The cochlea depicted: radiological evaluation of cochlear morphology and the implanted cochlea

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Chapter 7

Discussion

Discussion and implications for future developments

The goal of this thesis was to gain insight into cochlear morphology and the intra-cochlear position of cochlear implant electrode arrays and, in this way, contribute to the overall aim of cochlear implantation: to improve speech perception in recipients of cochlear implants.

Imaging techniques and applications

Since the first cochlear implantations were performed in the 1960's, the quality of both CTs and MRIs has improved enormously. Currently, CTs and MRIs are considered valuable assets for detecting the most clinically relevant pathologies and anatomical deviations prior to implantation and for evaluating the intra-cochlear position of the electrode array after implantation. Nevertheless, improving image quality to reveal more anatomical details is an important motivation for the ongoing development of imaging techniques and applications.

In the field of cochlear implantation, growing interest exists in improving assessments of cochlear shape, cochlear patency, and inner ear neural structures of candidates for cochlear implants. In Chapter 2, we explored the potential of ultra-high 7T MRI for improving the visualization of inner ear structures. Currently, MRI scanners with a magnetic field strength of 1.5T or 3T are routinely used in clinical practice. These images provide a clear depiction of the fluid-filled cochlea and labyrinth within the dense otic capsule. Additionally, the inner ear canal, with its facial, cochlear, and vestibular nerves, can be evaluated thoroughly with either 1.5T or 3T MRI. Nevertheless, visualizations of the membranous structures in the cochlea and the finer structures of the neural pathways remain challenging in inner ear imaging. In our study (described in Chapter 2), the increased SNR provided by 7T MRI enhanced the representation of most of the small-sized, delicate anatomic structures, compared to 3T MRI. Specifically, Reissner's membrane, which delineates the scala media, could be distinguished in 7 out of 52 evaluations of 7T images, compared to none of the evaluations of 3T images. Nevertheless, this benefit was modest; thus, further effort is required to improve scan quality and resolution. Furthermore, the clinical relevance of depicting this anatomic region has not been determined, although it is a region of interest, because it houses the Organ of Corti. In addition to more careful evaluations of individual anatomic features, improving the visualization of anatomic structures can generate normative data on, for instance, cochlear size and shape. These data would be particular interesting for cochlear implantations, because they could potentially influence the intra-cochlear positioning of the electrode array[1].

Several known difficulties related to an ultra-high magnetic field were encountered in our study. These difficulties presumably attribute to the fact that, currently, ultra-high 7T MRI is not widely clinically available. The inhomogeneity of the static (B_0) and radiofrequency (B_1) fields resulted in signal loss in the inner ear region. The high-permittivity dielectric pads containing a suspension of barium titanate were indispensable for optimizing the signal in the inner ear region and made it suitable for clinical evaluation[2]. This method is also applicable to other regions of interest, but each region requires a different pad configuration. For inner ear scanning, two geometric designs were developed, based on patient sex. The pads were placed in the head coil, in close proximity to the targeted inner ear.

Although dielectric pads were easy to apply and they optimized the homogeneity in the inner ear region, their clinical applicability is somewhat questionable, because they interfere with the workflow, and most researchers and clinicians lack experience with dielectric pads. Moreover, the usage of the pads prolonged the scan duration, although to a limited extent, and they are susceptible to misplacement or movements, which could lead to non-diagnostic images. Because different anatomic regions require different pad configurations, it takes time to design unique pads for each individual application. Consequently, the extra time, the lack of experience, and the lack of software and resources limit the use of this method by the entire MRI community. To improve accessibility, van Gemert et al. developed an easy-to-use software tool for designing application-specific pads.[3] Hopefully, this software will stimulate clinical implementations of dielectric pads and create more awareness of this method in all fields of MRI, including inner ear imaging. Furthermore, the specific type of scanner operating in our institution and the dielectric pads require CE marking (to declare conformity with European health and safety requirements) and reimbursement. This support is essential for applying our results to a clinical cohort of patients.

Another issue related to ultra-high magnetic field MRI, is the limited tolerance in patients. Dizziness and nausea are the most commonly described side effects associated with 7T scanning[4,5]. In our study, patients did not experience excessive discomfort. However, it is generally expected that, when the magnetic field strength is increased beyond a certain level, patient tolerance will be exceeded, and safety might be compromised. To date, studies have described in vivo human neuroimaging at a maximum of 9.4T for research purposes[6,7]. Once the maximum magnet strength is reached, the quality of images acquired with ultra-high MRI field strength might be further improved with software and hardware developments.

