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

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Chapter 1

Introduction

Introduction

Hearing loss and rehabilitation

Hearing loss affects a large part of the world's population; it is the fourth most common cause of disabilities worldwide[1]. The World Health Organization (WHO) reported that, currently, 466 million people, including 34 million children, experience disabling hearing loss[2]. This number will likely grow rapidly in the next decades, due to increases in life span and cumulative noise exposure. Apart from the primary effect of impaired communication, hearing loss also impacts an individual's psychosocial, health, and economic status[3]. Hearing loss can arise from many genetic or acquired defects, and its severity and progression vary widely among patients. A large part of the affected population has age-related hearing loss (i.e., presbycusis), which is mostly due to degeneration of the sensory hair cells of the organ of Corti in the cochlea. However, this process is often accelerated by the damaging effects of noise exposure, ototoxic drugs, or increased hair cell susceptibility, due to genetic disposition. This can lead to profound, sensorineural hearing loss, which is not always treatable with conventional hearing aids. Hearing loss is typically categorized as conductive or sensorineural. Conductive hearing loss is a limitation in the transmission of sound from the outer world towards the inner ear, due to pathology in the outer or middle ear. Normally, sound pressure alterations are transmitted from the eardrum, through the ossicular chain in the middle ear, towards the oval window. The oval window communicates with the perilymph fluid in the vestibule and the scala vestibuli of the cochlea. Thus, sound pressures cause movements in the perilymph, which bend the stereocilia of the sensory hair cells, and this bending elicits a neural signal. In contrast, sensorineural hearing loss is caused by functional impairments in the sensory hair cells, the neural components of the cochlea, or the auditory nerve. Most conductive hearing loss and most light or moderate sensorineural hearing loss can be treated by fitting the patient with conventional hearing aids, implanting a bone conduction device in the skull, or surgically restoring the ossicles. However, these interventions cannot sufficiently restore hearing in individuals with severe-to-profound sensorineural hearing loss. In these individuals, cochlear implantation became the standard of care.

Cochlear implantation

A cochlear implant device bypasses the middle ear and the damaged structures of the cochlea and directly stimulates the nerve fibres of the auditory nerve. The cochlear implant comprises an electrode array that is surgically placed within the cochlea, preferably in the scala tympani (Figure 1). The device consists of an external microphone that captures environmental sounds and a speech processor that filters and converts the sounds into a digital code. The digitized signal is sent to a headpiece, which transmits the signal to a subcutaneous receiver embedded in the skull. The receiver responds to these signals by sending electrical stimuli through an internal wire to the individual contacts in an electrode array. The electrode array is inserted into scala tympani of the cochlea. The electrode contacts sense frequency-specific signals. The frequency-specific electrode arrangement reflects the tonotopical organization of the cochlea. Thus, high frequency sounds are transmitted to the base of the cochlea, and lower frequency sounds are transmitted to the apical part of the cochlea.

The most common surgical procedure for a cochlear implantation consists of a canal wall up mastoidectomy and posterior tympanotomy, which provide access to the round window. Subsequently, the electrode array can be introduced into the cochlea, either through a(n) (extended) round window approach or a cochleostomy.

Figure 1: Illustration of a cochlear implant device (right ear) with the external and internal components. The external components include the microphone, speech processor and headpiece. The internal components consist of the internal receiver, internal wire and electrode array inside the cochlea. Image courtesy of Prof. Völter, head of Hearing competence centre Ruhr-University Bochum, Germany.

William F. House is considered the founder of cochlear implantation[4]. Early in his career, in 1958, one of his patients showed him a newspaper report that described an experiment performed by Djourno and Eyries in France. They had placed an electrode directly on part of an exposed auditory nerve[5]. With this electrode, a patient with hearing loss could experience sound; however, speech recognition was not yet achieved. Eventually, Dr. House became thoroughly involved in developing a cochlear implant. He developed the first implant, with a single electrode that could be placed into the cochlea, and it could stimulate the neural components by producing a periodic pitch. Since then, many researchers, clinicians, and engineers all over the world have become involved in developing cochlear implants. An early trial by House et al. tested a single-channel functioning cochlear implant, which showed some basic functions in 13 patients[6]. These patients could not understand speech through their implants; however, it significantly improved environmental sound recognition and enhanced their lip-reading capacities. Additionally, that trial demonstrated the safety of the procedure, which led to FDA approval. Subsequently, the Australian, Graham Clarke, developed a cochlear implant with multiple channels. This configuration allowed frequency place coding that mimicked the tonotopical organization of the cochlea[7]. The development of multi-channel cochlear implants represented a large leap towards a device that could provide speech understanding[8]. Currently, thousands of patients per year receive cochlear implants worldwide, and speech perception scores are gradually approaching the level of normal hearing.

