Imaging of the temporal bone in cochlear implant surgery

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Cover illustration: Stenvers plain film radiograph depicting the internal parts of a cochlear implant.

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Radiologische beeldvorming van het rotsbeen bij *cochlear implant* chirurgie
(met een samenvatting in het Nederlands)

Proefschrift

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In memoriam

W.G.E. Bettman, huisarts (1937 - 2002)

W.J.M. Gökemeyer, KNO-arts (1938 - 2003)

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Introduction

Historical background of cochlear implantation

Volta (1745 - 1827) demonstrated that the nervous system could be artificially activated; in his experiments, he stimulated the auditory system by connecting a battery to two electrodes that had been placed in the ears.[1] This created a shock in the head, after which the subject perceived the sound of ‘cooking soup’. Despite these early experiments, the idea of replacing the function of the cochlear apparatus in the totally deaf by means of direct electrical stimulation of the cochlear nerve seemed impossible - until the 1950s. From then on, great progress was made; the first permanent cochlear implantation, performed in 1962, allowed the patient to follow the rhythm of a piece of music and to discern differences between voices.[2] From 1973 on, cochlear implantation became routine, and the cochlear nerve can now be adequately stimulated.[2,3] Many patients are able to understand running speech, even without resorting to lip reading. In some, speech recognition can be improved through a combination of hearing with an implant and lip reading. Patients who cannot recognise speech still benefit from the implant because it gives them contact with their surroundings by picking up ambient sounds. And for all groups, the implant improves voice control.

In the late 1970s and early 1980s, the patients receiving treatment were predominantly postlingual adults. Later, it was realised that post- and prelingually deafened children could benefit from cochlear implantation too. However, this expansion of the patient group has sparked fierce debate within the deaf community.[4-12] The main concern is the presumed threat to deaf culture.[4,6] The increased use of cochlear implants is seen to pose a threat to the very existence of sign language, which has been promoted as warranting recognition as an official language. Deaf activists see their way of life as emotionally fulfilling, promising, and independent. They deny that deafness is a disability and therefore reject any attempt to make hearing an option for deaf children. It seems reasonable that only the parents should have the authority to make decisions on behalf of their children. To ensure that their decisions are well founded, they must be well informed; their decisions should be based on study and be grounded in objectively reported outcomes.

Candidates

Previously, the candidates for cochlear implantation were selected on the basis of strict criteria; at present, there is greater latitude. Sometimes a cochlear implant significantly improves the hearing capacity of individuals with a severe hearing loss who benefit to some degree from a hearing aid. The number of patients who might benefit from a cochlear implant will probably increase as the technology is refined. When combined with the option of reimplantation, depending on the survival rate of the implants, the demand for cochlear implantation will probably increase even more. These factors are uncertain, which makes it hard to put an exact figure on cochlear implant candidates. What is certain is that a candidate should have reasonable expectations, be adequately motivated and communicative, and possess the intellectual capacities needed to follow rehabilitation programs.

Cochlear implant system

At present, the cochlear implant system consists of external and internal parts, as depicted in figure 1. The external part has three components: a microphone, a speech processor, and a transmitter. The internal part consists of a receiver/stimulator and a bundle of ring-shaped electrodes. The electrodes are introduced into the scala tympani of the cochlea. The transmitter and receiver are held together by magnets on each side of the closed skin. The microphone picks up ambient sound, which is analysed and processed. Depending on the strategy used, sound information is transmitted internally to the electrical supply. There, intracochlear electrodes are controlled and stimulated for selective triggering of auditory nerve groups. The resulting signal is transported via the central acoustic pathway from the cochlear nuclei to the temporal acoustic area.

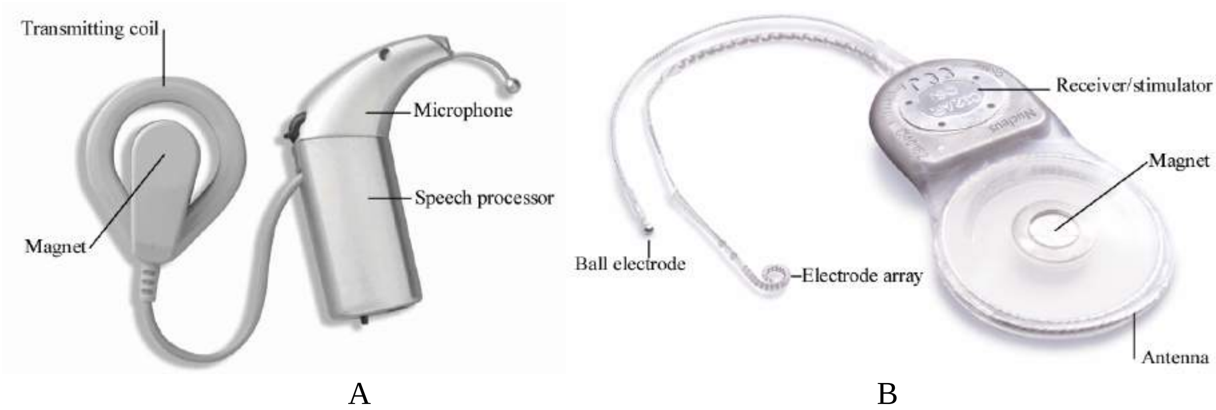

Figure 1: The external (A) and internal (B) part of a Nucleus 24® cochlear implant.

Surgical technique

An extended retroauricular incision is made and a caudal-based skin flap is created. Although incisions can be made directly into the bone, the flap is fashioned in two layers to prevent infection and extrusion. In order to optimise contact between the magnets of the receiver and transmitter, the flap can be thinned to approximately 5 mm. During mastoidectomy, the edges of the cavity might be kept overhanging, allowing for electrode array fixation. A posterior tympanotomy, or facial recess approach, is performed between the facial nerve and the chorda tympani, below the short process of the incus.[13] After posterior tympanotomy, the promontory with the stapedial footplate and round window niche and the incudal-stapedial joint should be visible. Approximately 0.5-1 cm behind the mastoid cavity, the receiver bed is drilled in the temporoparietal bone. For the transmitter to fit properly, the receiver should not be placed too close to the pinna. Furthermore, a speech processor, placed behind the ear as depicted in figure 1, can then be used. The scala tympani is opened slightly anterior to the round window on the promontory. This route permits us to access the cochlea in a straight line and thus to insert the electrodes deeply. Electrode damage is prevented by inserting a fitting dummy electrode, with which cochlear obstructions can be diagnosed. A more sophisticated but still experimental technique involves using a microendoscope with diameters ranging from 0.35 to 0.90 mm.[14-19] Neo-ossification appears as a chalky white substance of softer consistency than the cochlear capsule.[20] If we find proximal obstruction in the scala tympani, we drill until we reach endocochlear lumen. Several techniques are available for dealing with more extensive ossification: drilling along the basal turn; cochleostomy into the second turn; retrograde insertion into the scala vestibuli; and creating a trough in the basal turn.[18,21-34]

To prevent damage, hemostasis using mono- or bipolar cautery is carried out before the implant is placed. When either a complete or a partial electrode array insertion seems feasible, the implant is fixated in its skull bed and the electrodes are inserted in the cochlea. Some authors report use of a lubricant (hyaluronic acid) to facilitate electrode insertion. The outcomes are not uniform, however, and the biosafety of this procedure is not yet clear.[35-39] The cochleostomy is sealed with gelfoam®, and the electrode array may be sutured to the bony rims of the mastoid. The reference electrode is placed underneath the temporal muscle. The implant is tested with telemetry, impedance measurement, or stapedial reflex measurement, depending on the type of implant used. The skin flap is closed in three layers: muscle, subcutis, and cutis.

Surgical issues in children

Certain aspects of surgery warrant special attention in young children. Wen-Yang Su et al. studied the diameter of the cochlear aqueduct, the maximum diameters of the round and oval window and their niches, the depth of the round window niche, and the space in the facial recess; these aspects were studied in 558 cases, divided into four age groups.[40] One important conclusion they drew is that the otic capsule is mature at birth and does not grow afterwards. Because of the extreme variability in the size of the facial recess, preoperative evaluation is necessary. Eby reported extensively on the development of the facial recess in 73 individuals, aged from 8 weeks in utero to 7 years after birth.[41] No statistically significant growth of the recess after birth could be established. Similar results were obtained by Dahm et al., Young and Nadol, and Bielamowicz et al.[42-44] Thus, cochlear implantation seems feasible from term birth onwards. However, related neighboring temporal bone structures grow considerably, making early implantation potentially more difficult.[42] The posterior tympanotomy requires some degree of mastoid pneumatisation. By 16 months of age, there seems to be adequate pneumatisation.[45] Although the middle ear structures appear much as they do in adults, sometimes the vertical facial canal has a more anterior position and obscures the round window niche, making orientation difficult.[45] The electrode array should make a large loop in the mastoid, allowing the mastoid to grow without explanting the array.[29] It should be possible to extend the lead wire by up to 25 mm.[42,45] It should only be fixed at the receiver site and at the fossa incudis, as these structures are not subject to growth relative to the receiver bed and the cochleostomy.[42] To prevent metal fatigue and internal receiver failure, the implant has to be placed on a flattened surface.[45]

Surgical problems

Three consecutive stages in surgery have a strong influence on the possibility and extent of electrode array insertion.

1. The distance between the facial canal at the level of the eminentia pyramidalis and the posterosuperior margin of the tympanic anulus determines the amount of space available for performing a posterior tympanotomy.
2. The route towards the cochlea is preferably parallel to the initial course of the electrode array within the cochlea. Only this route allows us to enter the cochlea in a straight line and thus to insert the electrodes deeply. Thus, the relations between the orientation of the cochlear basal turn and the posterior tympanotomy are important in determining the route. Figure 2 depicts the result of a difficult orientation between the cochlea and the facial recess. In this case, the cochlea was not found; the drilling route ran tangential to the cochlea towards the carotid artery.
3. The postoperative auditory perception is related to the depth of electrode insertion.[39,46] That depth, in turn, depends on cochlear patency. Patency may be reduced in the event of cochlear fibrosis and ossification, which could develop from labyrinthitis caused by meningitis or hematogenic infection.[47-50] But cochlear patency could also be impaired as a secondary result of middle ear disease (e.g., chronic otitis or cholesteatoma), otospongiosis, Cogan’s syndrome, fractures, or prior surgery.[51] Figure 3 shows an obstruction of the right cochlear basal turn as seen on a preoperative semilongitudinal computed tomography (CT) scan.

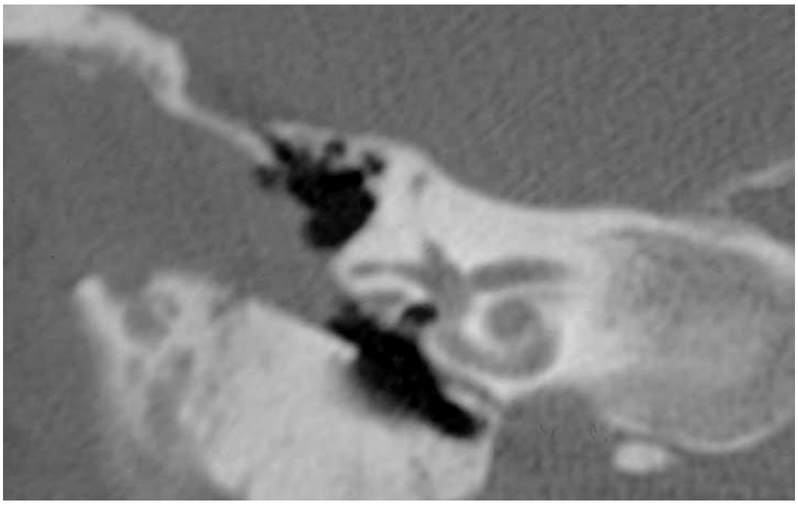

Fig. 2. Postoperative semilongitudinal CT scan of the right temporal bone showing a drilling route tangential to the cochlea, leading to the carotid artery.

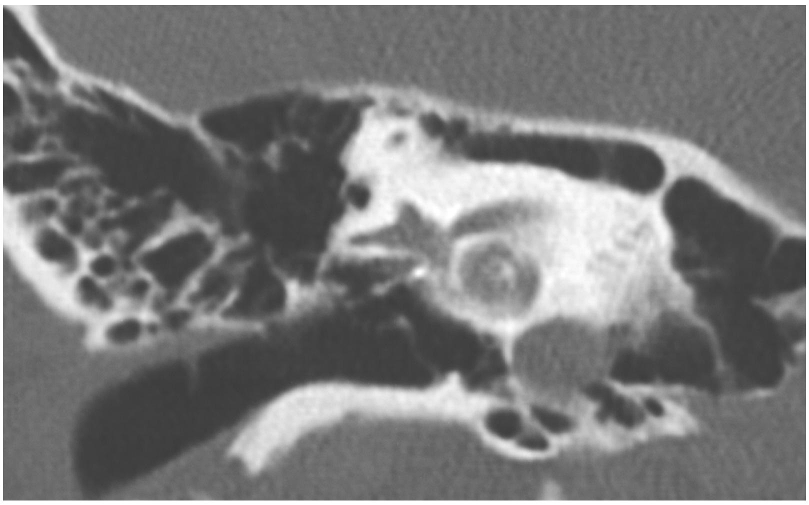

Fig. 3. Semilongitudinal CT scan of the right ear showing an obstruction of the cochlear basal turn.

Preoperative imaging of the temporal bone

As demonstrated and discussed above, several anatomical structures must be evaluated prior to surgery. First of all, the very feasibility of a cochlear implant procedure has to be assessed, and the intended surgical technique has to be specified. At our department, we use preoperative CT and magnetic resonance imaging (MRI) techniques for that purpose. CT has been part of the preoperative work up since 1985. MRI was added because of its supposedly superior reliability in assessing disorders of the cochlear nerve and cochlear patency. Table 1 presents an overview of all structures and their relationships that have to be evaluated preoperatively.

Table 1. Aspects of temporal bone anatomy that have to be evaluated preoperatively in cochlear implant candidates, modified after Frau et al.[52]

Anatomical structure	
Cochlea	Patency of the scalae
	Malformations
Cochlear nerve	Presence
Round window	Position
Oval window	Position
Carotid canal	Relation to cochlea
Jugular bulb	Relation to round window
Incus	Short process
Facial nerve	Tympanic and mastoidal course
	Size of facial recess
Mastoid	Extent of pneumatisation
Temporal squama	Thickness

Main aspects of preoperative imaging

Regarding preoperative imaging, this thesis focuses on the aspects which were discussed above in the surgical problems section: assessment of the facial recess width, the orientation between the cochlear basal turn and the facial recess, as well as of cochlear patency.

Facial recess width

The preoperative work up should include an evaluation of the facial nerve because it might take an aberrant course and the width of the facial recess might be restricted. On axial CT images, it is easy to recognise the facial nerve on its course through the labyrinth, tympanic cavity, and mastoid.

Using 1 mm contiguous slices, it is feasible to measure the facial nerve on axial and coronal CT examinations, as demonstrated by Dimopoulos et al.[53] They obtained similar results comparing CT and microscopic methods in 73 temporal bones. Multiplanar angulated 2-D reconstruction High Resolution CT (HRCT) can be useful in relating the facial nerve to temporal bony landmarks.[54] The quality, and thus the usefulness, of these multiplanar reformats will depend on the resolution and the direction of the plane of the original scan.

MRI is not useful for assessing the integrity of the facial nerve in its labyrinthine, tympanic, and mastoidal course due to the lack of reference to any bony landmarks. However, submillimetric gradient echo images can show the nerve, thus making a rough evaluation of its presence and course possible.[55,56]

Orientation of the cochlear basal turn and the facial recess

As stated earlier, the basal turn of the cochlea should be approached in a longitudinal direction in order to insert the electrode array parallel to the first part of the basal turn. Therefore, the surgeon needs to know the width of the facial recess as well as the relation between the posterior tympanotomy region and the basal turn of the cochlea. Once the facial recess has been opened and passed, the surgeon should be able to see the promontory with its surgical landmarks and the site of the intended cochleostomy.

Cochlear patency

The surgeon should have adequate information on the patency of the cochlea before surgery in order to anticipate any difficulties that might arise. If necessary, the surgeon can then consider other ways to insert the electrode array as far into the cochlea as possible. To obtain that information, 2-D or 3-D CT and MRI can be used.

Bath et al. demonstrate how the underestimation of cochlear ossification grade, using HRCT, can result in serious peroperative complications.[57] The drawback of conventional CT scans is that they do not discriminate sufficiently between bone and fluid at the level of the cochlea.[58,59] The problem lies in the customary slice thickness of 1-1.5 mm, which is wider than the intracochlear structures, resulting in partial-volume effects. Consequently, the resolution is relatively poor. It is hard to assess the intracochlear fluid on printed film, due to the slight differences in attenuation coefficient between fluid (0-10 Hounsfield Units) and soft tissue (40-50 Hounsfield Units).[47,60] More information might be obtained using a viewing station that allows the window's width and level to be adjusted.

An alternative approach is to use T_2-weighted MRI images, as they can clearly show the endolymphatic and perilymphatic spaces. In theory, they could thus allow the observer to differentiate between fluid and fibrotic occlusions.[61] Indeed, Klein et al. have demonstrated that the sensitivity of MRI is better than CT for assessing cochlear patency disorders.[60] On the other hand, MRI is said to be inferior to CT for diagnosing cochlear otosclerosis.[62,63] CT seems to be most useful in cases without meningitis.[62]

Postoperative imaging

The number of electrodes within the cochlea and their insertion depth are correlated with cochlear implant performance.[39,46] Therefore, it is important to establish how many electrodes are to be inserted and how they are to be positioned. The position of the electrode array within the cochlea is estimated during surgery by counting the inserted electrodes. This method has several drawbacks, however, and is said to result in a poor predictability of insertion depth.[64] The surgeon is hampered by the narrow view through the posterior tympanotomy, looking down along the axis of the electrode array. There is no convention on exactly where to start counting: at the level of the scala tympani, the cochleostomy, or the round window niche. Furthermore, cochleostomy sites may vary from one patient to the next. Even if a reliable estimate is made, postoperative slippage may occur. Particularly in the event of restricted auditory performance after implantation, it is necessary to determine the depth of the electrodes.[65] The literature describes several imaging techniques for the postoperative assessment of electrode insertion depth. The main ones are 2-D x-ray approaches, CT imaging, and MRI.[64,66-70] All of the 2-D x-ray approaches are said to have the same disadvantages: a true axial projection is difficult to obtain without underestimating the electrode length; and superimposed structures often mask details of interest. A good way to assess the position of an electrode array is with CT scans (axial slices and 2-D or 3-D reconstructions).[71-73] Not only do CT methods allow assessment of the depth to which the electrode array has been inserted, but relationships with temporal bone structures can be evaluated too.[74]

MRI is not capable of demonstrating the presence of extracochlear electrodes. The problem is that the image of the electrodes in MRI is similar to that of their environment in the middle ear; both are represented as dark areas. An even more serious drawback is that MRI poses several potential hazards due to the heating of the receiver and the electrode array, induced current, unintentional implant output, implant damage, and torque.[75]

Scope of this thesis

In this thesis, we assess the usefulness of pre- and postoperative imaging as used at our department with regard to certain aspects of anatomy and surgery.