A 3T vs. 7T MRI comparative study of the inner ear is ongoing, and it has included patients with Menière’s disease. Although the latter patient population does not specifically represent the population of individuals that require cochlear implants, unravelling the characteristics related to the underlying causes of hearing loss is extremely relevant to the entire population of patients with hearing loss. In future studies, the increased SNR provided with 7T MRI might benefit investigations of other features of inner ear anatomy, such as the auditory nerve volume. This approach could lead to evaluations of potential correlations between anatomy and speech perception outcomes following cochlear implantations. This information could facilitate patient counselling. Another structure that might benefit from 7T imaging is the cochlear nucleus, located at the dorso-lateral side of the brainstem. This structure is the target area for an auditory brainstem implant, but it is extremely difficult to characterize with routine MRI. Recently, a study showed that 7T diffusion tensor imaging could successfully visualize the location of the cochlear nucleus by evaluating the different orientations of fibres in the different neural pathways[8]. This technique might be used to facilitate the challenging surgical placement of an auditory brainstem implant.

CT image quality has improved over the years. Developments in several aspects of CT imaging, such as detector elements and image reconstruction algorithms, have led to an increased SNR, and images can be acquired within a limited time and radiation dose[9]. The radiation exposure time needs to be limited, due to the risks of cellular damage and cancer development[10]. Therefore, clinical scan protocols seek to apply the least radiation possible without compromising the image quality required for clinical evaluations. The image qualities achieved with current CT imaging techniques were essential for performing the automatic tracing technique we introduced in Chapter 3.

We found that the shape of the basal and second turns of the cochlea could be revealed with an automatic tracing method. This tracing method identified the cochlear boundaries based on differences in voxel density. The results provided insight into the irregularity of the diameter of the cochlear duct and the vertical trajectory of the scala tympani, up to and including the second turn. Beyond the second turn, the delicacy of the cochlear structures increased, and one voxel was too large to capture subtle differentiations. Consequently, the third turn could not be evaluated with this technique. Nevertheless, this tracing method can facilitate the study of individual cochleae, in high detail, before implantation. Thus, special attention can be given to features that might influence the trajectory of the electrode array and features that might increase the risk of electrode array translocation. Additionally, this method could be used to evaluate a large cohort of patients to establish a range of ‘normal’ cochlear dimensions.

In the future, if CT imaging accuracy can be increased with smaller voxels and better SNRs, our automatic tracing technique might be applicable to evaluations of the third turn. Although most existing electrode arrays are not designed to target the most apical areas of the cochlea, this targeting might become possible in the future. In the tracing method described here (Chapter 3), we determined 3 datapoints per cross-sectional mid-modiolus image: one on the innermost wall, one on the outermost wall, and one at the bottom of the scala tympani. In an ongoing study in our institution, Siebrecht et al. are further developing the automatic tracing algorithm. By determining the boundaries of the complete circumference of the cochlear duct, they could generate a 3D volume of the complete cochlear duct. This approach could provide valuable information about the vertical slope and tilting pattern of the scala tympani in individuals, which is relevant for identifying areas at risk of electrode array translocation during insertion. Secondly, evaluation of a large number of patients gains insight in the variability of cochlear duct volumes. Additionally, an accurate representation of the osseous spiral lamina is subject of their ongoing research and could permit an accurate distinction between the scala tympani and the scala vestibuli. Combining these details with the (automatically) determined locations of individual electrode contacts could enable a postoperative evaluation of the intra-cochlear, and potentially translocated, position of the cochlear implant electrode array. Moreover, the algorithm we used can also be applied to MRI datasets. Indeed, the enhanced SNR of the 7T MRI could further improve the accuracy of the tracing technique.