Imaging in cochlear implantation

Imaging plays a central role in several aspects of cochlear implantation. Depictions of the inner ear provide insight into the possible underlying causes of hearing loss and the variety of temporal bone anatomy. Previous studies have revealed that the human cochlea is extensively varied in shape, size, and coiling pattern[9–11]. This variability may have implications for cochlear implantation, in terms of surgical aspects, the choice of electrode array, and potentially, speech perception outcomes. In our institution, both computed tomography (CT) and magnetic resonance imaging (MRI) are performed in the preoperative work-up for cochlear implant candidates. These modalities have complementing capacities. However, it should be noted that this approach varies among cochlear implant centres worldwide.

Preoperative assessments provide insight into whether the cochlea is normally developed, with an average of 2.6 cochlear turns[11], and whether the cochlear duct is patent. In addition, retrocochlear pathology can be assessed and it provides a map of temporal bone anatomy. This information supports surgical planning and allows the surgeon to anticipate potential surgical difficulties[12]. For instance, a high jugular bulb can limit access to the round window niche, or an overhanging tympanic tegmen increases the risk of causing a cerebrospinal leak when drilling for the mastoidectomy. In some cases, preoperative imaging of the inner ear plays a crucial role in selecting the 'best' ear for implantation. CT is superior to MRI for delineating osseous components, and it is commonly used for preoperative evaluations of the temporal bone[13,14]. When cochlear implantation was first launched, the clinical value of MRI had not been standardized for cochlear implant candidacy[12]. Later, it was shown that fibrosis could be detected on T1- and T2-weighted MRI images of an obliterated cochlea[12]. However, despite this acknowledged added value, MRIs required thick slices and long acquisition times, which impaired accurate evaluations and made MRIs unsuitable for clinical applications. Subsequently, clinically applicable 1.5 Tesla (T) and 3T MRIs were introduced, with new pulse sequences and multi-channel phased array coils, which made it possible to achieve a high signal-to-noise ratio (SNR), within a limited scan duration[15]. In addition, the administration of intravenous gadolinium further increased the ability to detect small lesions[16]. Currently, the entire pathway, from the outer ear canal to the auditory cortex, can be depicted in high detail with high resolution MRI. MRI scans are superior to CT scans in depicting soft tissues; thus, MRIs are mainly deployed to evaluate the entire auditory nerve tract, from the cochlea to the brainstem.

Currently, 1.5 or 3T MRI scanners are used in clinical practice. However, scanners with higher field strengths might potentially increase the SNR. A better SNR allows analysis with a reduced voxel size, which provides a more refined delineation of the anatomical structures. However, in strong magnetic fields, image quality can be degraded, due to image artefacts caused by interactions between the patient and the radiofrequency field[17]. Furthermore, ultra-high magnetic field imaging increases the tissue temperature and causes unpleasant side effects, like dizziness and nausea, which impede its clinical use[18]. Brink et al. conducted a study to determine whether artefact issues in inner ear imaging might be overcome with dielectric ear pads[19]. The pads were filled with barium titanate, and they enhanced the B_1^+ field signal and improved the quality of imaging in the inner ear region. Additionally, they investigated subjective experiences and discomfort. Based on those results, the pads were deemed to be safe[18]. These pads facilitated further explorations that aimed to determine the potential of 7T imaging in the inner ear (Chapter 2).

In many centres, after implantation, part of the standard work-up is to assess the intra-cochlear position of the cochlear implant electrode array, typically with conventional X-ray or CT imaging. With conventional X-ray, patients are exposed to a limited radiation dose. However, a multi-section CT (MSCT) scan provides more detail in visualizing the temporal bone structures and the position of the electrode array after implantation[20]. MRI is avoided in evaluating the implanted cochlea, due to the risk of displacing or demagnetizing the subcutaneous receiver, which could require removal of the magnet. Nevertheless, for other indications that require MRI-based evaluations of the head region in patients with cochlear implants, some manufactures are developing MRI-compatible electrode designs, and a few designs have met safety requirements[21].