We used to perform preoperative CT and MRI in all cochlear implant candidates. CT is applied to analyse the anatomy of the temporal bone. Special attention is given to the facial recess width and the orientation between the cochlear basal turn and the facial recess. To our knowledge, there are no studies in the literature on these aspects. Therefore, in **Chapter 2,** we study the accuracy of the preoperative CT investigation of the facial recess and its relation with the longitudinal axis of the cochlear basal turn.

So far, CT imaging has been only moderately useful as a diagnostic tool for assessing cochlear patency, though that capability might improve with technological progress.[57,58,60] Meanwhile, clinicians can rely on other imaging procedures that do reveal precisely what they need to know. Concretely, by selecting different scanning planes, they can obtain information that would otherwise have gone unnoticed. Taking that strategy at our department, we use axial and semilongitudinal CT planes, the latter having been introduced by Zonneveld et al. and Damsma et al.[76,77] In **Chapter 3,** we investigate how cochlear patency as seen on axial plus semilongitudinal CT planes is correlated with findings at surgery in cochlear implant patients and how these results relate to the literature.

In **Chapter 4,** we review the literature and analyse our clinical data to determine whether MRI has any advantage over CT in the assessment of cochlear patency.[60-62] Ideally, one would apply just one imaging modality, preferably one that takes limited scanning time, to obtain all necessary information. This would reduce the need for anesthesia in children and, in due time, would lower costs and save on radiological capacity.

Our results from chapters 2, 3, and 4 enable us to set up a preoperative protocol. In **Chapter 5**, we present our imaging protocol for scanning the temporal bone in cochlear implant candidates. We define a single CT image plane from which all information can be obtained by using multiplanar reformats (MPRs). The reliability of the protocol is tested with studies performed on a cadaver head.

Chapter 6 is devoted to postoperative imaging. At our department, we estimate the position of the electrode array within the cochlea during surgery by counting the inserted electrodes. If there is any doubt about their number or position, a radiograph is made with a Stenvers projection, either during surgery or afterwards. So far, we have found the results of this method to be reliable. However, in view of the considerations in the reviewed literature, we decided to compare our surgical and radiological inventory of electrode insertion depth with the results of postoperative electrode function testing.

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2

Cochlear orientation and dimensions of the facial recess in cochlear implantation

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Abstract

Objective

To study the dimensions of the facial recess and the spatial relationship between the facial recess and the cochlea, using CT scanning in cochlear implantees.

Materials and methods

In 29 cochlear implantees preoperative CT scans of the temporal bone were compared with findings done at surgery. The dimensions of the facial recess and the relationship between the facial recess and the cochlea were both measured on a viewing station and classified on printed films by three blinded and independent reviewers.

Results

No significant relations could be found between either intuitive classification of facial recess width or electrode array insertion feasibility and the measurements with the viewing station. The three reviewers had poor interobserver reproducibility. In five cases, neither intuitive review of the CT scans nor viewing station measurements could predict any of the problems encountered during surgery.

Conclusion

Our findings show that intuitive review was not reliable in classifying facial recess width. Viewing station measurements, in classifying the spatial relation between the facial recess and the cochlear basal turn, need a more detailed review in terms of the relationship with the operation direction and the orientation of the basal turn of the cochlea. Advanced imaging techniques, specifically multislice CT, might improve the diagnostic capabilities.

Keywords

Cochlear implantation; Computed tomography; Temporal bone.

Introduction

A proper insertion of the electrode array is a prerequisite for successful cochlear implantation. To gain access to the promontory a posterior tympanotomy is performed after mastoidectomy. Both the access to the cochlea and the risk of facial nerve damage depend on the width of the facial recess and its position in relation to the basal and middle turn. After the cochleostomy, the electrode array is inserted. The preferred route for the initial course of the electrode array within the cochlea is a continuation of the route towards the cochlea. In that light, the anatomical relations between the orientation of the cochlear basal turn and the facial recess need to be evaluated.

In 1952, Wullstein developed in a canal wall down procedure the access to the meso and hypotympanum via the triangular space between the facial and chorda tympani nerves.[1] Jansen applied this technique with preservation of the posterior bony canal wall, thus creating the “posterior tympanotomy” or “facial recess approach”.[2] This technique provides access to the sinus tympani, visualising the superior and posterior mesotympanum, obtaining better exposure of the tympanic portion of the facial nerve, and gaining access to the pyramidal eminence, stapes, and round window. The space between the mastoid portion of the facial nerve, the tympanic anulus and chorda tympani is called the "facial recess". This area is bounded cranially by the fossa incudis, medially by the descending segment of the facial nerve, laterally by the tympanic anulus, and caudally by the chorda tympani.[3-5]

The space between the facial nerve and the chorda tympani may be small, i.e. less than 2 mm wide. House therefore introduced the concept of the “extended facial recess approach”.[6] In this technique, the chorda tympani is sacrificed. By dissecting between the fibrous anulus of the tympanic membrane and the facial nerve, the hypotympanum is exposed more widely. The size of the posterior tympanotomy increases as the chorda tympani is removed. At the level of the oval window, the extended facial recess is 1 mm wider than the facial recess. The space may be enlarged by 0.8 mm at the level of the round window by removing the chorda tympani.

The otic capsule and the facial recess are mature at birth.[5,7,8] However, the extreme variability in their geometry makes preoperative evaluation necessary.[9,10] The tympanic and mastoid portions of the facial nerve canal can easily be recognised on CT images.[11,12] Using High Resolution CT (HRCT) Parlier-Cuau et al. studied the anatomical relations of the retrotympanum.[13] Pickett et al. discussed the anatomy of the sinus tympani based on dissection and CT.[14] Although both studies review the anatomy of the retrotympanum in detail, they give no information on the relations between the cochlea and the facial recess. Hamamoto et al. studied the topographical relation between the facial nerve, the chorda tympani nerve, and the round window. They concluded that the best approach through the facial recess leads to the basal turn instead of the round window.[15]

Ideally, the surgeon should approach the first, straight part of the basal turn of the cochlea in a longitudinal direction to allow insertion of the electrode as a “straight shot”.[16] To do so the surgeon needs to know the width of the facial recess, but also how the facial recess is related to the basal turn of the cochlea. To our knowledge, no studies have been done on the relation between the posterior tympanotomy and the orientation of the longitudinal axis of the cochlear basal turn. Therefore, we decided to study the dimensions of the facial recess and its position with respect to the cochlea.

Materials and methods

Design

We performed a retrospective study of the dimensions of the facial recess and the spatial relationship between the facial recess and the cochlea. The study was done on preoperative CT scans in cochlear implantees and the outcome was compared with the findings from surgery.

Patients

For this purpose we collected data on 29 patients who had received a cochlear implant at our department from 1992 through 1998. The data consisted of preoperative CT scans of the temporal bone and surgical notes. The dimensions of the facial recess and the relationship between the facial recess and the cochlea were measured on a viewing station and classified on printed films by three blinded and independent reviewers.

CT scans

All CT scans were made in axial planes with 1-1.5 mm contiguous slices using a Tomoscan AV E1 CT scanner (Philips Medical Systems, Best, the Netherlands).

Viewing workstation measurements

The technique for measuring CT data was adopted from Spoor and Zonneveld.[17] All measurements were performed by the same researcher who was unaware of the results of surgery and of the results of intuitive CT scan review. The outcomes of these measurements were taken as the standard.

The chorda tympani nerve could not be identified on the scans. Therefore, we turned our attention to the facial recess, defined as the space between the facial nerve canal and the posterior tympanic anulus. We measured its width at the level of both the oval and the round window. Thus, an extended facial recess was studied.

The centerline of the first, straight part of the cochlear basal turn was identified by connecting the centerpoints of both ends of this part of the basal turn. We assumed that the interpolated centerline of the cochlear basal turn should cross the extended facial recess in order to allow a “straight shot” while introducing the electrodes. The relationship between the centerline of the cochlear basal turn and the facial recess was quantified by measuring the angle between the centerline and a line through the facial recess. The latter line crosses the posterior tympanic anulus and the centerline of the mastoid portion of the facial nerve canal at the level of the cochlear basal turn. The distance between the intercept of both lines and the facial nerve canal was also measured. See fig. 1 for a visualisation of the measurements.

Intuitive CT review

All 29 printed CT films were studied by three separate reviewers (a radiologist, an otorhinolaryngologist, and a resident in E.N.T.). None of them were aware of the results of the measurements or of the surgery. The reviewers were asked to classify the width of the facial recess (small versus larger). They were also asked to assess the feasibility of electrode array insertion with respect to the relation between the basal turn and the facial recess and to classify the feasibility as good or problematic.

Fig. 1. The extended facial recess (thickened line) is defined by the posterior tympanic anulus (small arrow) and the bony facial canal wall (large arrow). The line through the extended facial recess intersects with the centerline of the cochlear basal turn. The angle (double arrowed line) between both lines and the point of their intercept with respect to the facial nerve are considered indicative of the feasibility of electrode array insertion.

Findings at surgery

In each case, the surgical notes on the posterior tympanotomy and the cochleostomy were compared with the results of the CT scan review of the width of the facial recess and its relation to the cochlear basal turn.

Statistical analysis

The results of the measurements were taken as the standard. The width of the facial recess was compared at both levels using the paired samples *t*-test. A 95% confidence interval of the difference (95% CI) was then calculated.

The results of the three reviewers were compared and kappas were calculated to evaluate interobserver reproducibility. Kappa = (% actual agreement - % expected agreement)/(% potential agreement - % expected agreement).

To assess the reliability of intuitive review the results were compared to the standard. Concretely, the individual results and the mean result of the classification of facial recess width were compared to the standard. The analysis was done with independent samples *t*-tests, and 95% CIs were calculated.

The intuitive classifications of electrode array insertion feasibility were also compared with the standard, i.e. the angle between the centerline of the basal turn and the facial recess. The location of their intercept with respect to the facial nerve was evaluated too. Independent samples *t*-tests were applied, and 95% CIs were calculated.

Results

Facial recess width

The mean width of the facial recess as measured at the level of the round window was 4.5 mm, with a standard deviation of 1.3 mm. At the level of the oval window, it measured 5.4 mm, with a standard deviation of 0.9 mm. The facial recess was significantly larger (0.9 mm, with 95% CI of 0.4 to 1.5 mm) at the level of the oval window (paired samples *t*-test: $p < 0.001$).

The individual results and the mean result of intuitive classification of facial recess width were compared to the standard. No significant relations were found between the intuitive classifications of facial recess width and the standard (independent samples *t*-tests: $p > 0.07$): see table 1. There was a small interobserver reproducibility of the three reviewers as expressed in kappas < 0.20.

Relationship between the centerline of the cochlear basal turn and the facial recess

The mean angle between the centerline of the cochlear basal turn and the facial recess was 78.9 degrees, with a standard deviation of 13.3 degrees. The mean distance of the intercept of the centerline and the facial recess towards the facial nerve was 0.92 mm, with a standard deviation of 1.16 mm. Thus, the mean position of the intercept was located in the facial recess.

The intuitive classifications of electrode array insertion feasibility were not significantly related to the angle between the centerline of the cochlear basal turn and the facial recess (independent samples *t*-test: $p = 0.23$). The distance of the intercept of both lines towards the facial nerve bore no significant relation with the intuitive classifications either (independent samples *t*-test: $p = 0.08$): see table 2. The interobserver reproducibility (kappa) in intuitive classification of electrode array insertion feasibility was 0.78 for observer pair 2+3, thus indicating high agreement. Kappa values for the other observer pairs were < 0.00, implying a small degree of interobserver agreement.

Table 1. Measured mean differences (mm) between cases intuitively classified as having a small versus a large facial recess. For each reviewer and for the mean of their classifications, these differences with corresponding p value and confidence interval (95% CI) were calculated on the level of both the round and oval window.

	Reviewer	Mean difference (p value)	95% CI
Round window	1	0.47 (0.56)	-1.2 to 2.1
	2	-0.86 (0.15)	-2.0 to 0.3
	3	-0.31 (0.55)	-1.4 to 0.7
	Mean	-0.88 (0.07)	-1.8 to 0.1
Oval window	1	-0.15 (0.79)	-1.3 to 1.0
	2	-0.17 (0.15)	-1.0 to 0.7
	3	0.03 (0.94)	-0.7 to 0.8
	Mean	-0.50 (0.14)	-1.2 to 0.2

Table 2. Individual and mean results of intuitive classification of electrode array insertion feasibility compared with measurements on CT data. Cases classified as having good versus problematic insertion feasibility were compared with respect to their angle between the centerline of the cochlear basal turn and the facial recess (angle; degrees) as well as to the distance of intercept of these lines towards the facial nerve (intercept; mm). 95% CI = 95% confidence interval.

	Reviewer	Mean difference (p value)	95% CI
Angle	1	-7.9 (0.23)	-21.3 to 5.4
	2	-5.0 (0.62)	-25.3 to 15.3
	3	0.2 (0.98)	-16.8 to 17.2
	Mean	-5.6 (0.32)	-16.9 to 5.8
Intercept	1	0.99 (0.08)	-0.14 to 2.1
	2	-0.29 (0.74)	-2.1 to 1.5
	3	0.39 (0.59)	-1.9 to 1.1
	Mean	0.53 (0.44)	-0.5 to 1.5

Comparison of CT scan review with findings at surgery

All five cases with surgical difficulties are described in table 3. In four patients, the promontory could only be partially visualised, presumably due to a large angle between that structure and the facial recess. Because the number of cases was small, the results could not be subjected to statistical analysis. Nevertheless, the facial recess width, the angle between the cochlear basal turn and the facial recess and the distance of the interception seemed not to differ from the mean values in the total study population. During surgery on case 5, the facial recess width seemed small and the chorda tympani was exposed but not sacrificed. The actual width as measured on the viewing workstation did not differ from the mean values. In three other cases, the chorda tympani was also exposed. In these three cases, however, the facial recess was considered to be wide enough during surgery.

Intuitive review of the CT scans did not predict any of the problems experienced during surgery.

Table 3. All five cases in which during surgery a limited facial recess width (FRW) was found or a difficult spatial relation between the facial recess and the cochlea was encountered. The FRW (at the level of the round/oval window; mm), the angle between the centerline of the cochlear basal turn and the facial recess (angle; degrees), as well as the distance of the interception of both lines towards the facial nerve (interception; mm) were measured on the viewing workstation.

Case	Surgical problem	FRW	Angle	Interception
1	Limited view on promontory	3.9/5.4	81.8	2.20
2	Limited view on promontory	4.5/6.2	74.9	1.50
3	Limited view on promontory	7.0/6.4	93.0	1.90
4	Limited view on promontory	5.3/4.8	100.4	-0.10
5	Limited facial recess width	3.9/6.3	67.5	0.70

Discussion

Using preoperative CT scans, we studied the spatial relation between the facial recess and the cochlear basal turn. The results were compared with findings at surgery. When the outcome of intuitive CT scan review was compared with the standard, i.e. measurements taken at a viewing workstation, it proved that intuitive review is not a reliable method for classifying facial recess width. Nor is it reliable for classifying the spatial relation between the facial recess and the cochlear basal turn. The interobserver reproducibility was poor.

The standard, however, did not help us either in identifying cases with a limited facial recess width or with a difficult spatial relation between the cochlear basal turn and the facial recess. Because the structures of interest are small, the CT resolution and slice thickness (1-1.5 mm) are important confounding factors. They contribute to the relatively large standard deviations of our measurements (0.9 and 1.3 mm in measurements of the facial recess).

Our CT measurements of the extended facial recess showed a mean width of 4.5 mm at the level of the round window and a mean width of 5.4 mm at the level of the oval window. Table 4 shows the results of findings in histological studies. Although our measurements seem larger, the difference between the width of the extended facial recess at both levels is comparable with the results of histology.[5,8,10] The distinctive landmarks we used for measuring were probably not projected in their closest relation, since they were projected respectively in a single CT slice.

Table 4. Results of histologic studies on facial recess width in mm. * Measurement at the level of the pyramidal eminence. ** The results were recalculated.

Study	Cases (n)	Facial recess definition	Measurement level	
			Round window	Oval window
Su [10] *	356	Extended	-	4.01
Bielamowicz [8] **	20	Normal	2.65	3.02
		Extended	3.43	4.01
Young and Nadol [5] **	87	Extended	2.98	3.91

Parlier-Cuau et al. studied anatomical relations in the retrotympanum. They used HRCT with 1.2 mm slices at 1 mm intervals in axial and coronal planes.[13] In 66 temporal bones, they were able to visualise the facial recess up to 80%, with a mean width of 1.6 mm. The obvious differences from our CT study are explained by the way they define the facial recess. They measured the air containing lumen of the recess instead of the distance between the facial nerve canal and the posterior tympanic anulus, including air and bone. Furthermore, they did not report the exact level of measurement.

In our study, the influence of the spatial relation between the facial recess and the basal turn of the cochlea was hard to assess. Goycoolea et al. in contrast, were able to compare the facial recess approach and the combined mastoidectomy/tympanotomy approach with respect to the electrode insertion angles.[18] They found that the number of degrees per mm of bending of the electrode array after its initial straight course in the basal turn depends on the angle of insertion. Thus, when the spatial relation between the cochlear basal turn and the facial recess appears to make insertion difficult, a combined approach is advised to improve accessibility of the cochlea and to decrease the bending of the electrode array.