Visualizing the implanted cochlea is challenging, due to the presence of metallic artefacts. Blooming artefacts deteriorate the surrounding anatomical details, which makes it difficult to determine the precise intra-cochlear position of the electrode array. The method we described in Chapter 5 was developed to overcome this problem. By placing the corresponding preoperative image adjacent to the image of the implant in situ, we could determine the intra-cochlear position of individual electrode contacts more accurately. An advantage of this method was that we could avoid using complex, and sometimes time-consuming, co-registration software. The good image quality provided with the latest generation of scanner was a fundamental factor in this method. Surprisingly, although our evaluation of the electrode array location had improved, compared to using only the postoperative scan, we found no difference between using a preoperative CT or a preoperative MRI scan. In fact, we expected that the MRI would provide an advantage, based on its high resolution. A potential explanation for the similarity in CT and MRI results might be that the image quality deteriorated after retrieving, processing, and storing the images on multiple computer systems and after applying multiple programs to create multiplanar reconstructions (MPRs) for 3D image processing. Additionally, part of the explanation could be that some of the observers were more familiar with CT images than with MRIs. Nevertheless, at this point, this method is highly eligible for clinical evaluation, due to its feasibility and its independence from any additional software. Future evolution of techniques involving image quality are likely to improve the abilities of both CT and MRI to visualize the anatomic structures depicted in mid-modiolus cross-sectional images.

Several other methods have been described for thoroughly evaluating the intra-cochlear position of cochlear implant electrode arrays. Among those methods, some have incorporated image segmentation techniques[11]. This image processing technique uses computer algorithms to partition a digital image into multiple segments. For example, Huetink et al.[12] described an automatic segmentation method, based on a deep learning framework, developed with an extensive clinical dataset of ultra-high resolution CT images. Following segmentation, the obtained image volumes were used for comprehensive measurements; however, they could also be used for co-registration or image fusion techniques. Image fusion techniques provide a means to combine details from two different scans. In the context of cochlear implantation, it is interesting to combine scans acquired before and after implantation. With this approach, it is possible to avoid the deterioration of intra-cochlear anatomic details, due to metallic artefacts caused by the electrode array. With co-registration techniques, it is possible to align scans from different modalities, like MRI and CT, where each scan shows different anatomic details. Previous studies have described various applications of co-registration in the field of cochlear implantation; for example, co-registration was used to align a clinical postoperative scan with a preoperative CT scan of the same patient; with the contralateral ear of the postoperative scan; or with a model, based on micro-CT data [13–15]. Because cochlear morphology is highly variable among patients (see Chapter 3), one must be aware that, when a general model is used, these variations may cause inaccurate alignments.

The development of functional imaging techniques is beyond of the scope of this thesis, but these techniques are potentially relevant for future implications. Functional imaging techniques rely on activity, rather than anatomic detail. Increasingly, the potential of these techniques for visualizing the auditory pathway has been explored, and they may be applicable to cochlear implant patients and candidates. The regularly used imaging modalities do not portray the fine neural structures of the auditory nerve, the hair cells of the Organ of Corti, the spiral ganglion neurons, or their connecting neural pathways, from the inner ear to the auditory cortex. Information about the condition of these neural structures, indicated by their functioning, might be correlated to the underlying cause of hearing loss, and the probability or prognosis of partially restoring hearing.

Intra-cochlear position of the cochlear implant electrode array

Improvements in imaging techniques and applications have made it possible to assess the intra-cochlear position of a cochlear implant electrode array more carefully. In fact, the intra-cochlear positions of several cochlear implant electrode array designs can be evaluated to determine whether they achieve the position they were specifically designed to target. Frequently, studies assess three features of the intra-cochlear position of cochlear implant electrode arrays that are thought to influence speech perception outcomes: the angular insertion depth, the proximity of the electrode to the modiolus, and more recently, the scalar location.

In Chapter 4, we compared the intra-cochlear positions of the straight HiFocus 1J electrode array and the pre-curved HiFocus MS electrode array. Compared to the HiFocus MS electrode array, on average, the angular insertion depth of the HiFocus 1J electrode array was 50 degrees deeper, with a mean depth of 478°. However, its angular insertion depth was less consistent, with a 37 degrees larger standard deviation, than those observed with the HiFocus MS array. However, in two groups of patients that had been matched, based on the preoperative speech perception scores, the duration of deafness, and the age at implantation, we found similar speech perception outcomes; moreover, the outcomes were not influenced by the angular insertion depth or frequency mismatch.