Postoperative images provide feedback on the surgical procedure; for example, imaging is performed to ensure the (entire) electrode array is correctly placed in the targeted scala tympani. In addition, imaging provides a means to check for signs of kinking in the wire or a fold at the tip. Although rare, sometimes imaging reveals that the electrode array is situated in an undesirable position, like in the internal auditory canal or in the middle ear[22]. In more detail, the insertion depth of the electrode array and proximity of the individual electrode contacts to the modiolus can be evaluated. These postoperative findings may have clinical implications; thus, increasingly, researchers are investigating the postoperative position of electrode arrays for potential influences on speech perception outcomes.

Intra-cochlear position

Variability in speech perception with a cochlear implant is thought to be partly due to differences in the intra-cochlear position of the electrode array and the presence and degree of insertion trauma. Current imaging techniques provide an accurate depiction of the intra-cochlear position of the electrode array for evaluations of surgical- and design-related effects on speech perception. Various studies have investigated the insertion depth of the electrode array, described as either a linear or angular depth, and its relationship to speech understanding. Based on some theories, it was postulated that a deeper insertion might provide better speech understanding, because this placement could facilitate stimulation of the lower frequencies in the more apical region of the cochlea[23,24]. Opposing theories postulated a negative impact on speech perception outcomes, because (1) the gradually decreasing size of the cochlear duct presents a higher risk of insertion trauma and loss of residual hearing[25], (2) a deep insertion might limit stimulation of the high frequency regions in the basal part of the cochlea, or (3) the spiral ganglion cells are more closely organized in the apical region, which might lead to pitch confusion[26]. However, a recent systematic review that addressed this topic did not find evidence to support any of these hypotheses[27]. A potential explanation for this lack of evidence might be the heterogeneity of the studied populations. Frequently, studies are not comparable, in terms of inclusion criteria, baseline characteristics and evaluation methods. Fair comparisons between studies are limited, when the results are not consistently stratified for well-recognized patient-related factors that can influence speech recognition. These factors include: age at implantation; some aetiologies of deafness, such as meningitis; the presence or absence of residual hearing; the duration of deafness; and the preoperative level of speech recognition[28–31]. In addition, presumably, intelligence, brain plasticity, and motivation for rehabilitation might explain some of the variability in performance among patients with cochlear implants, but these influences are difficult to objectify.

Another frequently investigated radiological feature is the distance between the electrode contacts and the inner cochlear wall. This distance can be measured, due to the SNR improvements achieved with the advent of high resolution MSCT imaging[32]. The distance between an electrode contact and the inner cochlear wall influences the pattern of stimulation at the neural fibres in the modiolus. Cochlear implants generally aim to stimulate as many neural fibres as possible, while limiting stimulating overlapping regions by adjacent electrode contacts. Various electrode designs were proposed to achieve the ultimate stimulation by achieving different horizontal intra-scalar positions, either resting on the lateral wall or hugging the modiolus, combined with different speech coding strategies. However, in addition to implant design, it is important to be aware of the large variety of cochlear morphologies, which also impact the electrode position, in terms of the insertion depth and proximity to the modiolus[9]. Postoperative imaging techniques allow an evaluation of the specific cochlear implant design, the individual morphological characteristics, and their potential influences on speech perception. To date, no study has demonstrated superiority for any of the specific electrode designs. However, comparison of electrode designs is difficult due to selection bias and, in case of multicentre studies, data heterogeneity due to differences in clinical approach. Nevertheless, a recent study comparing a straight and precurved cochlear implant design from one manufacturer showed superior speech perception outcomes in the group of 85 patients who received a precurved electrode array[33].

Improvements in the abilities of cochlear implants to enhance speech perception have led to more flexibility in patient selection criteria; thus, patients with residual hearing are also considered candidates for cochlear implants[34,35]. These extended selection criteria have prompted improvements in cochlear implantation techniques. Companies began to investigate electrode array designs that reduced the risk of insertion trauma to preserve residual hearing and to maintain the integrity of intra-cochlear anatomy as much as possible. Thus, it is possible to consider a combination of electric and acoustic stimulation (EAS) for patients with residual hearing[36]. With the EAS approach, a cochlear implant stimulates the basal neurons and a conventional hearing aid rehabilitates the lower frequency range. This combination has improved hearing capabilities, compared to a conventional hearing aid or a cochlear implant alone[37]. The ambition of preserving residual hearing has also led to the development of so-called soft-surgery techniques. These techniques were first described in 1993, and they aimed to limit intra-cochlear damage caused by the electrode array insertion[38].