The diagnostic capability of CT scans depends on the CT technique and on the experience of the reviewers. Our experienced radiologist is used to study preoperative CT and MRI scans in cochlear implant candidates. The ENT surgeon, although not performing cochlear implant procedures himself, is trained in evaluation of temporal bone CT scans for otologic and otoneurosurgical procedures. Finally, the resident has been trained in CT scan reviewing, in preparation for this study and related studies.

Thus, our reviewers had substantial experience in examining CT scans of the temporal bone. Therefore, we expect improvement from advanced imaging techniques, specifically multislice CT.[19] In the future, image-guided surgical navigation might aid in this anatomically complex area, provided that better resolution becomes attainable.[20]

Although our retrospective results suggest that currently preoperative CT scans are of little use with respect to the accurate evaluation of the facial recess and its topographical relationship to the cochlea, we would not advise to abandon preoperative CT. CT remains crucial for review of mainly the anatomy of the mastoid, middle ear, facial nerve and the cochlea with its contents. MRI might add information on the cochlear patency, the cochlear nerve and the anatomy of the central acoustic pathway, from the cochlear nuclei to the temporal acoustic area.[21]

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3

Semilongitudinal and axial CT planes in assessing cochlear patency in cochlear implant candidates

Auris Nasus Larynx, in press

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Abstract

Objective

To investigate how cochlear patency as seen on CT, using axial plus semilongitudinal planes, is correlated with findings at surgery in cochlear implant patients.

Materials and methods

Preoperative CT scans of 45 patients were reviewed by three, independent observers. They classified the cochlear patency and recorded the location of any suspected decreased patency. The results were compared with the findings noted during surgery.

Results

In nine patients a decreased cochlear patency was found at surgery. The sensitivity and specificity of CT assessment were, respectively, 56% - 33% - 11% and 100% - 86% - 94%. The interobserver reproducibility is reflected in a mean kappa of 0.46. The sensitivity increased when only patients suffering from postmeningitic deafness were considered.

Conclusion

Our study suggests that CT scans can be useful in assessing cochlear patency, especially in patients with postmeningitic deafness. This good performance might be explained by the combined use of scans in semilongitudinal and axial planes.

Keywords

Cochlear implants; Computed tomography; Cochlea ossification

Introduction

In cochlear implantation the postoperative auditory perception is related to electrode insertion depth.[1-4] For best results, the surgeon will try to insert the electrode array as far as possible into the cochlea. However, it may be difficult to insert the electrode array when cochlear patency is decreased. This happens in the event of cochlear fibrosis and ossification, for example, which could develop from labyrinthitis caused by meningitis or hematogenic infection.[5-8] But cochlear patency could also decrease as a result of disease of the middle ear (e.g. chronic otitis or cholesteatoma), otospongiosis, fractures, or prior surgery.[9-11]

Before operating, the surgeon should have adequate information on the patency of the cochlea. It is then easier to anticipate the difficulties that might arise during surgery. If necessary, the surgeon can then consider other ways to insert the electrode array as far into the cochlea as possible. To obtain that information, 2-D or 3-D CT and MRI can be used.

We have reviewed the literature on CT that relates to surgical findings in cochlear implantees. The pertinent studies are listed in table 1, along with a summary of the most salient results. [5,12-24] We then proceeded to recalculate the data on cochlear patency. For our purposes, round window ossification is not regarded as a cochlear obstruction, since it is now common practice to perform a cochleostomy at the promontory. Our calculations indicate a moderate overall sensitivity of 64% (range: 41 to 100%) with an overall specificity of 98% (range: 50 to 100%). Of course, when comparing diagnostic studies, any differences that come to light must be carefully evaluated. The discrepancies may be related to the technology and methods used, the investigator’s experience in interpreting anatomy, the composition of the study population, and other factors.[25]

So far, CT imaging has been only moderately useful as a diagnostic tool, though that capability might improve with technological progress. Meanwhile, clinicians can use other imaging procedures to find out precisely what they need to know. Concretely, by selecting different scanning planes, they can obtain information that would otherwise have gone unnoticed. Taking that strategy in our department, we use axial and semilongitudinal CT planes, the latter having been introduced by Zonneveld et al. and Damsma et al.[26,27]

In this study, we investigate how cochlear patency as seen on axial plus semilongitudinal CT planes is correlated with findings at surgery in cochlear implant patients. Furthermore, we compare the CT assessment of a radiologist, an ENT surgeon and an ENT resident.

Table 1. Summary of studies on sensitivity and specificity of CT in assessment of cochlear patency in cochlear implantees. *Patients were selected on the basis of cochlear obstruction during surgery. ** Results are for attending and senior radiologists respectively. These results could not be included in the overall results.

Author	Year	Slice thickness (mm)	Patients (n)	Meningitis (%)	Sensitivity (%)	Specificity (%)
Jackler [12]	1987	1.5	36	22	54	100
Balkany [13]*	1988	-	15	47	79	100
Wiet [14]	1990	1.5	26	-	73	100
Klein [15]	1992	1	40	-	0	100
Bath [16]	1993	1	26	81	58	71
Parisier [17]	1993	1	22	100	42	100
Frau [18]**	1994	1.5	81	37	67/91	100/90
Seidman [19]	1994	1.5	81	40	41	98
Johnson [5]	1995	1.5-2	13	100	82	50
Langman [20]	1995	1.5	28	14	100	86
Silberman [21]	1995	1.5	17	41	50	100
Luetje [22]	1997	-	43	-	61	100
Axon [23]	1998	-	32	100	72	93
Nair [24]	2000	1.5	335	26	70	100

Materials and methods

Design

We performed a retrospective study of the cochlear patency assessed by preoperative CT scanning in the axial and semilongitudinal planes and compared the results in cochlear implantees with the findings at surgery.

Patients

For this purpose, 46 cochlear implantees (30 adults, 16 children), were selected on the basis of availability of their preoperative CT scans. The causes of their deafness are listed in table 2.

Table 2. Causes of deafness in the study population.

Cause	Adults	Children
Meningitis	11	4
Congenital hearing loss of unknown cause	-	6
Otosclerosis	5	-
Progressive hearing loss of unknown cause	4	-
Genetic; hearing loss of unknown cause	4	-
Usher's syndrome	-	2
Waardenburg's syndrome	-	1
Cogan's syndrome	3	-
Hearing loss of unknown cause	1	2
Rubella AD/progressive hearing loss of unknown cause AS	1	-
Sudden deafness	-	1
Chronic otitis	1	-
Total	30	16

CT scans

Preoperatively, patients were scanned in axial and semilongitudinal planes with 1-1.5 mm contiguous slices using a Tomoscan AV E1 CT scanner (Philips Medical Systems, Best, the Netherlands). Theoretically, the semilongitudinal CT plane has the advantage of an excellent visualisation of the basal and second turns of the cochlea. Moreover, it visualises the surgical pathways to the middle ear in both the endaural and the transmastoidal approach (see fig. 1).

For the semilongitudinal plane, the patient was in a prone position with the head in a coronal headrest. The table was swiveled 20° in such a way that the homolateral shoulder was closest to the patient aperture cone; see fig. 2 for a diagram of patient positioning and orientation of the scan plane.[28] The semilongitudinal plane thus makes a 20° angle with the coronal plane. The axial plane intersected the nasion and the superior margins of the external acoustic meati.

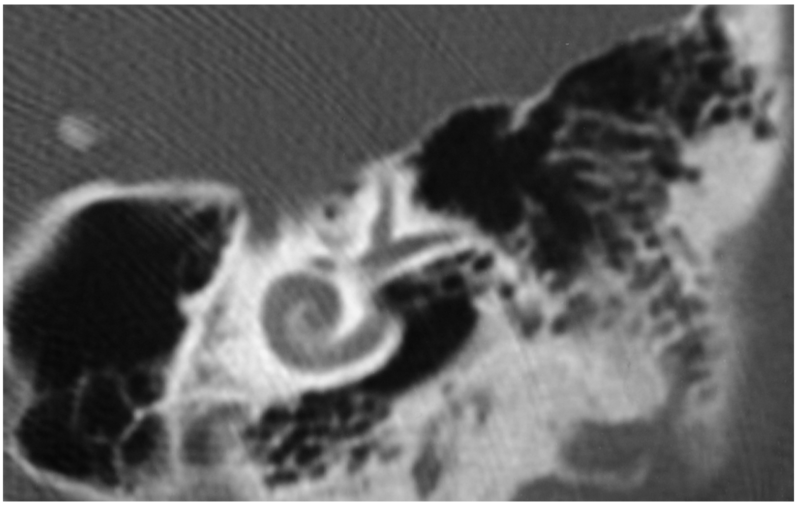

Fig. 1. Preoperative CT scan in the semilongitudinal plane of the left temporal bone, visualising the cochlea and the transmastoidal route of surgery.

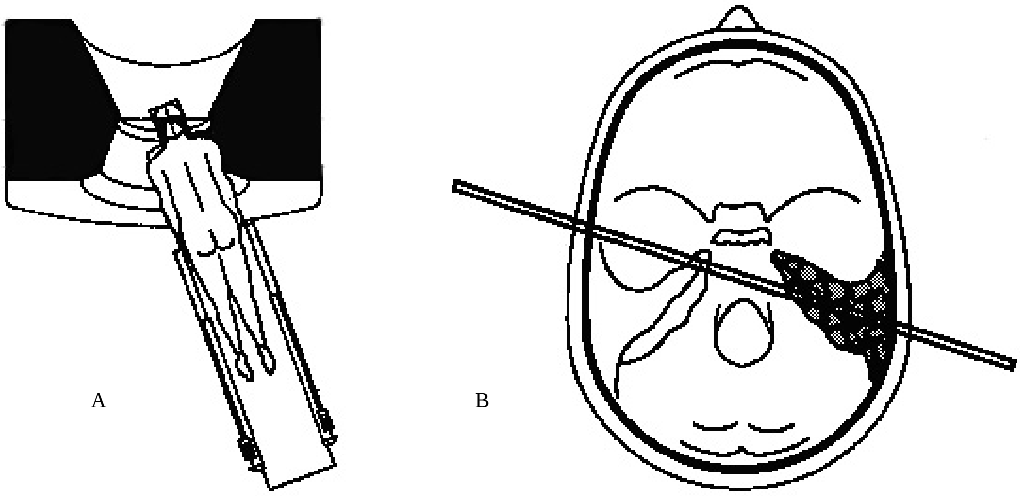

Fig. 2. Patient positioning for examination of the temporal bone in the semilongitudinal plane (modified after Zonneveld [28]).

A. Patient position, table swivel, and gantry position

B. Scan plane orientation

CT scan review

All printed CT scans were independently reviewed, in random order, by a senior ENT surgeon, an ENT resident, and a senior radiologist. This was done to calculate the interobserver reproducibility, as well as to compare the diagnostic capabilities. The reviewers were not aware of the etiology of deafness or the results of surgery in the study population. They classified the cochlear patency as either normal or disturbed. If they found any abnormality, they recorded the location of the suspected decreased patency. The results of the CT reviews were compared with the findings noted during surgery.

Findings at surgery

All patients were operated on by the same surgeon. After mastoidectomy, a posterior tympanotomy was performed to gain access to the middle ear and promontory. With a cochleostomy at a distance of approximately 1 mm anterior to the round window, the scala tympani was opened. A MED-EL (C40 or C40+) or a Nucleus (CI24M or CI22M) implant was inserted. The MED-EL implants have an array thickening, which should be located near the cochleostomy. In contrast, the Nucleus implants have support electrodes, all of which should be inserted. When recording the surgical findings, note was made of any cochlear obstructions discovered, any need for drilling in order to find cochlear lumen, and the number of electrodes inserted. The findings recorded during surgery constituted the reference standard.

Statistical analysis

To allow comparison with the literature, we calculated the sensitivity and specificity of the CT scans used to assess cochlear patency. Predictive values were computed as well. To estimate interobserver reproducibility, we calculated kappa values which are chance-corrected measures of agreement. Kappa = (% actual agreement - % expected agreement)/(% potential agreement - % expected agreement).

Results

We were able to analyse the data on 45 patients. One had to be left out because the cochlea could not be found during surgery. In that particular case, postoperative imaging showed a drilling route tangential to the cochlea running towards the carotid artery.

Table 3 tabulates the sensitivity, specificity, and predictive values of the CT review with respect to cochlear patency. The interobserver reproducibility is reflected in a mean kappa of 0.46 (range: 0.29 - 0.38 - 0.72).

Table 3. Sensitivity, specificity, and predictive values of axial and semilongitudinal CT in assessing cochlear patency in 45 patients.

	Sensitivity (%)	Specificity (%)	+ Predictive value (%)	- Predictive value (%)
Radiologist	56	100	100	90
ENT resident	33	86	38	84
ENT surgeon	11	94	31	81

The sensitivity and positive predictive value obtained by the ENT resident increased to a more useful level when only patients suffering from postmeningitic deafness were considered. This increase can be seen in table 4 where the sensitivity, specificity, and predictive values of the CT review in all cases of postmeningitic deafness are tabulated. Although the ENT surgeon obtained similar results compared to the resident in the total study population, the sensitivity and positive predictive value dropped to 0% in the post-meningitic subgroup.
For the radiologist both predictive values were high, both in the total study population as well as in the subgroup containing only postmeningitic deafened cases.

Table 4. Sensitivity, specificity, and predictive values of axial and semilongitudinal CT in assessing cochlear patency in 14 cases of postmeningitic deafness.

	Sensitivity (%)	Specificity (%)	+ Predictive value (%)	- Predictive value (%)
Radiologist	60	100	100	82
ENT resident	60	89	76	80
ENT surgeon	0	89	0	61

Table 5 describes all patients in whom cochlear patency was found to be compromised at surgery. In nine out of the 45 cases, some amount of drilling was required before the surgeon could insert the electrode array. For five out of the nine patients in whom decreased cochlear patency was found at surgery, the cause of deafness was meningitis.

Table 5. Findings on CT in all patients with compromised cochlear patency as diagnosed at surgery. TP = true positive, FN = false negative.

CT score			Cause of deafness	Surgery
ENT resident	Radiologist	ENT surgeon		
TP	TP	FN	Meningitis	Basal turn obstruction; extended drilling. Partial insertion
TP	TP	FN	Meningitis	Basal + middle turn obstruction; extended drilling. Partial insertion
TP	TP	FN	Meningitis	Basal turn obstruction; extended drilling. Partial insertion
FN	FN	FN	Meningitis	Basal turn obstruction; drilling. Full insertion
FN	FN	FN	Meningitis	Basal turn obstruction; extended drilling. Partial insertion
FN	TP	FN	Otosclerosis	Basal turn obstruction; extended drilling. Full insertion
FN	TP	FN	Sudden deafness	Basal turn obstruction; extended drilling. Partial insertion
FN	FN	TP	Genetic hearing loss of unknown cause	Basal turn partition; no drilling. Full insertion
FN	FN	FN	Cogan's syndrome	Basal turn obstruction; extended drilling. Partial insertion

Discussion

We studied the extent to which the assessment of cochlear patency with CT scanning in the axial and semilongitudinal planes corresponds to the findings at surgery in cochlear implantees.

The results of the assessment of cochlear patency with CT scans, as reviewed by three independent observers (sensitivity 56% - 33% - 11%; specificity 100% - 86% - 94%), are comparable with the results reported in the literature, as summarised in Table 1.[5,12-24] A mean kappa of 0.46 signifies adequate interobserver reproducibility. In the majority of patients in our study, the cause of deafness was meningitis (15/45), congenital deafness (6/45), or deafness due to otosclerosis (5/45).

The sensitivity and specificity of CT depend on the prevalence of some disturbance in cochlear patency such as fibrosis and ossification. This prevalence is higher in post-meningitic deafness.[5-8] Therefore, we would expect to find an increase in sensitivity and specificity in the assessment of these patients. Table 6 presents the salient outcomes of all previous studies dealing exclusively with postmeningitic deafness.[5,12,16,17,19,23] The overall CT sensitivity of these studies is 54% (range: 32-82%), with an overall specificity of 84% (range: 0-100%). These results suggest a poor predictability of cochlear obstruction using CT in cases of postmeningitic deafness. CT was considered to be most useful in those cases without meningitis.[29] However, our results improved when we restricted the analysis to cases of postmeningitic deafness (sensitivity 60% - 60% - 0%; specificity 100% - 89% - 89%).

Table 6. Studies on sensitivity and specificity of CT in assessing cochlear patency in cochlear implantees with postmeningitic deafness.

Author	Year	Slice thickness (mm)	No. of patients	Sensitivity (%)	Specificity (%)
Jackler [12]	1987	1.5	8	63	0
Bath [16]	1993	1	21	58	56
Parisier [17]	1993	1	22	42	100
Seidman [19]	1994	1.5	32	32	100
Johnson [5]	1995	1.5-2	13	82	50
Axon [23]	1998	-	32	72	93

Other causes of cochlear obstruction, e.g. otosclerosis, have not been studied in enough patients to justify quantitative analysis. Our study included five patients with otosclerosis and only one with an apparent cochlear obstruction.

Our study suggests that CT scans can be useful in assessing cochlear patency, especially in patients with postmeningitic deafness. This good performance might be explained by the combined use of scans in semilongitudinal and axial planes. Nevertheless, CT scans do not discriminate sufficiently between obstructions and fluid at the level of the cochlea.[11,19] In a study similar to ours, Bath et al. demonstrate how High Resolution CT can underestimate the degree of cochlear obstruction, resulting in serious postoperative complications.[16] The customary slice thickness of 1-1.5 mm is wider than the intracochlear structures, resulting in partial volume effects. Consequently, the relatively poor resolution complicates the interpretation of the image. It is hard to assess the intracochlear fluid on printed film, due to the slight differences in attenuation coefficient between fluid (0-10 Hounsfield Units) and soft tissue (40-50 Hounsfield Units).[5,15] More information could have been obtained using a viewing station that allowed the window's width and level to be adjusted. In the future, multislice techniques might improve the diagnostic capability of CT.[30]

An alternative approach is to use T_2-weighed MRI images, as they can clearly show the endolymphatic and perilymphatic spaces in particular. In theory, they could thus allow the observer to differentiate between fluid and fibrotic occlusions.[21] On the other hand, MRI is said to be inferior to CT in diagnosing cochlear otosclerosis.[29,31] In that light, we plan to investigate whether MRI has any advantage over CT.

