodes the relayed neural impulse and the original signal is recognised as speech or music (*schematic taken from product information*).

Figure 2: Intra-operative site during cochlear implantation in an 8-month-old infant (own image)

Opening of the facial recess, facial nerve covered by bone, blood-forming bone marrow around the facial nerve channel. 1.2 mm suction tool on the left.

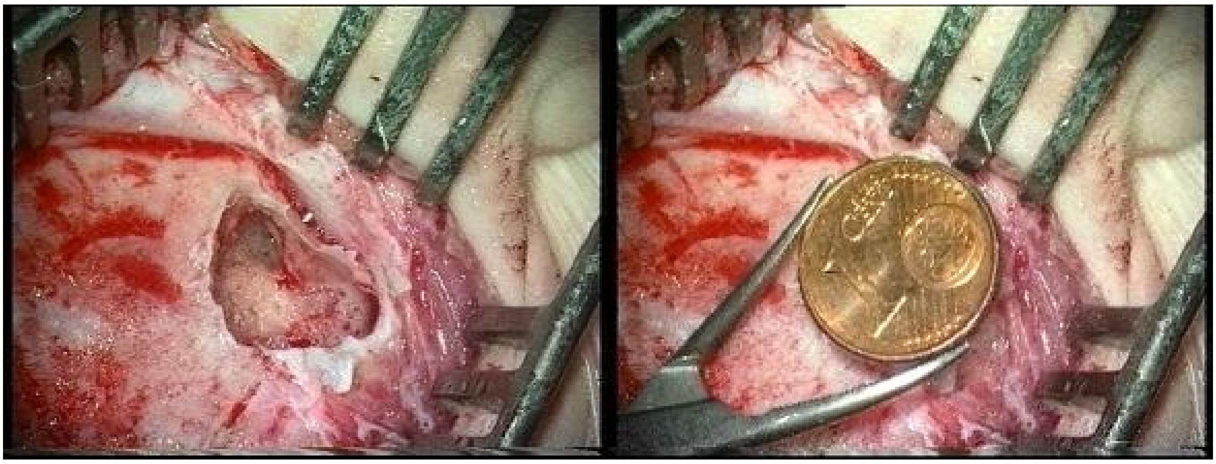

Figure 3: Dimensions of mastoid of 6-month-old infant during cochlear implantation compared to sterile 1-Eurocent coin.

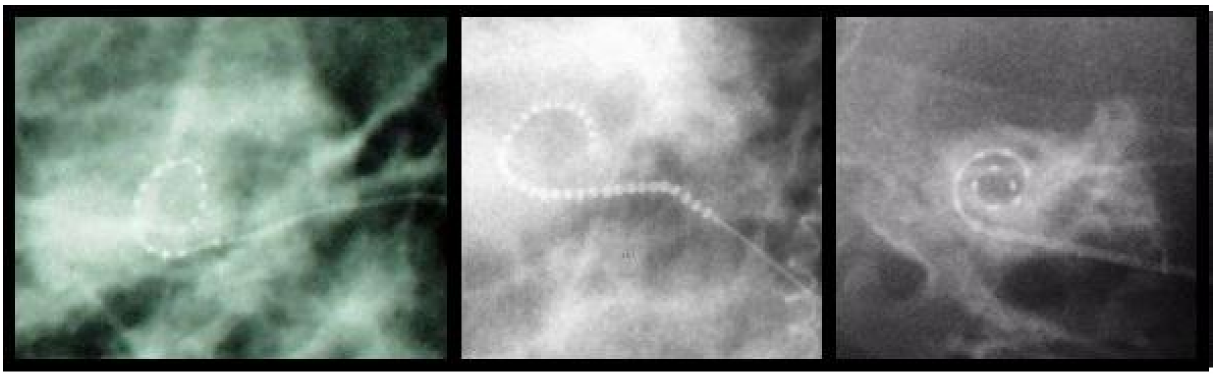

Figure 4: Examples of complete electrode insertion for different CI systems (from left to right: Clarion implant, Nucleus implant, MED-EL implant). The right image shows a deep electrode insertion.