The angular insertion depth depends on the length of the electrode array, surgical insertion depth, the intrascalar position of the electrode array and the size of the cochlea. Hypothetically, an electrode array that covers a larger part of the cochlea should result in better speech recognition. However, convincing support for this hypothesis is lacking[16], due to conflicting outcomes from studies that evaluated different electrode designs and their related angular insertion depths[16]. Contributing to this ambiguity, it is debated which part of the neural pathway is stimulated, or should ideally be stimulated, by the cochlear implant electrode contacts. It remains unclear what role is played by the peripheral processes between the Organ of Corti and the bodies of the spiral ganglion cells in Rosenthal's canal. If they contribute substantially to hearing, then stimulating the more apical regions of the cochlea might improve speech perception outcomes. However, the curvy alignment of the central axons in the more apical regions are likely to result in broader, overlapping excitation regions; thus, stimulating the lower frequencies might provide limited benefit[17]. Furthermore, the potential advantage of deeply inserted cochlear implant electrode arrays might be offset by the increased risk of insertion trauma and the subsequent formation of fibrosis, or in cases of extensive trauma, damage to neural structures. Additionally, the cochlear blood flow toward the apical neural structures might be pinched, when the diameter of the cochlear implant electrode array is not matched to the diameter of the cochlear duct.

Another issue of debate is the optimal proximity of the electrode contacts to the modiolus. Cochlear implant electrode arrays that hug the modiolus can achieve a more focussed stimulation, and they have a longer battery life, due to less power consumption. However, this type of cochlear implant electrode array also increases the risk of insertion trauma, due to its increased stiffness. In addition, a potential mismatch between the curve of the array and the individual coiling pattern of the cochlea can cause the electrode array to be positioned too close or too far away from the inner wall, which can result in less effective electric current focussing. To date, there is no convincing evidence that either modiolus-hugging or lateral wall proximity results in superior speech perception outcomes. Consequently, this issue remains a subject of ongoing research.

Over time, it became clear that in a certain number of cases the CI electrode array inadvertently translocates from the targeted scala tympani into the scala vestibuli during insertion. Indeed, some studies have reported a 100% incidence of translocation[18]. Due to the expansion of patient inclusion criteria, interest has focussed on preventing insertion trauma to retain residual hearing. It is generally believed that retaining the intra-cochlear architecture as much as possible will provide the most favourable situation for electrically stimulating the neural components. Nevertheless, previous studies that focused on the effects of electrode array translocation on speech perception outcomes have reported ambiguous findings[19–23]. For example, in the study we described in Chapter 6, we did not find a difference in speech perception outcomes between patients with translocated electrode arrays and patients with electrode arrays located completely in the scala tympani, despite corrections for factors known to influence speech perception outcomes. Zelener et al. found a perfect intelligibility score of 100% in a patient with a translocated HiFocus MS electrode array[22], which further illustrated the uncertain relationship between traumatic insertions and speech perception outcomes. Perhaps the electrical stimulus bypasses the damaged parts of the cochlea and predominantly stimulates the central axons of the auditory nerve located within the modiolus. Nevertheless, despite the lack of unambiguous proof that insertion trauma is strongly correlated with hearing outcomes, an atraumatic insertion remains the goal, to preserve residual hearing, allow EAS, and prevent fibrosis and ossification. Preventing fibrosis and ossification is important, in case a future re-implantation is necessary, which is particularly common among children with cochlear implants. Therefore, identifying risk factors related to insertion trauma remains an important goal.

The most frequently studied potential risk factors for insertion trauma are the surgical approach and the implant design. Previous studies showed that pre-curved electrode arrays and insertions through a cochleostomy were the most harmful insertion methods[24]. In Chapter 6, we investigated the effects of the surgical approach and the time of insertion on the risk of translocation. An insertion time of 25 s or longer was associated with less frequent translocations of the cochlear implant electrode array. A determination of whether the electrode array has translocated constitutes important feedback for the surgeon. With this information, the surgeon can study the relationship between translocations and the characteristics of the surgical procedure, such as the directional vector of insertion, the experience of resistance during insertion, or problems with twisting or buckling of the electrode array. A prolonged insertion time is applicable to all implant designs, and it is potentially most relevant in cochleae with a steep increase in the vertical trajectory, which can be measured with the method we introduced in Chapter 3. However, implant designs are highly variable in the relevant mechanical properties. Therefore, the optimal surgical approach and insertion time must be evaluated for each electrode design. In addition, the surgical approach also depends on round window accessibility, because the angulation of the round window and the route of the facial nerve are potential limitations[25].