In most previous studies, the results of CT were only expressed in terms of sensitivity and specificity. However, predictive values are actually more suitable for establishing the usefulness of diagnostic procedures. Considering the predictive values, our radiologist with large experience in the assessment of cochlear patency with CT had excellent scores. Moreover, in cases of postmeningitic deafness, the predictive values of CT remained excellent. For the ENT surgeon and resident the positive predictive values in the total study population were mediocre. This might be explained by lack of routine in CT assessment of the cochlear patency. In order to avoid bias we did not select the experienced cochlear implant surgeon to assess the cochlear patency on CT retrospectively. Furthermore, although our study population consisted of 46 cases, only nine cases with compromised cochlear patency were encountered. Misjudgement of only a few cases thus results in a strong decline of the sensitivity and positive predictive value.

Conclusion

Axial and semilongitudinal CT planes are useful in assessment of the cochlear patency in cochlear implant candidates. Furthermore, this method is reliable in cases deafened due to meningitis. Experience in CT assessment of the cochlear patency improves the result.

Acknowledgement

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4

MRI versus CT in assessment of cochlear patency in cochlear implant candidates

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Abstract

Objective

To investigate how cochlear patency as seen on preoperative CT and MRI scans correlates with findings at surgery in cochlear implant patients.

Materials and methods

CT and MRI scans of 25 patients were reviewed by three independent observers. The reviewers classified the cochlear patency and recorded the location of any suspected decrease in patency. Their results were compared with the findings noted during surgery.

Results

Decreased cochlear patency was found in six patients at surgery. The mean sensitivity/specificity of CT and MRI assessment was respectively 33%/88% and 41%/91%.

Conclusion

Our study suggests that CT, using axial and semilongitudinal planes, is equivalent to MRI in predicting cochlear patency.

Keywords

Cochlear implants; Cochlea ossification; CT; MRI.

Introduction

In cochlear implantation, the number of inserted electrodes determines the postoperative performance.[1] Several disorders, such as labyrinthitis, meningitis, otosclerosis, temporal bone fractures and prior surgery, may decrease the cochlear lumen, thus limiting the electrode insertion depth.[2-5] Therefore, cochlear patency is preoperatively investigated with CT and/or MRI.

Slice-to-slice CT scans have some shortcomings. In particular, they do not adequately discriminate between obstructive fibrotic scar-tissue lesions and cochlear fluid for several reasons.[4,6] Firstly, The customary slice thickness of 1-1.5 mm is wider than the intracochlear structures, resulting in partial volume effects. Consequently, the relatively poor resolution complicates the interpretation of the image. Finally, it is difficult to establish the presence of intracochlear fluid due to small differences in attenuation between fluid (0-10 Hounsfield Units (HU) and soft tissue as found in fibrosis (40-50 HU).[2,7]

Endolymphatic and perilymphatic spaces can be visualised with T_2-weighted MRI. In theory, this makes it possible to differentiate between fluid and fibrotic occlusions.[8] However, for visualising disorders associated with bone transformation, such as cochlear otosclerosis, MRI is inferior to CT.[9,10]

The limited body of literature on the possible superiority of MRI in predicting cochlear patency is inconclusive.[8,11,12] Although the specificity of both MRI and CT was 100% in all subpopulations, Klein et al. and Silberman et al. demonstrated a better sensitivity of MRI compared to CT.[7,8] However, neither Seitz et al. nor Ellul et al. could establish any difference between these imaging modalities in assessing cochlear patency.[11,12]

Until now, both MRI and CT have been performed at our department as part of the diagnostic work up of candidates for cochlear implantation. We wondered whether MRI was actually required in addition to CT in the assessment of cochlear patency. Therefore, we analysed the preoperative CT and MRI findings in cochlear implantees and compared these with findings at surgery.

Materials and methods

Design

We performed a retrospective study of cochlear patency, as assessed with preoperative CT and MRI scans in cochlear implantees. Patency was judged independently by three reviewers who were unaware of the surgical findings. Their judgements were compared with the findings at surgery.

Materials

We selected 25 cochlear implantees on the grounds of the availability of their preoperative CT and MRI scans. The causes of their deafness are listed in Table 1.

Table 1. Causes of deafness in the study population.

Cause	n
Meningitis	8
Otosclerosis	4
Cogan’s syndrome	3
Genetic hearing loss of unknown cause	2
Progressive hearing loss of unknown cause	2
Unknown	2
Usher’s syndrome	1
Recurrent otitis	1
Congenital hearing loss of unknown cause	1
AD Rubella /AS progressive hearing loss of unknown cause	1
Total	25

CT scans

Preoperatively, the patients were scanned in axial and semilongitudinal planes with 1-1.5 mm contiguous slices using a Tomoscan AV E1 CT scanner (Philips Medical Systems, Best, the Netherlands). The semilongitudinal CT plane was introduced by Zonneveld et al. and Damsma et al.[13,14] Theoretically, this plane has the advantage of providing an excellent visualisation of the basal and second turns of the cochlea. For the semilongitudinal plane, the patient was in a prone position with the head in a coronal headrest. The table was swivelled 20° in such a way that the homolateral shoulder was closest to the patient aperture cone.[15] The semilongitudinal plane thus makes a 20° angle with the coronal plane. The axial plane intersected the nasion and the superior margins of the external acoustic meati.

MRI scans

Twenty-one patients were scanned with T_2-weighted Turbo-Spin-Echo 3D MRI and reconstructed with slices of 1 mm and an overlap of 0.5 mm and a magnetic field strength of 1.5 T, using a Gyroscan ACS NT scanner (Philips Medical Systems, Best, the Netherlands). Four early patients were scanned using slices of 2-2.5 mm and overlaps of 0.2-1 mm.

CT and MRI scan review

All printed CT and MRI scans were independently reviewed, in random order, by an ENT resident, a senior ENT surgeon, and a senior radiologist. The reviewers were not aware of the cause of deafness or the findings at surgery. They were asked to classify the cochlear patency as “normal” or “compromised”. If any abnormality was found, the location of the suspected decrease in patency was to be indicated. The results of the scan reviews were compared with the findings at surgery.

Findings at surgery

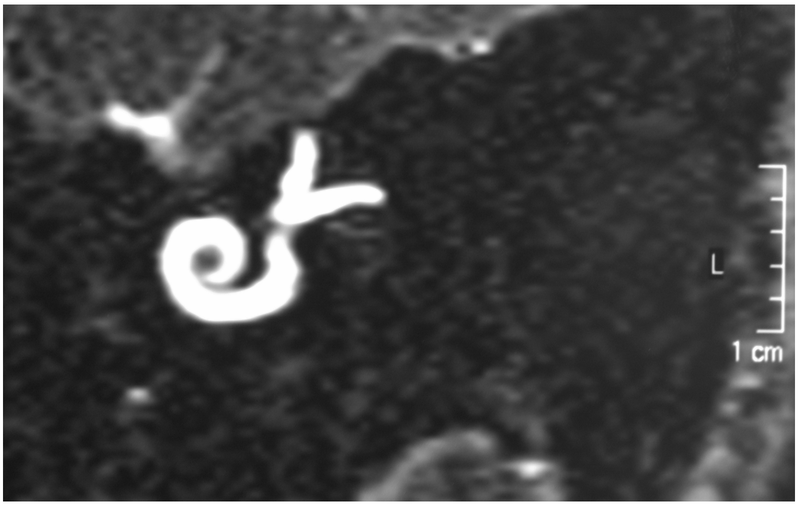
All patients were operated on by the same surgeon. After mastoidectomy, posterior tympanotomy was performed to gain access to the middle ear and promontory. Cochleostomy at a distance of approximately 1 mm anterior to the round window opened up the scala tympani. A MED-EL (C40 or C40+) or a Nucleus (CI24M or CI22M) implant was inserted. The MED-EL implants have an array thickening, which should be located near the cochleostomy hole. In contrast, the Nucleus implants have support electrodes, all of which should be inserted. When recording the surgical findings, note was taken of any cochlear obstructions, the need for drilling in order to find cochlear lumen, and the number of inserted electrodes. The findings during surgery constituted the standard.

Statistical analysis

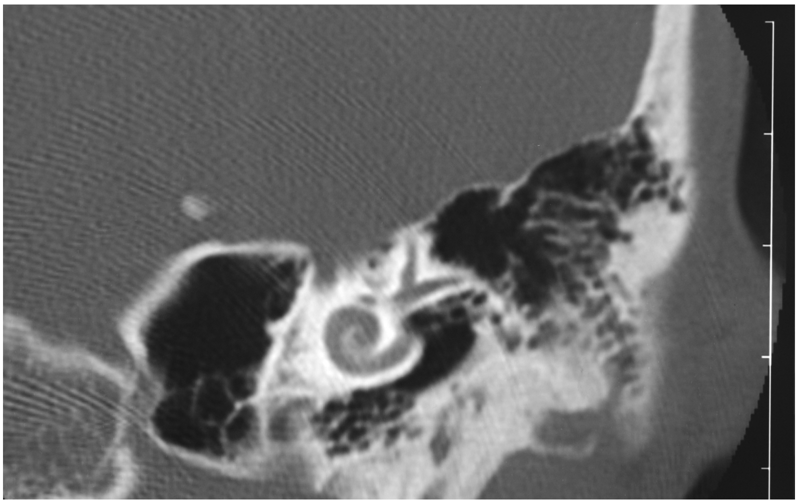
The results of the review of CT and MRI scans were expressed as rates of sensitivity and specificity, thereby allowing comparison with the literature.

Results

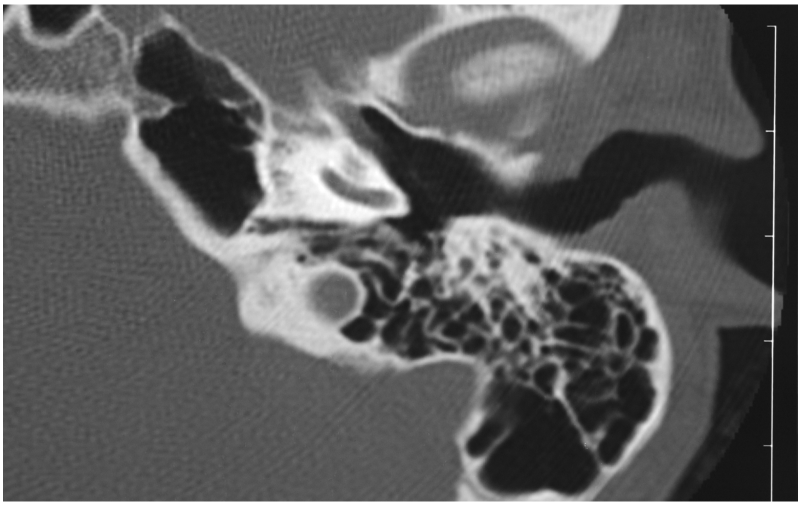
Fig. 1 shows images of a normal patent cochlea as seen with MRI and CT. The MRI and CT images made in the semilongitudinal plane enable visualisation of the basal and second turns of the cochlea. The axial CT image provides an overview of the temporal bone.



1A



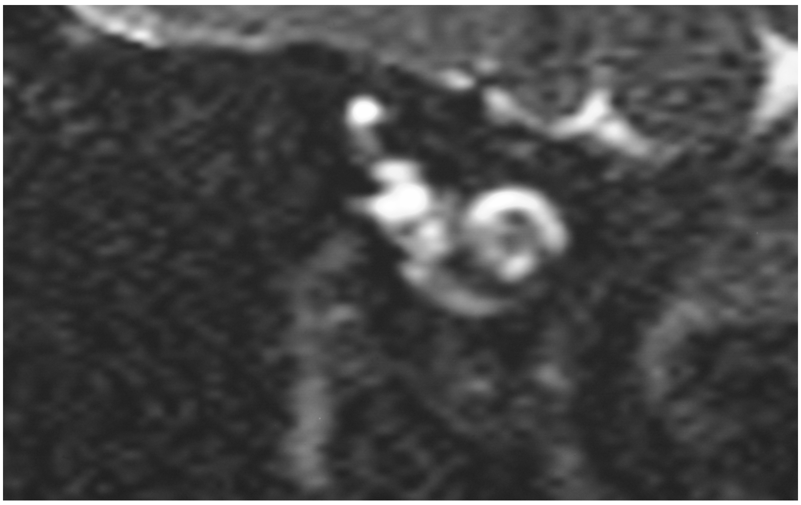
1B



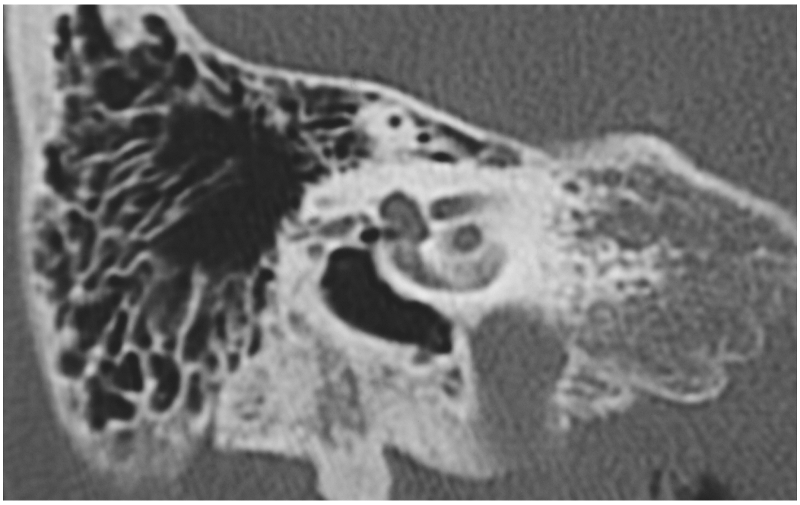
1C

Fig. 1. A normal patent cochlea as seen on MRI (A) and CT (B and C). The MRI (A) and CT (B) images made in the semilongitudinal plane provide visualisation of the basal and second turns of the cochlea. The axial CT image (C) provides for an overview of the temporal bone.

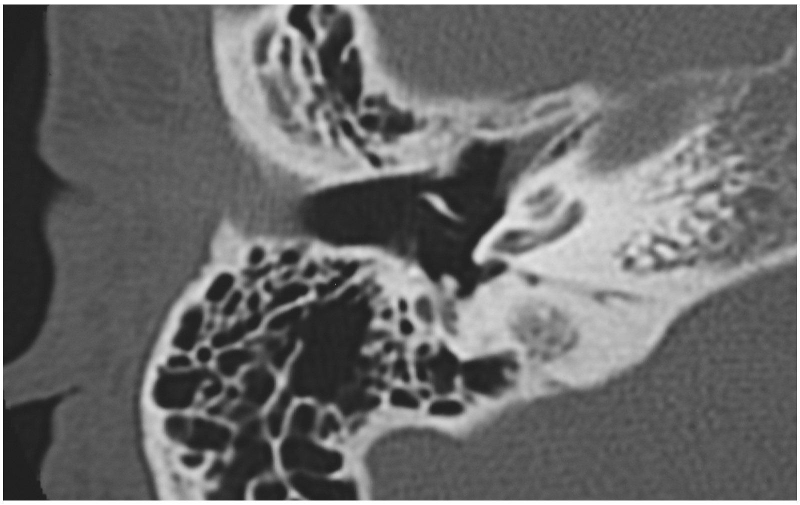
In fig. 2 a patient, deafened as a result of meningitis, with obstruction of the cochlea is presented, as seen with both CT and MRI. At surgery the obstruction was confirmed.



2A



2B

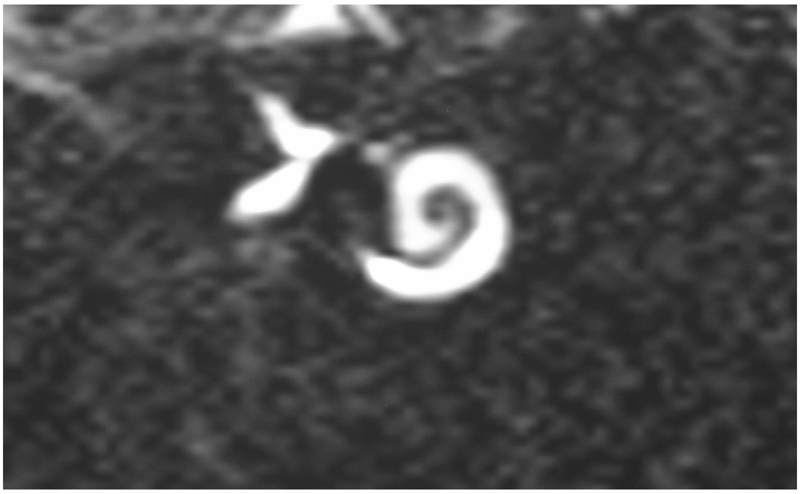


2C

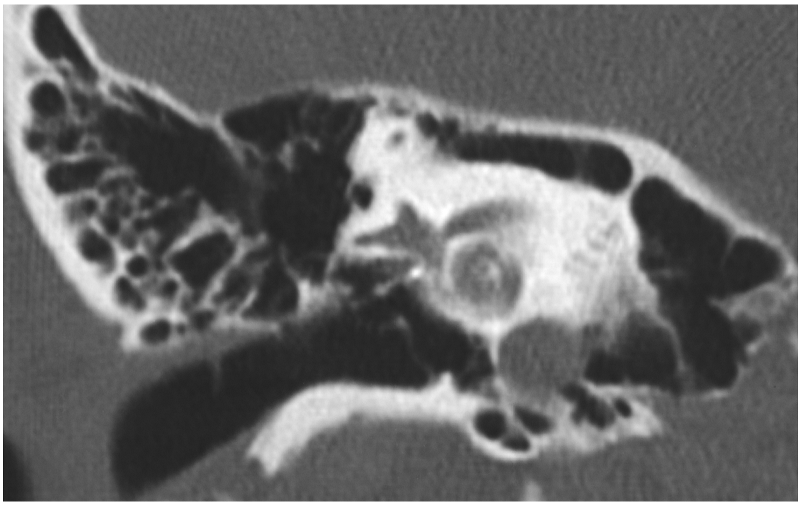
Fig .2. In a case deafened as a result of meningitis cochlear obstruction is seen on both MRI (A) and CT (B and C).