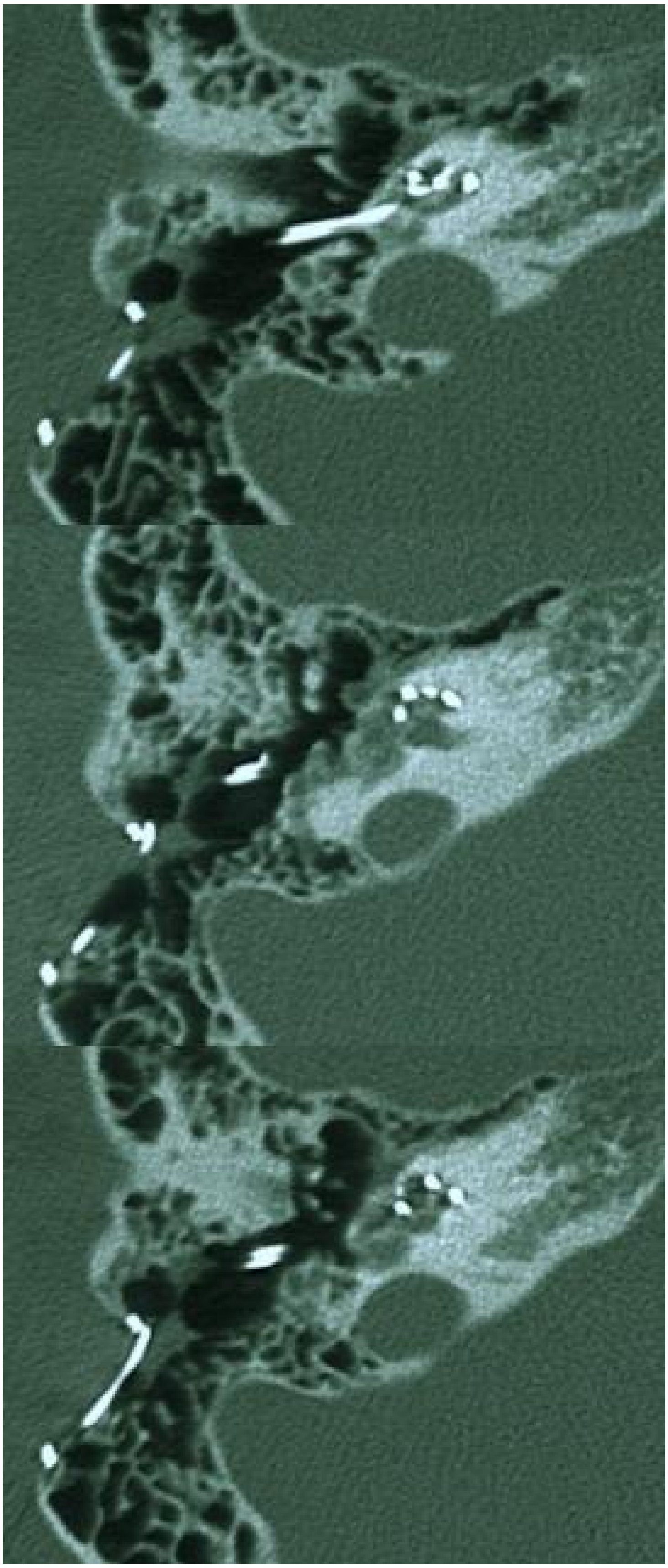

Figure 5: CT sequence before implantation of contralateral side: deep electrode insertion. Electrode carrier placed in second cochlear turn.

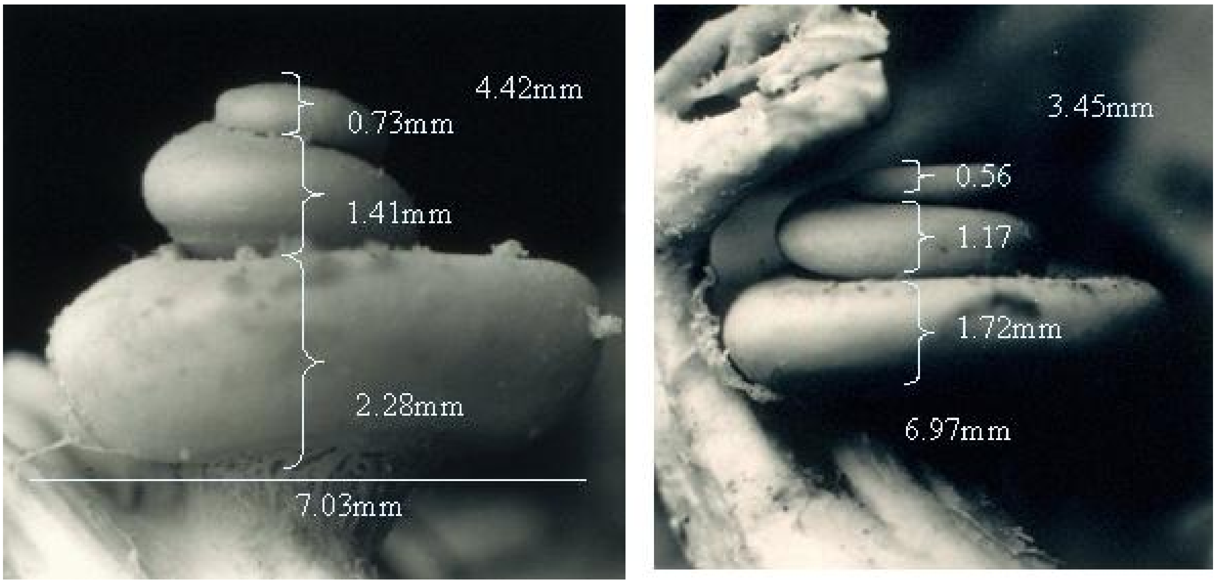

Figure 6: Different diameters and slopes of cochlear turns to illustrate individual variations of the human cochlea

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