Future research should investigate other ways, beyond the topics of this thesis, to gain insight into the course of the electrode array during insertion, by obtaining direct, real-time feedback during surgery. It has been proposed that this feedback could be achieved with electrocochleography (ECochG). With ECochG, cochlear function can be determined by measuring reflective hair cell activation, a process called cochlear microphonics. Hypothetically, when insertion trauma occurs, the hair cells are damaged, and cochlear microphonics can no longer be detected. Adunka et al. studied cochlear responses after different, consecutive surgical steps[26]. Cochlear microphonics remained intact during the first surgical steps, which included drilling a cochleostomy and opening the round window membrane. After the electrode array was inserted, the cochlear microphonic amplitudes dropped, but they remained detectable, which implied persistent cochlear function. However, in many cases, no residual hearing could be detected after implantation. That finding suggested that drilling and a drop in perilymph pressure after opening the scala tympani did not stress the hair cells sufficiently to cause damage, but introducing the electrode array into the cochlear canal probably caused damage, either due to the steep increase in fluid pressure[27] or due to direct mechanical stress. Another interpretation of these results might be that the damage did not occur during surgery, but developed later, due to the molecular and cellular responses to the foreign object[28]. This mechanism might also explain the change in residual hearing over time; indeed, in some cases, hearing is partially restored a long time after surgery. This ‘dynamic’ factor makes it difficult to correlate ECochG measurements with cochlear implant outcomes. Other investigators who have studied ECochG patterns during insertions to predict the scalar also showed largely variable changes of the ECochG patterns during insertion among different patients and with different cochlear implant designs[29,30]. Consequently, ECochG has not been accepted as a completely reliable method for scalar localization.

Other methods proposed for real-time feedback during surgery include the detection of evoked compound action potentials and impedances[31,32]. Furthermore, it has been suggested that intraoperative imaging, with conventional X-ray, CT, or fluoroscopy, could provide feedback during the insertion of the cochlear implant electrode array[33]. However, that method has major drawbacks, including radiation exposure, prolonged surgical and anaesthesia times, and the associated increase in cost. Therefore, many institutions have reserved intraoperative imaging for cases with difficult anatomy that is expected to impede electrode placement.

Methods are also being explored for (partially) restoring or limiting intra-cochlear damage, for situations when insertion trauma is unavoidable. Corticosteroids, applied either locally or intravenously, have been tested prior to, during, or following implantation, to reduce stress reactions and the activation of ototoxic cytokines. Some studies have reported that residual hearing was improved with steroid treatments, and a recent meta-analysis indicated that intraoperative topical and postoperative oral steroids were beneficial[34]. Hypothermia is another method that was proposed for reducing damage during or after insertion[35,36].

However, the limited evidence from available studies did not convincingly support this proposal.

Towards patient-tailored implantation

The key to improving speech perception outcomes with cochlear implants might be patient-tailored cochlear implantations. Currently, several prototypes of cochlear implant designs are available on the market, but the choice of design generally depends less on patient characteristics, than on the experience of the surgeon and the availability of a design in a given cochlear implant centre. An exception is the dual electrode array design, which can be used in a partially ossified cochlea, which may occur after meningitis. Moreover, some studies have described deliberate partial insertions. This approach specifically focuses on impairments in the high frequencies; partial insertions aim to stimulate only the neural components located at the basal part of the cochlea, without affecting residual hearing in the lower frequency areas; thus, making EAS feasible. Then, when lower frequency hearing deteriorates, for example, due to aging, the same electrode array can be advanced deeper into the cochlea[37].

The large variability in cochlear dimensions described in Chapter 4, has emphasized the need to step away from the ‘one size fits all’ concept of cochlear implant electrode arrays. By studying the morphology of the cochlea in high detail, prior to implantation, areas at risk of translocation can be predicted, and the surgeon can adjust the surgical technique accordingly. For instance, a specific surgical approach might be indicated, or the surgeon might simply slow down the insertion, when approaching high-risk areas. Moreover, the type or length of the electrode array can be chosen, based on morphological or even genetic characteristics. Of course, this requires a different, and presumably more time-consuming approach in the pre-operative work-up. However, appropriate work-ups may eventually lead to improved speech understanding in recipients of cochlear implants.

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