In contrast, fig. 3 represents a case with otosclerosis, in which MRI indicates a patent cochlea whereas CT suggests basal turn obstruction. Although the surgeon was not hampered by cochlear obstruction, the electrode array could not be inserted completely. Six support electrodes remained outside the cochlea.

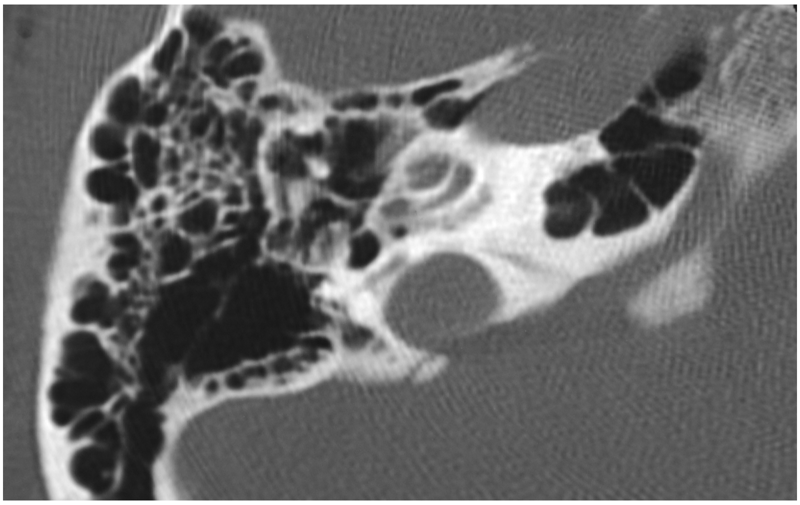
Fig. 3 (opposite page). In a case with otosclerosis in whom MRI (A) indicates a patent cochlea, CT (B and C) suggests basal turn obstruction. At surgery no cochlear obstruction was found, although the electrode array could not be inserted completely.



3A



3B



3C

The sensitivity and specificity of CT and MRI in predicting cochlear patency for all the reviewers are shown in Table 2. The specificity of CT and MRI in predicting cochlear patency turned out to be similar: 88% and 91%, respectively. Their mean sensitivity was comparable too, being 33% and 41%, respectively.

Table 2. Sensitivity and specificity of CT and MRI in predicting cochlear patency.

	CT		MRI	
	Sensitivity (%)	Specificity (%)	Sensitivity (%)	Specificity (%)
ENT resident	33	74	50	79
ENT surgeon	16	89	40	95
Radiologist	50	100	33	100
Mean	33	88	41	91

In six patients, the cochlear lumen was found to be compromised at surgery. These cases are classified in Table 3 as true-positive or false-negative results and are individually described. Of the six cases with decreased cochlear patency, there was only one instance (the patient with otosclerosis) of a discrepancy between the CT and MRI assessments of the ENT resident and the radiologist. The assessments of the ENT surgeon were discrepant in three cases of decreased patency. For the three reviewers as a whole, there were five reviews of CT and MRI scans (in four afflicted cases) in which the outcomes diverged: CT gave two true-positive diagnoses, whereas MRI diagnosed correctly in three cases.

Discussion

The diagnostic capabilities of CT and MRI for assessing cochlear patency in cochlear implantees were compared by retrospective assessment of preoperative scans by three independent reviewers. CT and MRI had a similar mean specificity in predicting cochlear patency: 88% and 91%, respectively. The mean sensitivity of CT and MRI was also comparable: 33% and 41%, respectively.

Theoretically, MRI is indicated for soft-tissue obstructions, whereas CT is better suited for the diagnosis of bony lesions in the cochlea. Unfortunately, we were unable to corroborate this “rule”. In our patients, the causes of deafness (meningitis, otosclerosis and Cogan's syndrome) are known to give rise to both bony and soft-tissue cochlear obstructions.[2,3,16] At surgery, however, we only found cases with bony obstructions in the cochlea.

Table 3. Findings on CT and MRI in six patients with compromised cochlear patency as diagnosed at surgery. TP = true-positive, FN = false-negative. * MRI with 2.5 mm slices and 0.3 mm table increments.

CT/MRI score			Cause of deafness	Surgery
ENT resident	ENT surgeon	Radiologist		
FN/FN	TP/FN	FN/FN	Genetic of unknown cause	Basal turn partition; no drilling. Full insertion
FN/TP	FN/FN	TP/FN	Otosclerosis	Basal turn obstruction; extended drilling. Full insertion
FN/FN	FN/FN	FN/FN	Cogan’s disease*	Basal turn obstruction; extended drilling. Partial insertion
TP/TP	FN/TP	TP/TP	Meningitis	Basal turn obstruction; extended drilling. Partial insertion
FN/FN	FN/TP	FN/FN	Meningitis	Basal turn obstruction; extended drilling. Full insertion
TP/TP	FN/FN	TP/TP	Meningitis*	Basal + middle turn obstruction; extended drilling. Partial insertion

In contrast to the findings reported in previous studies, we did not see any evident advantages of MRI over CT for assessing cochlear patency.[7,8] In an earlier study, in which we investigated the diagnostic capability of CT, we found a similar rate of sensitivity and specificity for predicting cochlear patency.[17] When the analysis was restricted to cases with deafness after meningitis, the sensitivity of CT improved.

We suggest that the reason why CT was not found to be inferior to MRI lies in the use of the semilongitudinal plane in addition to the standard axial plane. CT using axial and semilongitudinal planes seems to be equivalent to MRI in predicting cochlear patency.

MRI is used not only to evaluate cochlear patency but also to establish the presence of the cochlear nerve. It should be noted that this can also be done on CT images, assuming that a normal cochlear nerve canal is only formed in the presence of a normal cochlear nerve.[18-

[21] In contrast, the size of the internal auditory canal may be normal in the absence of the cochlear nerve.[20,22]

CT is always needed to obtain information on mastoid and middle-ear anatomy. However, we suggest that, in those cases with a cause of deafness well known to be located outside of the central acoustic pathway, MRI could be omitted from the preoperative work up routine. Doing so would reduce the need for anaesthesia during the diagnostic work up, especially in young children. Furthermore, omitting MRI from the work up would save time, money and radiologic capacity.

In those cases with a possibility of central nervous system disease, MRI is mandatory to investigate the anatomy of the central acoustic pathway, from the cochlear nuclei to the temporal acoustic area.[23]

We should point out that the image quality is constantly improving in both MRI and CT. The slices keep getting thinner, and multislice CT, for example, allows for multiplanar reformats in all directions without loss of image quality. Furthermore, because multislice CT is fast, this modality reduces motion artefacts, making it more useful for children. Another example is functional MRI, which visualises and tests the central auditory pathway in response to auditory stimuli.[24] In this way, new, useful criteria can be added for the selection of cochlear implant candidates.

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5

Preoperative imaging protocol for cochlear implant candidates

Acta Otolaryngologica (Stockholm), in press

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Abstract

Objective

To formulate and test a CT imaging protocol for preoperative scanning of the temporal bone in cochlear implant candidates.

Materials and methods

A human head was scanned in three CT planes: axial, axiopetrosal, and semilongitudinal. Multiplanar reformats (MPRs), based on axial slices, were created and compared with the corresponding images obtained by direct scanning in the respective planes. All scans were analysed on a viewing workstation.

Results

The axial plane allowed for an overview of the temporal bone. The facial recess width and the cochlear nerve canal could be studied on combined axial and axiopetrosal images. The cochlear patency could be evaluated with combined axial and semilongitudinal images. Axiopetrosal and semilongitudinal MPRs could replace the images that were obtained by direct scanning in the respective planes.

Conclusion

The combination of the axial CT plane and MPRs was found to be sufficient for preoperative analysis of the temporal bone morphology.

Keywords

Cochlear implantation; Computed tomography; Multiplanar reformat.

Introduction

In the preoperative work up for cochlear implantation, the surgeon studies the morphology of the patient's temporal bone as visualised by both CT and MRI. Attention is given to variation in the position of surgical landmarks, particularly that of the short incudal process, the vertical part of the facial nerve, the chorda tympani, the oval window, and the round window. Variations might be encountered in the morphology of the facial nerve, the chorda tympani, the jugular bulb, and the thickness of the parietal bone; congenital malformations of the middle and inner ear and abnormalities due to previous surgery might also be encountered.[1-19]

The distance between the facial canal at the level of the eminentia pyramidalis and the posterosuperior margin of the tympanic anulus, known as the extended facial recess, determines the space for performing a posterior tympanotomy.[20]

Initially, the course taken when inserting the electrode array into the cochlea is in line with the basal turn. Thus, the relations between the position of the cochlear basal turn and that of the posterior tympanotomy pathway must be evaluated.[20]

Prior to insertion of the electrodes, the bony structures should be identified, but so should other features: cochlear patency and the presence of the cochlear nerve should be checked as well.[21,22] For instance, in patients with congenital deafness, the cochlear nerve may be hypoplastic or even absent. In such cases, where there are too few nerve fibers or none at all, cochlear implants will be of no benefit. Several of these cases have been reported, demonstrating the importance of a preoperative evaluation of cochlear nerve presence.[23,24]

It is difficult to assess the diameter of the nerve; this requires better CT and MRI resolution than is currently available.[25] Yet CT images do allow us to judge the width of the internal auditory canal. However, the internal auditory canal may be normal in size even when the cochlear nerve is absent.[26,27] The presence of the cochlear nerve is readily assessed by combining MRI with gradient-echo techniques.[26,28-32] However, its presence may also be ascertained on CT images, based on the assumption that a normal cochlear nerve must be present if the cochlear nerve canal is normal.[26,33-35]

At our department, CT has been part of the preoperative work up since 1985; we always use CT to study the temporal bone anatomy. Later on, MRI was added to the work up because it was supposedly more reliable for assessing disorders of the cochlear nerve as well as cochlear patency. Nonetheless, our study of the value of CT and MRI in assessing cochlear patency showed no clear advantage of MRI as compared to CT using both axial and semilongitudinal planes.[21] We therefore concluded that it was justified to use only CT in the preoperative imaging process.

Consequently, we decided to formulate a CT imaging protocol for cochlear implant candidates. Ideally, we would apply just one imaging modality, preferably one that takes limited scanning time, to obtain all the necessary information. As a result of limiting the imaging procedures to CT, there would be less need for anesthesia in children, and in due time the costs would decline and radiological capacity would be saved.

In this paper, we present our CT imaging protocol for preoperative scanning of the temporal bone in cochlear implant candidates. We have defined a single image plane from which we could obtain all necessary information when using multiplanar reformats (MPRs). The reliability of the protocol was tested by performing studies on a cadaver head.

Materials and methods

Material

A fresh human cadaver was decapitated with the head hanging down to prevent leakage of blood and cerebrospinal fluid. The veins, arteries, and cerebrospinal fluid compartment were ligated. The head then was transported to the CT scanner.

Computed Tomography

A Tomoscan AV E1 CT scanner (Philips Medical Systems, Best, the Netherlands) was used to scan the head in three planes; these have been extensively described by Zonneveld.[36] We selected these particular planes because they provide excellent visualisation of the structures of interest. The scan slices were 1 mm in thickness with an overlap of 0.5 mm. Multiplanar reformats, based on axial slices, were created and compared with the corresponding images obtained by direct scanning in the respective planes.

Scan planes

Direct scans were made in the following planes:

Axial plane. This plane intersects the nasion and the superior margins of the external acoustic meati, visualising most of the anatomic details.

Semilongitudinal plane. For scanning in the semilongitudinal plane, the imaginary body was in a prone position; the actual head was in a coronal headrest. The table was swiveled 20° in such a way that the imaginary homolateral shoulder was closest to the aperture cone. The semilongitudinal plane thus forms a 20° angle with the coronal plane.[37] The cochlear basal turn as well as the surgical pathways to the middle ear are particularly well visualised in this plane.

Axiopetrosal plane. The imaginary body was in a prone position, exactly as for the coronal plane. However, the table was swiveled 20° in such a way that the imaginary contralateral shoulder was closest to the aperture cone. Furthermore, a special swiveled headrest added an extra rotation of 20°, adding up to a total difference of 40° with respect to the coronal position. The ossicles, the facial recess, and the cochlear nerve canal are transected nicely in this plane.

CT scan review

All scans were analysed on a viewing workstation using a modified guideline for cochlear implant pre-evaluation, as originally published by Frau et al. in 1994; see table 1.[38]

Results

The axial scan plane was found most suited to for an overview of the temporal bone, because all structures of interest were visualised. On various levels in the data set, this plane allowed a perfect assessment of how the jugular bulb and the carotid artery were related to the cochlea. This plane also made it possible to judge the pneumatisation of the mastoid and the thickness of the parietal bone. The facial nerve was easily recognised on the axial plane. The width of the facial recess at the level of the cochlear basal turn - the level where the posterior tympanotomy would be performed - could also be measured adequately; see fig. 1.

Table 1. Our modified guidelines for CT imaging in cochlear implant pre-evaluation, originally according to Frau et al.[38]

Anatomical structure	
Cochlea	Patency of the scalae
	Malformations
Cochlear nerve canal	Size and width[34]
Round window	Position
Oval window	Position
Carotid canal	Relation to cochlea
Jugular bulb	Relation to round window
Incus	Short process
Facial nerve	Tympanic and mastoidal course
	Size of facial recess[20]
Mastoid	Extent of pneumatisation
Temporal squama	Thickness

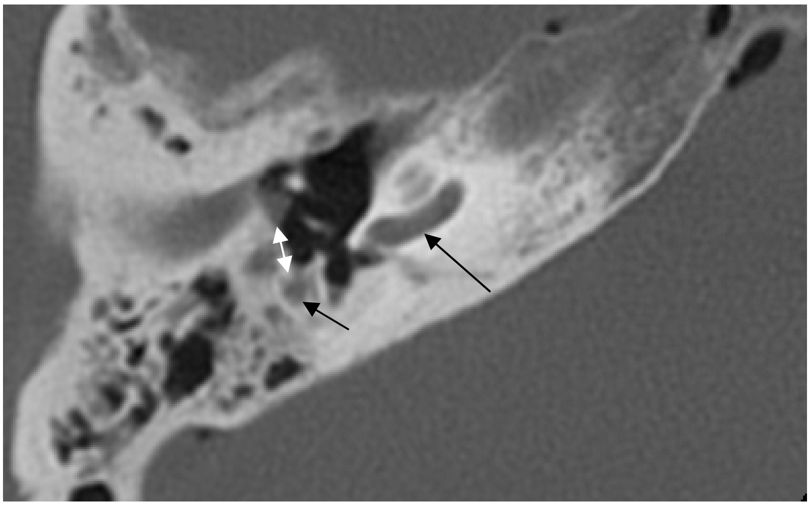
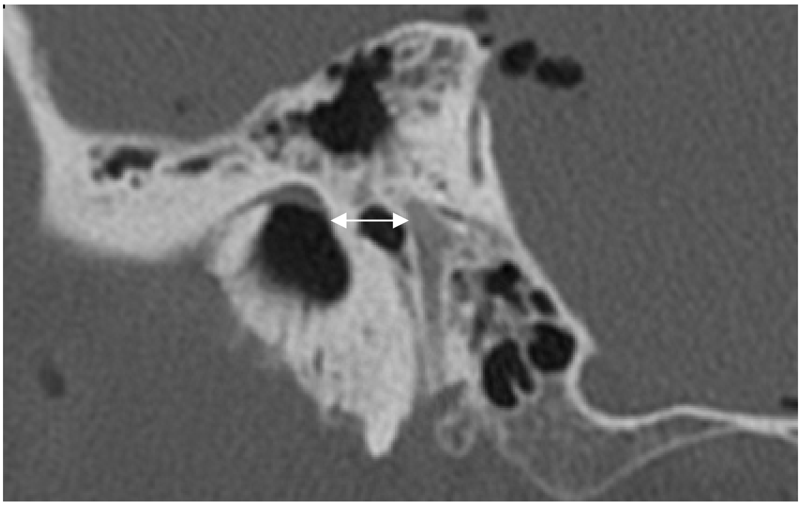


Fig. 1. Axial CT scan of the right temporal bone. The small black arrow points to the facial nerve. The double-headed white arrow indicates the facial recess. The large black arrow corresponds to the basal turn of the cochlea.

The entire facial recess could be visualised in a single axiopetrosal plane, although a reference to the cochlear basal turn is lacking; see fig. 2a. Fig. 2b shows an axiopetrosal

MPR created from the axial data set that corresponds with the original axiopetrosal image in fig. 2a.

2A



2B

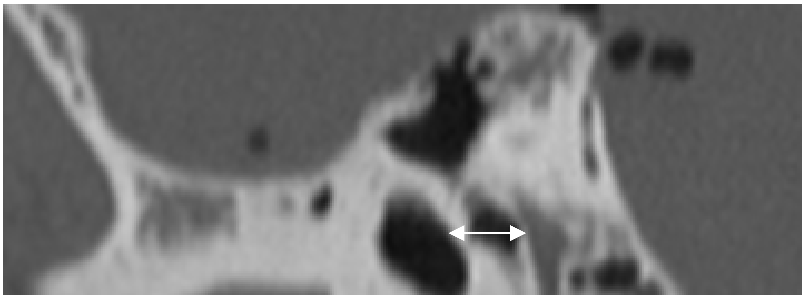
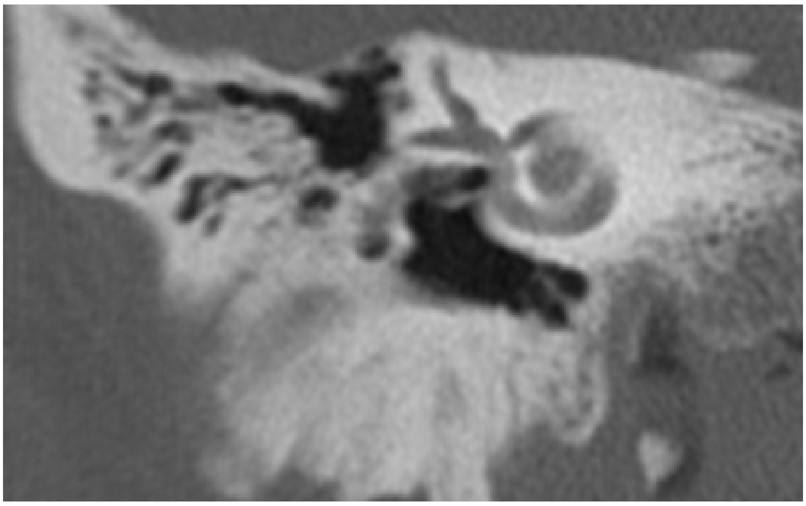
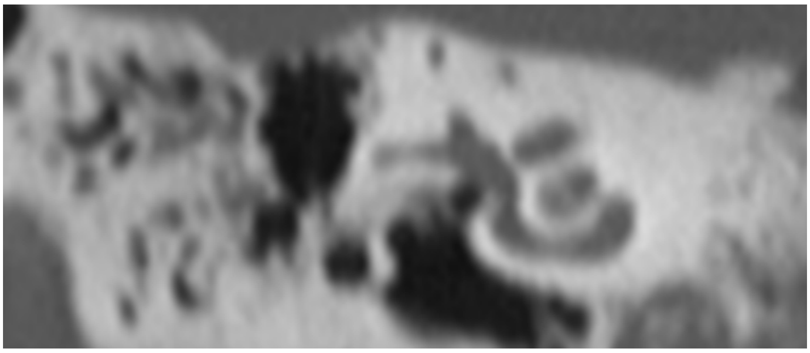


Fig. 2 Axiopetrosal CT scan (A) and axiopetrosal MPR (B) of the right temporal bone. The double-headed arrow indicates the facial recess.

The patency of the cochlea was best assessed in the axial plane combined with the semilongitudinal plane. Fig. 1 and 3a depict the cochlear basal turn. A multiplanar reformat from the axial data set could replace the direct semilongitudinal image; compare fig. 3a and b.



3A

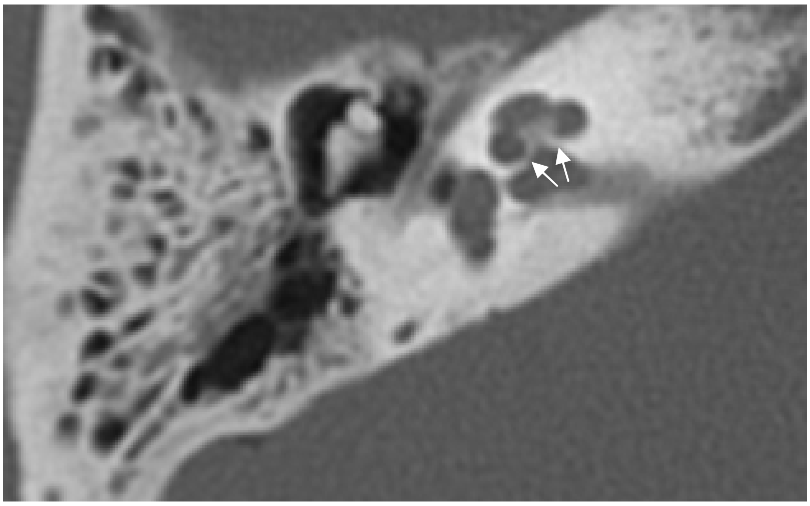


3B

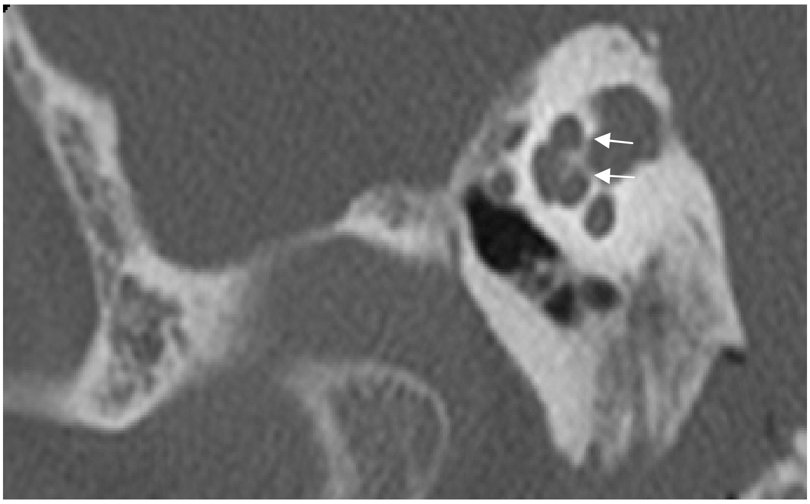
Fig. 3. Semilongitudinal CT scan (A) and semilongitudinal MPR (B) of the right temporal bone, showing the cochlear basal turn.

We studied the size and width of the cochlear nerve canal using axial and axiopetrosal images; see fig. 4a and b. Axiopetrosal multiplanar reformatting from the axial data set provided adequate information on the size and diameter of the cochlear nerve; compare fig. 4b and c.

4A



4B



4C

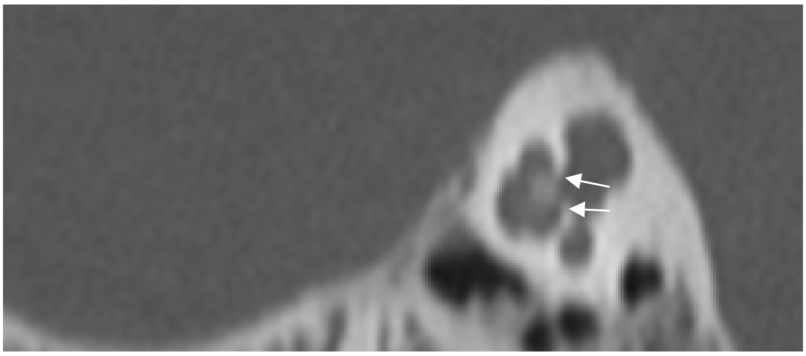


Fig. 4. Axial CT scan (A), axiopetrosal CT scan (B) and axiopetrosal MPR (C) of the right temporal bone. White arrows point to the margins of the cochlear nerve canal**.**

Discussion

In light of our previous studies and the available literature, we decided to leave MRI out of our routine preoperative imaging procedures in cochlear implant candidates.[21,22,33] Consequently, we formulated a preoperative imaging protocol that only uses CT. Ideally, a limited scanning time should be adequate to obtain all relevant information. We have chosen the axial image plane, which, combined with MPRs, could provide all requested information. The axial plane is scanned while the patient is in a comfortable supine position. Scanning in this one plane, together with MPRs, reduces the radiation dose while avoiding dental filling artifacts. By limiting the CT scanning time and skipping MRI, the need for anesthesia in children is reduced and, in due time, savings are made in terms of costs and radiological capacity.

We performed a study on a cadaver head to determine the imaging quality of CT MPRs in comparison with direct CT scanning of the temporal bone. We found the axial plane combined with MPRs to be sufficient for preoperative analysis of temporal bone morphology.

Once a complete axial data set is obtained - ranging from the superior semicircular canal to the hypotympanum - MPRs can be made from the images. The axial images provide an overview of the temporal bone. For a detailed analysis, perpendicular MPRs in the axiopetrosal and semilongitudinal planes should be made.

The width of the facial recess can be measured at the level of the cochlear basal turn in the axial plane and in an axiopetrosal MPR. The cochlear patency can be assessed on the axial image in combination with a semilongitudinal MPR; the latter is parallel to the straighter basal turn of the cochlea, which is also shown in the axial plane. Finally, the cochlear nerve canal can be visualised on an axiopetrosal MPR and on an axial image. Measurements of the size and width of the cochlear nerve canal and the facial recess should be taken using the technique described by Spoor and Zonneveld and applied in our previous study.[20,34,39]

We used a 1 mm slice-to-slice CT technique with a 0.5 mm slice overlap. There was little or no loss of quality in our MPRs because the partial volume effects were limited. Multislice CT scanners create isotropic data sets that can be used to create MPRs without any loss of imaging quality.[40] However, the requested slice thickness and reconstruction index is not yet available.

In the future, virtual endoscopy might make it possible to train surgeons in the operative procedure before they go into surgery.[41-44] Image-guided surgical navigation is already available, but the currently used CT resolution may not be adequate for microsurgical procedures.[45] Multislice CT is expected to solve this problem. Because the head is usually rotated during surgery, a fixation mouthpiece, under vacuum or other types of head restraint, is an ideal base for markers. Intraoperative CT imaging might also be feasible, although its infrastructural and logistic demands are high. In that approach, surgery would either have to be performed in the radiology department or a dedicated CT unit would have to be used in the operation theater.[46,47]

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6

Electrode insertion depth in cochlear implantees estimated during surgery, on plain film radiographs and with electrode function testing

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Abstract

Objective

To study and compare three methods of determining electrode insertion depth in cochlear implantees: intraoperative counting of inserted electrodes, plain film radiography using Stenvers projection, and postoperative electrode function testing.

Materials and methods

In 16 cases the number of electrodes inserted in the cochlea were counted both by the surgeon at surgery and by two independent observers on plain film radiographs using Stenvers projections. The electrode function was tested postoperatively. The differences between the three methods in estimation of the number of intracochlear electrodes were analysed with *t*-tests, and 95% confidence intervals (95% CI) of the mean differences were calculated.

Results

The mean difference between the radiograph observers was 0.25 electrode (95% CI: -0.69 to 1.19 electrodes). The mean difference between radiography observations and the surgical counts was 0.60 electrode (95% CI: -0.71 to 1.91 electrodes). The mean difference between surgical counting and electrode function testing was 0.40 electrode (95% CI: -0.66 to 1.46 electrodes). The mean difference between radiograph observations and electrode function testing was 0.50 electrode (95% CI: -0.51 to 1.51 electrodes). No significant differences existed between the three methods.

Conclusion

Our findings showed similar results in estimating electrode array insertion depth with the three methods. Plain film radiography using Stenvers projection is satisfactory if imaging is indicated for determining the number of inserted electrodes.

Keywords

Cochlear implantation; Radiography.

Introduction

The performance of a cochlear implant is correlated with the number of electrodes inserted within the cochlea and with their position.[1,2] Because it is so important to assess the status of the electrodes after implantation, the surgeon counts them during surgery. There are several drawbacks to this method, however, which may result in an inaccurate indication of the depth to which the electrodes have been inserted.[3] First of all, posterior tympanotomy provides only a narrow access opening to the promontory. From that viewpoint, the surgeon is looking down along the axis of the electrode array. Secondly, there is no consensus on where counting should start: at the level of the scala tympani; at the cochleostomy; or at the round window niche. Furthermore, the cochleostomy sites can vary from one case to the next. And even when the estimate is reliable, postoperative slippage might occur.

Particularly in the event of restricted auditory performance after implantation, it is necessary to evaluate the depth of the electrodes.[4] The literature describes several imaging techniques for the postoperative assessment of electrode insertion depth. These are described below.

Shpizner et al. evaluated electrode insertion depth intraoperatively in 135 patients with a Stenvers or a transorbital anteroposterior projection of the temporal bone on plain film.[5,6] Regardless of which x-ray view they used, the discrepancy between surgical assessment and radiographic assessment amounted to two electrodes or less. Because the electrode array is considered to overlap in a Stenvers projection, Marsh et al. used a modified Stenvers view, which allowed them to demonstrate the electrode array as a whole.[3] Taking a different approach, Czerny et al. studied a Chausse III projection, allowing them to see the electrode array within the cochlea without any overlap.[7] Lawson et al. preferred digital radiography to conventional radiography, as it is comfortable, easy to reproduce, and has a better contrast resolution.[8]

All of these 2-D x-ray approaches have the same disadvantages: a true axial projection is difficult to obtain without underestimating the electrode length and superimposed structures often mask details of interest. A good way to assess the position of an electrode array is with CT scans (axial slices and 2-D or 3-D reconstructions).[9-11] Not only do CT methods allow assessment of the depth to which the electrode array has been inserted, but relationships with temporal bone structures can be evaluated, too.[4,10,12] The metal artefacts associated with this technique make it difficult to distinguish the active electrodes separately.[5] However, the image of the metal electrodes can be improved by using a high window width. Ketten et al. demonstrated the benefits of spiral CT scanning. Not only does this technique provide better longitudinal resolution than that of conventional CT, but it also allows retrospective slice reconstruction at several thicknesses from a single CT data set.[10] By making 3-D reconstructions of midmodiolar images, Ketten et al. were able to estimate electrode insertion depth and the position of the electrodes within the cochlea. Other authors, namely Kumakawa et al. and Qaiyumi et al., suggested using conventional tomography because it has less metal artefacts, although it is difficult to estimate the exact position of the electrodes by this method due to the coarse resolution of the images.[13,14]

MRI is not capable of demonstrating the presence of extracochlear electrodes. The problem is that the image of the electrodes in MRI is similar to that of their environment in the middle ear; both are represented as dark areas. An even more serious drawback is that MRI has several potential hazards as a result of the heating of the receiver and the electrode array, induced current, unintentional implant output, implant damage and torque.[15] Depending on the ease with which the implant magnet can be removed and on the strength of the magnetic field, MRI is compatible with cochlear implants.[16-18] Thus, MRI should only be performed when strictly indicated; when considering MRI, the implant type and the magnetic field strength should be taken into account.[19]

In our department, we estimate the position of the electrode array within the cochlea during surgery by counting the inserted electrodes. If there is any doubt about their number or position, a radiograph with Stenvers projection is made, either during surgery or afterwards. So far, the results of this method have seemed reliable to us. However, in view of the above considerations, we decided to compare our inventory of electrode insertion depth - as made both during surgery and afterwards with plain film radiography using Stenvers projections - with the results of postoperative electrode function testing.

Materials and methods

Patients

Out of 81 patients who underwent surgery between July 1993 and February 1998, in 16 cases postoperative plain film radiographs using Stenvers projection were available for analysis.

Surgery

Our standard operation procedure comprised a posterior tympanotomy and a cochleostomy on the promontory. The electrode array was fixated with sutures to the overhanging edges of the mastoid cavity. At surgery, the depth to which the electrode array had been inserted was determined by counting the number of extracochlear electrodes. Most patients received a Nucleus (CI 22 or CI 24) device; these have 22 active and 10 support electrodes. The early patients were implanted with a MED-El C40 or C40+ device. It is harder to estimate the depth of their electrode array, since these implants have an array thickening instead of support electrodes. They have 8 or 12 active electrodes, respectively.

Plain film radiography

Two independent observers, namely RB and AvO, determined electrode insertion depth using plain film radiography with Stenvers projections. They were not aware of the surgical outcome. The slight but plainly visible bend in the electrode array at the cochleostomy was considered to define the lateral margin of the cochlea (see fig. 1).

Electrode function test

Initial electrode function was tested approximately six weeks after surgery. The electrodes were considered to be functional if no deviations were found in the threshold map and no short-circuiting was encountered.

Statistical analysis

The inter-observer differences for plain film radiography were analysed using the paired samples *t*-test. A 95% confidence interval (95% CI) of the mean difference was calculated. The mean counts of electrode insertion depth made by both observers were compared to the intraoperatively counted number of inserted electrodes. The differences were analysed using the paired samples *t*-test; a 95% CI of the mean difference was calculated. The number of active electrodes, as counted during surgery, was compared to the number of functioning electrodes discerned in the postoperative electrode function test. The differences between these numbers were analysed using the paired samples *t*-test, and a 95% CI of the mean difference was calculated. Finally, the number of functioning electrodes in the function test was compared with the number of inserted active electrodes as counted by way of plain film radiography. Again, the differences between these numbers were analysed using the paired samples *t*-test, and a 95% CI of the mean difference was calculated.

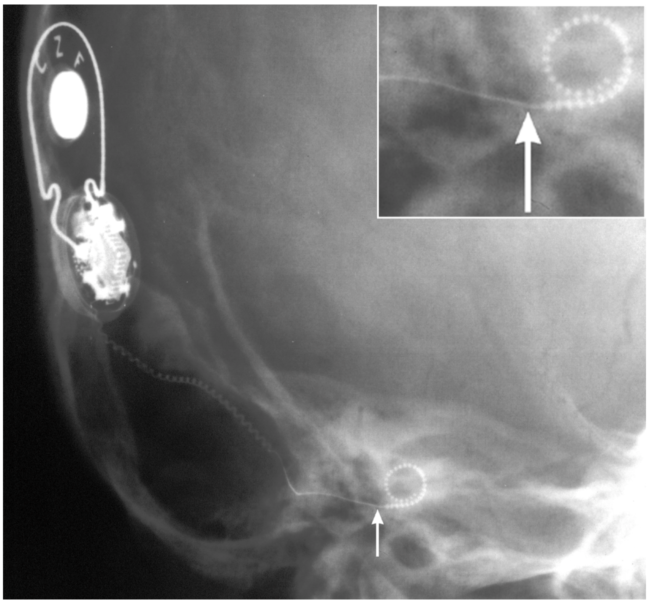

Fig. 1. Plain film radiograph using Stenvers projection showing the intracochlear position of the electrode array of the cochlear implant. The arrow demonstrates the site of the cochleostomy as marked by the slight bend in the electrode array.

Results

Table 1 shows the results for all 16 cases. Postoperative electrode function testing demonstrated complete functioning of the electrode array in 13 cases. In case no. 6, counting during surgery suggested insertion of 20 active electrodes, whereas all 22 active electrodes were functional in the function test. In case no. 11, the number of electrodes that had been inserted at surgery was 32. However, that number could not be confirmed on the plain film radiograph, which showed only 24 intracochlear electrodes. In two cases, nos. 10 and 11, partial electrode short-circuiting could not be predicted either during surgery or on the radiographs. The problem was that no resistance was met during insertion and the radiographs showed no array kinking. In case no. 2, the cochlear implant array seemed to be completely inserted in the cochlea. On postoperative radiography, however, it showed up as being in the posterior semicircular canal. In this case, function testing was not performed, which is why it is only included in fig.2.

Table 1. Number of inserted electrodes counted at surgery, detected with plain film radiography, and demonstrated by postoperative electrode function testing.

Case number and implant type		Surgery		Plain film radiography			Function testing
		All electrodes	Active electrodes	RB	AvO	Mean	
1	Med-El C40	8	8	8	8	8	8
2	Med-El C40	8	8	0	0	0	-
3	Med-El C40	8	8	8	7	7,5	8
4	Med-El C40	8	8	8	8	8	8
5	Med-El C40+	12	12	12	12	12	12
6	Nucleus CI22	20	20	20	24	22	22
7	Nucleus CI22	27	22	26	27	26,5	22
8	Nucleus CI22	32	22	32	30	31	22
9	Nucleus CI22	32	22	32	31	31,5	22
10	Nucleus CI22	32	22	32	32	32	15
11	Nucleus CI22	32	22	24	24	24	21
12	Nucleus CI22	32	22	32	31	31,5	22
13	Nucleus CI22	29	22	32	28	30	22
14	Nucleus CI24	24	22	27	25	26	22
15	Nucleus CI24	32	22	28	30	29	22
16	Nucleus CI24	32	22	32	32	32	22

Fig. 2 shows the results of plain film radiography interpretation by RB versus AvO. The *t*-test showed no significant differences between the results found by the two observers. The mean difference was 0.25 electrode with 95% CI, -0.69 to 1.19 electrodes.

Fig. 3 plots the intraoperative inventory of inserted electrodes against the mean number of inserted electrodes as counted by both observers using plain film radiography. The *t*-test

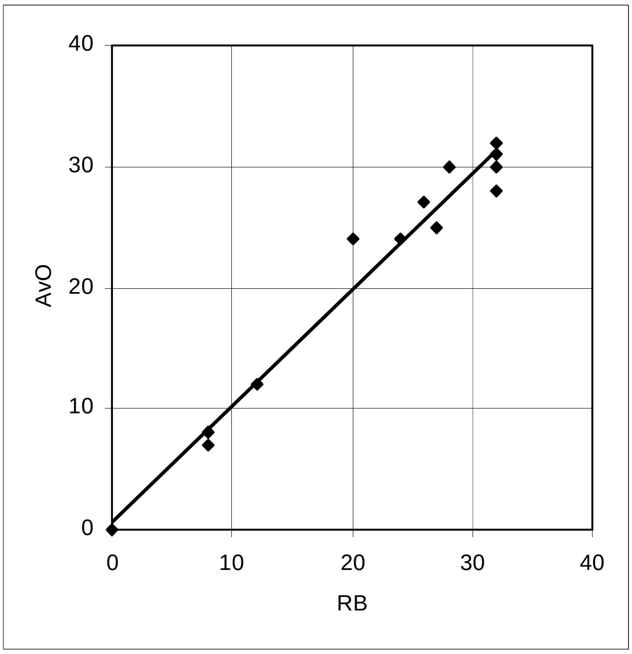

Fig. 2. Correlation between the number of inserted electrodes (◆) counted by the two observers in 16 cases. Computer-generated trend line.

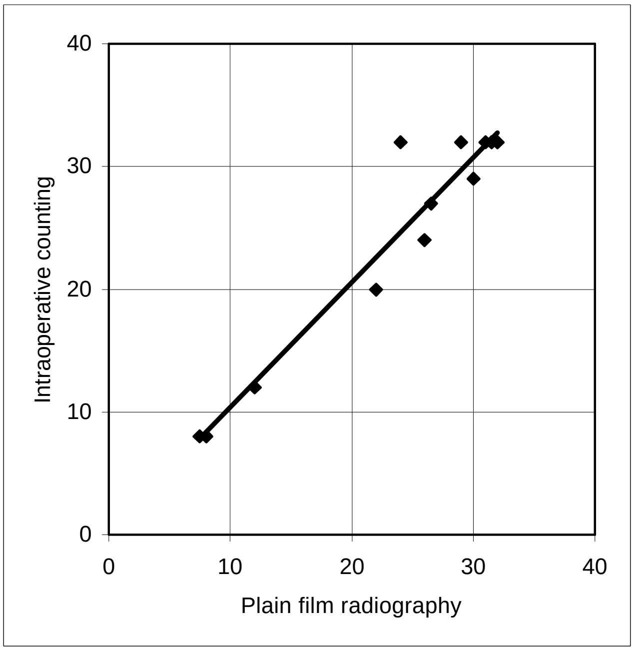

Fig. 3. Number of inserted electrodes (◆) as counted at surgery versus the mean number counted using plain film radiography in 15 cases. Computer-generated trend line.

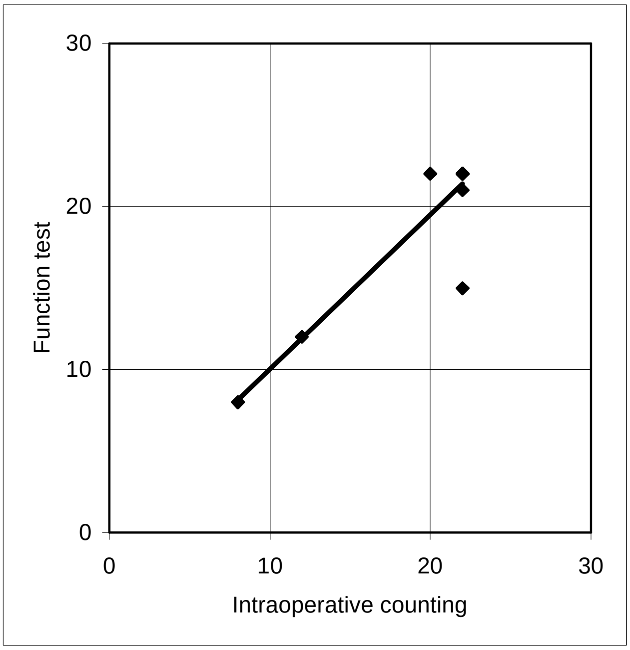

Fig. 4. Number of functioning electrodes at function testing versus number of inserted active electrodes counted during surgery in 15 cases; ◆ = number of electrodes. Computer-generated trend line.

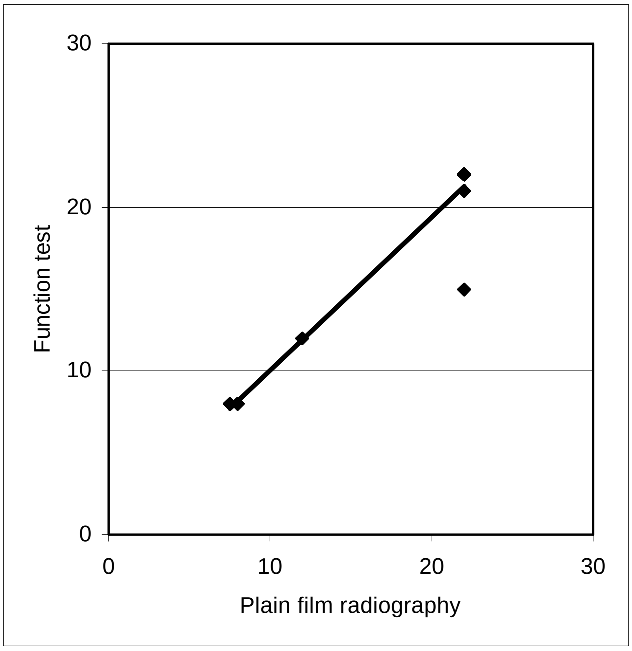

Fig. 5. Number of functioning electrodes at function testing versus mean number of inserted active electrodes determined using plain film radiography in 15 cases; ◆ = number of electrodes. Computer-generated trend line.

showed no significant differences between the intraoperative inventory of inserted electrodes and the results of the inventory using plain film radiography. The mean difference was 0.60 electrode with 95% CI, -0.71 to 1.91 electrodes.

Fig. 4 compares postoperative function testing with intraoperative counting of inserted active electrodes. The *t*-test showed no significant differences between the two methods. The mean difference was 0.40 electrode with 95% CI, -0.66 to 1.46 electrodes.

Finally, fig. 5 compares the outcomes of function testing with those of plain film radiography. With the *t*-test showing no significant differences, the mean difference was 0.50 electrode with 95% CI, -0.51 to 1.51 electrodes.

Discussion

We investigated three methods of determining electrode insertion depth in cochlear implantees: intraoperative electrode counting, plain film radiography using Stenvers projection and postoperative electrode function testing. Our findings showed very few discrepancies in the capacity of these three methods to estimate the depth of electrode array insertion.

There is an interval of approximately six weeks between surgery and electrode function testing. In that light, the results of the three methods indicate that there was no postoperative electrode array slippage with extrusion of active electrodes. This conclusion runs counter to findings by Marsh et al.[3] In case no. 11, some array slippage might have occurred, although all active electrodes remained inside of the cochlea. The technique of fixation of the electrode array in the mastoid might be of influence. We used sutures to fixate the array to the overhanging edges of the mastoid cavity.

It is uncertain whether or not stimulation levels during function testing can be used to distinguish between electrodes in an intra- or extracochlear position. In case no. 6, for example, function testing suggested 22 functioning electrodes, whereas only 20 active electrodes had been inserted. The explanation might be that an active extracochlear electrode might have stimulated the cochlear neurons. However, we would only expect this to occur at a higher level of stimulation.[2] The radiograph observers disagreed with one another in this case, counting respectively 20 and 22 active electrodes.

The number of inserted electrodes as estimated during surgery corresponded closely with the number of functioning electrodes detected by postoperative testing. Therefore, imaging is indicated when there is a discrepancy between findings during surgery and electrode function testing. For example, a postoperative shift in the position of an electrode array can lead to a marked change in hearing. Imaging is also indicated when there is reason to suspect array kinking at surgery or electrode dysfunction in proximity to the cochleostomy.

In our study, plain film radiography with standard Stenvers projections yielded highly consistent estimates of electrode array insertion depth. The bend in the electrode array at the cochleostomy depicted on Stenvers projections proved reliable as a tool for estimating the number of inserted electrodes. The mean discrepancies of 0.60 electrode and 0.50 electrode, respectively, as compared with the data of surgery and function testing, are similar to the findings of Shpizner et al.[5] Their radiographic estimates - using either Stenvers or anteroposterior projections - demonstrated an error of plus or minus two electrodes when correlated with surgical and psychophysiologic data.

To assess the intracochlear position of the electrode Marsh et al., Czerny et al. and Chen et al. measured insertion angles on radiographs using anteroposterior, modified Stenvers and Chausse III projections.[3,7,12] The angle of insertion reflects more precisely the position of the electrode tip than the inserted distance measured in millimetres. This is the result of the variable location of the electrode array within the scala tympani.[20]

We conclude that standard Stenvers radiography projections are satisfactory for determining the mere number of inserted electrodes. Therefore, we believe we can omit more sophisticated imaging techniques from our routine.[3-5,7-9,11,14] A CT scan could then be performed if the radiographs fail to demonstrate the location of the electrode array adequately, as, for example, when a cochlea is malformed or when characteristic frequency mapping is needed for speech-processing strategies.[10]

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7

Summary and conclusions

Summary

Cochlear implants are devices that allow for direct electrical stimulation of the spiral ganglion and the acoustic nerve, restoring auditory perception in the profoundly deaf. In this thesis, we investigate the usefulness of pre- and postoperative imaging modalities in cochlear implant surgery. We have studied the literature and analysed retrospectively our data on cochlear implantees.

Chapter 1 forms the introduction to this thesis. Cochlear implantation has become an accepted and effective treatment for profoundly pre- and postlingually deaf patients. The work up for surgery has to clarify, among other things, the accessibility of the temporal bone and in particular the cochlea. For that purpose, preoperative CT and MRI are currently applied.
The surgical route to the cochlea may be made difficult by a narrow passage at the facial recess or a deviant position of the cochlear basal turn. Furthermore, cochlear patency may be decreased due to congenital malformation, disease, or trauma. Such situations might hamper the surgeon when inserting the electrode array, leading to incomplete electrode placement. That, in turn, will have a negative effect on post-operative auditory perception.
In our experience, the results of preoperative imaging are not always congruent with surgical findings. Furthermore, there is no consensus in the literature on the diagnostic value of the preoperative imaging modalities for the analysis of temporal bone anatomy and cochlear patency.

In **Chapter 2,** we use CT scans of cochlear implantees to study the dimensions of the facial recess and the spatial relationship between the facial recess and the cochlea. The printed scans were arranged in random order and then intuitively reviewed independently by three observers. They were asked to classify the width of the facial recess and the feasibility of electrode array insertion. Their results were compared with measurements taken from the corresponding digital data; these measurements were performed on a viewing station by a fourth independent observer. The intuitive reviews and the measurements were then linked to the findings at surgery.

Neither the intuitive classification of facial recess width nor the feasibility of electrode array insertion showed any significant relation to the measurements performed with the viewing station. The interobserver reproducibility of the intuitive judgments was poor. Neither the intuitive review of the CT scans nor the viewing station measurements were capable of predicting the problems that were actually encountered during surgery.

We conclude that intuitive review is not a reliable method of classifying either facial recess width or the feasibility of electrode array insertion. When viewing station measurements are used to classify the spatial relation between the facial recess and the cochlear basal turn, these measurements must be scrutinized in detail. They must be subjected to a more detailed analysis to clarify the relationship to the direction of the operation route and the orientation of the basal turn of the cochlea. Advanced imaging techniques, specifically multislice CT, might improve the diagnostic capabilities.

Chapter 3 focuses on the analysis of cochlear patency by means of preoperative CT imaging. Cochlear patency was independently classified on randomly arranged prints of preoperative CT scans by a senior ENT surgeon, an ENT resident, and a senior radiologist. The reviewers were not aware of the etiology of deafness or of the findings at surgery. The results of the CT reviews were compared with the findings at surgery.

The outcome of our study suggests that CT scans may be useful in assessing cochlear patency. The literature seems to contradict this, though, reporting poor predictability of cochlear obstruction using CT in cases of postmeningitic deafness. Accordingly, CT is generally considered most useful when meningitis is not involved. However, the sensitivity and specificity of CT will depend on the prevalence of impaired cochlear patency. It is well known that impaired cochlear patency is most common in postmeningitic deafness. Therefore, we would expect to find an increase in sensitivity and specificity in the assessment of these cases. Indeed, we did find higher sensitivity and specificity when we restricted the analysis to cases of postmeningitic deafness.

Most authors report using axial and coronal CT planes to assess temporal bone anatomy and particularly cochlear patency. The good performance of CT in our study might be explained by our use of scans in the axial and particularly in the semilongitudinal plane. The latter provides excellent visualisation of the basal and second turns of the cochlea.

Although more information can be obtained using a viewing station that allows the window's width and level to be adjusted, the results of CT performed under these circumstances are less favorable than desired. First of all, the customary slice interval of 1-1.5 mm is larger than the intracochlear structures, resulting in partial volume effects. Consequently, the relatively poor resolution complicates the interpretation of the image. Furthermore, it is difficult to establish the presence of intracochlear fluid due to small differences in attenuation between fluid and soft tissue as found in fibrosis. In the future, multislice techniques might improve the diagnostic capability of CT.

An alternative approach would be to use T2-weighted MRI images, as they would clearly reveal the endolymphatic and perilymphatic spaces in particular. In theory, they would thus allow the observer to differentiate between fluid and fibrotic occlusions.

In that light, in **Chapter 4,** we investigate whether MRI has any advantage over CT. The limited body of literature on the possible superiority of MRI in predicting cochlear patency is inconclusive. We wondered whether the assessment of cochlear patency actually required T2-weighted TSE 3-D MRI in addition to CT, using axial and semilongitudinal planes. Therefore, corresponding preoperative CT and MRI scans were reviewed independently by three observers. They were asked to classify cochlear patency and to record the location of any obstruction. Their findings were compared with those obtained at surgery.

CT and MRI showed a comparable mean specificity and sensitivity in predicting cochlear patency. We suggest that the reason why CT was not found to be inferior to MRI is that we used scans in the semilongitudinal plane in addition to scans in the standard axial plane.

CT is always needed to obtain information on mastoid and middle ear anatomy. It should be kept in mind that the presence of the cochlear nerve can be assessed on CT images too. Therefore, we suggest that when the cause of deafness is known to be located outside the central acoustic pathway, MRI could be left out of the preoperative work up routine. This would reduce the need for anesthesia during the diagnostic work up, especially in young children. Furthermore, omitting MRI from the work up would save time, money, and radiological capacity.

Chapter 5 integrates the conclusions of the preceding ones (2, 3, and 4). In this chapter, we present a routine CT imaging protocol for preoperative scanning of the temporal bone in cochlear implant candidates. We defined a single image plane from which, with use of multiplanar reformats (MPRs), all information can be obtained. The reliability of the protocol was tested by studies on a cadaver head.

The axial scanning plane is found to be the most suitable one for an overview of temporal bone anatomy because all structures of interest are visualised in this plane. The relation of the jugular bulb and the carotid artery with the cochlea can be assessed perfectly on these scans. Furthermore, the pneumatisation of the mastoid and the thickness of the parietal bone may be evaluated on scans made in this plane. The facial nerve is clearly recognisable on an axial plane, and the width of the facial recess can be measured adequately. The patency of the cochlea is best assessed in the semilongitudinal plane combined with the axial plane. The width of the cochlear nerve canal is studied using axial and axiopetrosal images. The quality of the MPRs is comparable with that of images obtained by direct scanning in the corresponding planes.

Therefore, a complete axial CT data set with MPRs in the semilongitudinal and axiopetrosal direction is recommended for a routine preoperative imaging work up. The use of only the axial plane with MPRs decreases the radiation dose while avoiding dental filling artefacts. The limited scanning time reduces the need for anesthesia in children, and in due time it leads to savings in costs as well as in radiological capacity.

Chapter 6 studies postoperative imaging. The performance of a cochlear implant is correlated with the number of electrodes inserted into the cochlea and with their position. Because the position of the various electrodes should be assessed after implantation, the surgeon counts them during surgery. The number of inserted electrodes can also be counted on postoperative radiological images.

The literature mainly describes the use of plain film radiography and CT techniques to obtain information about the number of inserted electrodes. The value of plain film radiographs is debatable. One problem is that it is hard to obtain a true axial projection without underestimating the electrode length. Superimposed structures often mask details of interest. Furthermore, reports in the literature question the reliability of counting the number of inserted electrodes during surgery.

Our data on the inventory of electrode insertion depth - as counted during surgery and afterwards with plain film radiography using Stenvers projections - was compared with the results of postoperative electrode function testing.

The number of inserted electrodes as estimated during surgery corresponded closely with the number of functioning electrodes found by postoperative testing. Therefore, we conclude that imaging is only indicated when there is a discrepancy between findings during surgery and electrode function testing.

Plain film radiography with Stenvers projections yielded highly consistent estimates of electrode array insertion depth. We conclude that the Stenvers radiography projections are satisfactory for determining the number of inserted electrodes. A CT scan might be performed if the radiographs fail to adequately demonstrate the location of the electrode array or when characteristic frequency mapping is needed for speech-processing strategies.

General conclusions

1. In the routine clinical practice of cochlear implantation, when performing preoperative CT of the temporal bone, it is sufficient to use an axial plane combined with MPRs in the axiopetrosal and semilongitudinal planes.
2. Temporal bone anatomy - in particular cochlear patency, facial recess width, and cochlear nerve canal width - can be assessed on scans as described above under point 1.
3. It should be kept in mind that CT has a limited sensitivity for assessing cochlear patency and facial recess width.
4. MRI is needed when the cause of deafness might be located in the central acoustic pathway.
5. Surgical counting of the number of inserted electrodes is reliable.
6. Imaging of the inserted electrodes is only indicated when there is a discrepancy between findings during surgery and electrode function testing.

7. Plain film radiography with Stenvers projection is adequate to determine the number of inserted electrodes.
8. A CT scan is only needed when the radiographs fail to demonstrate the location of the electrode array or when characteristic frequency mapping is performed in speech-processing strategies.

Future developments

We used a slice-to-slice CT technique with slice overlap. Currently, multislice CT scanners create isotropic data sets that have better image resolution and will allow for convenient creation of adequate MPRs. In the future, virtual endoscopy might provide possibilities for training in the operative procedure before actual surgery. Image-guided surgical navigation is already possible, but the currently available CT resolution is inadequate for microsurgical procedures. Multislice CT is expected to solve this problem in the future.

Another approach may be intraoperative CT imaging, although its infrastructural and logistic demands are high. Surgery would then have to be performed in the radiology department, or a dedicated CT unit would have to be used in the operation theater.

In its present form, MRI is only indicated in cases with a possibility of central nervous system disease. In such cases, MRI is used to investigate the anatomy of the central acoustic pathway from the cochlear nuclei to the temporal acoustic area. In the near future, functional MRI, which visualises and tests the central auditory pathway in response to auditory stimuli, might provide useful new criteria for the selection of cochlear implant candidates.

8

Samenvatting en conclusies

Samenvatting

Cochleaire implantaten zijn hulpmiddelen die via directe stimulatie van het ganglion spirale en de gehoorzenuw, de auditieve perceptie herstellen bij ernstig slechthorenden en doven. In dit proefschrift wordt het nut van pre- en postoperatieve beeldvorming bij cochleaire implantatie onderzocht. De literatuur werd bestudeerd en de data van onze patiënten werden retrospectief geanalyseerd.

Hoofdstuk 1 vormt de introductie van het proefschrift.
Cochleaire implantatie wordt tegenwoordig beschouwd als een geaccepteerde en effectieve behandeling bij pre- en postlinguaal, ernstig slechthorenden en doven. Ter voorbereiding op de operatie moet, onder andere, de toegankelijkheid van het rotsbeen en in het bijzonder van de cochlea worden onderzocht. Daartoe worden momenteel preoperatieve CT en MRI toegepast.
De chirurgische route naar de cochlea kan lastig zijn door een nauwe recessus facialis of een deviante positie van de cochlea. Bovendien kan de cochleaire doorgankelijkheid verminderd zijn tengevolge van congenitale misvormingen, ziekten of trauma. Als gevolg daarvan kan de elektrodeninsertie verstoord worden of onvolledig zijn, hetgeen postoperatief een beperkte auditieve perceptie tot gevolg kan hebben.
Naar onze ervaring zijn de resultaten van preoperatieve beeldvorming niet altijd in overeenstemming met de bevindingen tijdens de operatie. In de literatuur is geen consensus over de diagnostische waarde van preoperatieve beeldvorming van het rotsbeen.

In **Hoofdstuk 2** werden met CT de afmetingen van de recessus facialis en de ruimtelijke verhouding tussen de recessus facialis en de cochlea onderzocht.
Afgedrukte foto's werden in gerandomiseerde volgorde door drie onafhankelijke onderzoekers bestudeerd. Zij werden gevraagd de breedte van de recessus facialis en de mogelijkheid tot elektrodeninsertie intuïtief te beoordelen. De resultaten werden vergeleken met metingen op corresponderende, digitale data. Deze metingen werden verricht door een vierde onafhankelijke onderzoeker op een zogenaamd werkstation. De intuïtieve beoordelingen en de metingen werden vergeleken met peroperatieve bevindingen.

Er waren geen significante relaties aantoonbaar tussen intuïtieve classificatie van de recessus facialis breedte of de mogelijkheid tot elektrodeninsertie en de metingen op het werkstation. De *interobserver* reproduceerbaarheid van de intuïtieve beoordelingen was matig. Noch intuïtieve beoordeling, noch de metingen op het werkstation voorspelden peroperatieve problemen.

Wij concluderen dan ook dat intuïtieve fotobeoordeling niet betrouwbaar is bij bestudering van de recessus facialis breedte en inschatting van de mogelijkheid tot elektrodeninsertie. Werkstation metingen, bij beoordeling van de ruimtelijke relatie tussen de recessus facialis en de cochlea, dienen nader geanalyseerd te worden voor wat betreft de relatie tussen de operatieroute en de oriëntatie van de cochlea.

Geavanceerde beeldvormende technieken, zoals *multislice* CT, zullen waarschijnlijk de diagnostische mogelijkheden vergroten.

Hoofdstuk 3 richt zich op de beoordeling van de cochleaire doorgankelijkheid met behulp van preoperatieve CT.

Op afgedrukte foto’s werd de cochleaire doorgankelijkheid beoordeeld door respectievelijk: een ervaren KNO-arts, een KNO-arts in opleiding en een ervaren radioloog. De onderzoekers waren niet op de hoogte van de oorzaken van doofheid en de bevindingen tijdens de operaties. De resultaten van de CT beoordelingen werden vergeleken met de peroperatieve bevindingen.

Onze studie toont aan dat CT scans nuttig kunnen zijn bij beoordeling van de cochleaire doorgankelijkheid. De literatuur suggereert een matige voorspelbaarheid van cochleaire obstructie door middel van CT, bij patiënten met doofheid na meningitis. CT wordt dan ook vooral als nuttig beschouwd in die gevallen met doofheid door een andere oorzaak. Echter, de sensitiviteit en specificiteit van CT zijn afhankelijk van de prevalentie van cochleaire obstructie. Deze obstructie is heel gebruikelijk in patiënten met doofheid na meningitis. Onze verwachting van een stijging van de sensitiviteit en specificiteit in deze gevallen werd in onze studie dan ook bevestigd.

In de literatuur gebruiken de meeste auteurs axiale en coronale CT scanvlakken om de anatomie van het rotsbeen, en de cochleaire doorgankelijkheid in het bijzonder, te bestuderen. De gunstige resultaten van onze studie laten zich mogelijk verklaren door het

gebruik van axiale gecombineerd met semilongitudinale vlakken. Vooral het semilongitudinale CT vlak toont fraai de eerste en tweede winding van de cochlea.
Hoewel het gebruik van een werkstation met mogelijkheden tot bijstelling van de zogenaamde *window's width* en *level* de resultaten nog zou kunnen verbeteren, zijn ze toch minder goed dan gewenst. Ten eerste is de gebruikelijke plakdikte van 1-1.5 mm groter dan de structuren binnen de cochlea, wat resulteert in het zogenaamde *partial volume effect*. De hierdoor matige resolutie bemoeilijkt de interpretatie van de afbeeldingen. Bovendien is het moeilijk om onderscheid te maken tussen de aanwezigheid van vocht dan wel fibrotische obstructies in de cochlea. Dit komt door slechts kleine verschillen in attenuatie van de röntgenstraling. In de toekomst verwachten wij dat de diagnostische mogelijkheden van CT, in dit kader, zullen toenemen met behulp van *multislice* technieken.
Een alternatief vormt T_2-gewogen MRI, waarmee de endo- en perilymphatische ruimten duidelijk kunnen worden gezien. Theoretisch kan gedifferentieerd worden tussen vocht en fibrotische obstructies.

Gezien bovenstaande onderzochten wij in **Hoofdstuk 4** of MRI voordelen biedt ten opzichte van CT, bij de beoordeling van de cochleaire doorgankelijkheid.
De beperkte hoeveelheid literatuur over dit onderwerp is niet conclusief. Wij vroegen ons af of T_2-gewogen Turbo-Spin-Echo 3-D MRI nodig is, naast CT met gebruik van axiale en semilongitudinale vlakken. Daartoe werden corresponderende, preoperatieve CT en MRI scans beoordeeld door drie, onafhankelijke onderzoekers. Zij classificeerden de cochleaire doorgankelijkheid en noteerden de locatie van eventuele obstructies. De resultaten hiervan werden vergeleken met de peroperatieve bevindingen.
CT en MRI toonden een vergelijkbare sensitiviteit en specificiteit bij voorspelling van de cochleaire doorgankelijkheid.
Wij suggereren dat het gebruik van het semilongitudinale naast het axiale CT vlak de reden kan zijn van de, met MRI vergelijkbare, betrouwbaarheid van CT. In de preoperatieve voorbereiding is CT steeds nodig om informatie te verkrijgen over het mastoid en het middenoor. Omdat de aanwezigheid van de nervus cochlearis ook met CT beoordeeld kan worden suggereren wij, dat in die gevallen met doofheid ten gevolge van

een bekende oorzaak, gelegen buiten de centrale akoestische zenuwbanen, MRI niet meer nodig is in de routinematige, preoperatieve beeldvorming. Hiermee vermindert, in het bijzonder bij kinderen, de behoefte aan anaesthesie tijdens de diagnostische fase. Bovendien bespaart het weglaten van MRI tijd, geld en radiologische capaciteit.

Hoofdstuk 5 integreert de conclusies van hoofdstukken 2, 3 and 4. In dit hoofdstuk presenteren wij een CT protocol voor het preoperatief scannen van het rotsbeen, bij kandidaten voor cochleaire implantatie.
Wij definieerden een scanvlak waarmee met behulp van reconstructies, zogenaamde *multiplanar reformats* (MPR's), alle gewenste informatie kan worden verkregen. De betrouwbaarheid van het protocol werd getest op een kadaver hoofd.
Met het axiale vlak kunnen alle belangrijke structuren in beeld worden gebracht. In dit vlak kunnen de relaties van de arteria carotis en de bulbus jugularis met de cochlea worden beoordeeld. Bovendien kan de pneumatisatiegraad van het mastoid en de dikte van het os parietale geëvalueerd worden. De nervus facialis en de recessus facialis zijn goed herkenbaar. De doorgankelijkheid van de cochlea is te beoordelen in het axiale vlak in combinatie met het semilongitudinale vlak. De diameter van de benige begrenzing van de nervus cochlearis is meetbaar op axiale en axiopetrosale afbeeldingen. De kwaliteit van MPR’s uit het axiale vlak is vergelijkbaar met afbeeldingen verkregen door direct scannen in de corresponderende richtingen.
Concluderend wordt voor routinematige, preoperatieve beeldvorming bij cochleaire implantatie kandidaten een complete axiale CT dataset aangeraden, met reconstructies in de semilongitudinale en axiopetrosale vlakken. Het gebruik van alleen het axiale CT scanvlak vermindert de stralenbelasting en artefacten door gebitsvullingen worden vermeden. De beperkte scantijd vermindert de behoefte aan anaesthesie bij kinderen en tijd, geld en radiologische capaciteit worden bespaard.

In **Hoofdstuk 6** wordt de postoperatieve beeldvorming belicht.
De resultaten van cochleaire implantatie hangen onder meer af van het aantal ingebrachte elektroden en hun positie in de cochlea. Daarom telt de chirurg tijdens de operatie het

aantal ingebrachte elektroden. Een alternatief hiervoor vormt radiologische afbeelding van het aantal ingebrachte elektroden.

In de literatuur worden voornamelijk röntgenfotografie en CT technieken besproken. Röntgenfoto's worden bekritiseerd omdat hiermee de elektrodenlengte onderschat wordt. Door overprojectie worden interessante details vaak gemaskeerd. Voorts wordt in de literatuur getwijfeld aan de betrouwbaarheid van de peroperatieve telling.

Wij vergeleken onze vaststelling van het aantal ingebrachte elektroden - door middel van peroperatieve telling en postoperatieve röntgenfotografie met Stenvers projectie - met de resultaten van postoperatieve functiemeting van de elektroden. Het aantal ingebrachte elektroden zoals geschat tijdens de operatie kwam overeen met het aantal functionerende elektroden bij postoperatieve meting. Hier uit volgt dat postoperatieve beeldvorming alleen nodig is wanneer er een discrepantie bestaat tussen de peroperatieve telling en de postoperatieve meting.

Röntgenfotografie met Stenvers projectie leverde betrouwbare schattingen op van het aantal ingebrachte elektroden. Wij concluderen dan ook dat röntgenfoto's met Stenvers projectie adequaat zijn voor vaststelling van het aantal ingebrachte elektroden.

Een CT scan hoeft alleen gemaakt te worden wanneer röntgenfoto's geen uitsluitsel bieden of wanneer *characteristic frequency mapping* is gewenst voor *speech-processing* strategieën.

Conclusies

1. Bij de routinematige beeldvorming voor cochleaire implantatie volstaat CT in het axiale vlak met reconstructies in de axiopetrosale en semilongitudinale vlakken.
2. Hiermee kan de anatomie van het rotsbeen - in het bijzonder de cochleaire doorgankelijkheid, de recessus facialis breedte en de diameter van de benige begrenzing van de nervus cochlearis - worden beoordeeld.
3. Hierbij dient men zich te realiseren dat CT een beperkte sensitiviteit en specificiteit heeft bij beoordeling van de cochleaire doorgankelijkheid en de recessus facialis breedte.

4. MRI is alleen nodig bij patiënten met doofheid die mogelijk veroorzaakt wordt door een probleem in de centrale akoestische zenuwbanen.
5. Peroperatieve tellingen van het aantal ingebrachte elektroden zijn betrouwbaar.
6. Radiodiagnostiek ter vaststelling van het aantal ingebrachte elektroden is alleen nodig wanneer er een discrepantie bestaat tussen het peroperatief vastgestelde aantal ingebrachte elektroden en de postoperatieve functiemeting.
7. Röntgenfoto's met Stenvers projectie volstaan voor vaststelling van het aantal ingebrachte elektroden.
8. Een CT scan hoeft alleen gemaakt te worden wanneer röntgenfoto's geen uitsluitsel bieden of wanneer *characteristic frequency mapping* gewenst is voor *speech-processing* strategieën.

Toekomstige Ontwikkelingen

In onze studies werd gebruik gemaakt van de zogenaamde *slice-to-slice* CT techniek met *slice overlap*. Tegenwoordig kunnen *multislice scanners* isotrope datasets creëren met een verbeterde beeldresolutie zodat eenvoudig kwalitatief hoogwaardige reconstructies te maken zijn.

In de toekomst zou virtuele endoscopie mogelijkheden kunnen bieden om de chirurgische procedure preoperatief te oefenen. Zogenaamde *image guided* chirurgische navigatie wordt al in diverse medische gebieden toegepast, echter de beeldresolutie is vooralsnog te gering voor microchirurgische procedures. Men verwacht dat *multislice* CT dit probleem zal oplossen.

Een andere aanpak zou peroperatieve CT zijn, hoewel dit hoge eisen stelt aan de infrastructuur en logistiek. De operatie zou dan moeten worden uitgevoerd op de radiologie afdeling of men zou een speciale CT scanner in de operatiekamer moeten plaatsen.

MRI in de huidige vorm is alleen nodig bij patiënten met een mogelijke aandoening van het centrale zenuwstelsel, waarbij dan de anatomie wordt onderzocht van de centrale akoestische zenuwbanen: van de cochleaire nuclei tot aan de akoestische hersenschors.

In de nabije toekomst zou de zogenaamde functionele MRI - waarmee de respons van de centrale akoestische zenuwbanen op auditieve stimuli wordt getest - nieuwe criteria kunnen toevoegen in de selectieprocedure van kandidaten voor cochleaire implantatie.

9

Dankwoord

Dankwoord

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Curriculum vitae

Curriculum vitae

Robert Bettman werd geboren op 29 juni 1970 te Utrecht. In 1988 behaalde de auteur het VWO diploma, waarna hij begon met de studie Geneeskunde aan de Rijksuniversiteit Groningen. De co-schappen werden ondermeer doorlopen in Bombay, Deventer en Maastricht. Het artsexamen werd behaald einde 1995. Nadien volgde een korte periode als arts-assistent Longziekten in het toenmalig St Maartens Gasthuis te Venlo.

De opleiding tot KNO-arts werd van medio 1996 tot medio 2002 gevolgd in het Universitair Medisch Centrum Utrecht, onder leiding van achtereenvolgens prof. dr. E.H. Huizing en prof. dr. G.J. Hordijk. De B-opleiding werd gevolgd in Apeldoorn onder leiding van drs. J.B. Antvelink. In 2002 werd toegetreden tot de maatschap KNO in het Ziekenhuis St Jansdal te Harderwijk.

Dit proefschrift werd geschreven in de periode 1997-2003.

De auteur is gehuwd met Anouk Gökemeyer. Zij hebben een zoon, genaamd Govert.