Insertion trauma

When the cochlear implant is inserted, the electrode array is targeted to the scala tympani (Figure 2), one of the three fluid-filled compartments of the cochlea. The rationale behind this positioning lies first in accessibility; i.e., the scala tympani can be reached through the round window; and second, proximity, because the electrode array can be placed close to the targeted spiral ganglion cells. From previous studies, we know that the central axons of the spiral ganglion cells are less susceptible to degeneration than the more peripheral parts of the neural fibres[39]; thus, the central axons are favoured for stimulation. In some unfortunate cases, the electrode array becomes translocated; that is, it traverses from the scala tympani into the scala vestibuli, by penetrating the basilar membrane, the osseous spiral lamina, or both. In those cases, the peripheral neural components deteriorate, and the electrode contacts are positioned further away from the targeted spiral ganglion cells and their central axons. Furthermore, translocation may lead to extensive fibrosis or even ossification, which limits the electrical stimulation of neural fibres, impairs residual hearing, and reduces the probability of an optimal re-implantation in the future, which is necessary in a large part of the younger population, due to the expected lifespan of the implant. Apart from an implant translocation, other, more subtle, traumas can occur after the electrode array is introduced into the cochlea. For example, a leak of perilymph fluid can reduce the intra-scalar pressure; or the cells may mount a response to the foreign body, which can cause damage from toxins, fibrosis, and/or ossification[40]. Unfortunately, these subtle changes cannot be detected with current clinical imaging techniques.

Several imaging techniques are used in in-vivo studies to determine the intra-cochlear position of the electrode array, including cone beam CT, flat-panel CT, conventional X-rays, or MSCT. However, depending on the type of scanner employed, it can be challenging to obtain an accurate determination of the position of the individual electrode contacts, due to blooming artefacts that emanate from the implant's metal components. A blooming artefact can blur anatomical structures, such as the osseous spiral lamina, and the basilar membrane. Several solutions have been proposed to overcome this problem. For instance, anatomic structures can be reconstructed with registration techniques, based on one or multiple templates from micro-CT data[41,42]. Another option is to overlay a preoperative scan of the patient[43]. However, because cochlear morphology is known to be highly variable among patients, it must be kept in mind that general templates might not be useful, due to the potential for inaccurate alignments.

Insertion trauma is not an uncommon event. A systematic review by Hoskinson et al. reported an overall insertion trauma rate of 17.6%[44]. That rate was based on data from both in-vivo and ex-vivo studies; thus, in addition to array translocations into the scala vestibuli, the trauma rate included elevations and disruptions of the basilar membrane, which were detected on histological images. To evaluate the probability of translocation for cochlear implant electrode arrays, we must identify relevant risk factors. Risk factors might be associated with the surgical approach or technique, the morphological characteristics of the cochlea, or the design of the cochlear implant electrode array. Moreover, the impact of a scalar translocation must be further clarified. A few studies have shown the benefit of positioning the array completely in the scala tympani[42,45,46].

Figure 2: Histological mid-modiolus cross-sectional image of a cochlea. The electrode array is targeted to the scala tympani (*); translocation can occur into the scala vestibuli (º) or the scala media (•). The scala media is the location of the actual hearing organ, the Organ of Corti. Image courtesy of F. Linthicum, House Ear Institute, USA

Aims and outline of this thesis

The aims of this thesis were:

(1) to gain insight into cochlear morphology by investigating the inner ear with high-resolution 7T MRI and by measuring variations in the shape of the cochlear duct by analysing clinical CT images with an automatic tracing method;

(2) to evaluate the intra-cochlear positions of cochlear implant electrode arrays on postoperative CT images, with a special emphasis on insertion trauma, and to correlate these findings with speech intelligibility and surgical techniques.

Chapter 2 describes an investigation into the applicability of using clinical 7T MRI for visualizing the inner ear. It also describes a comparison of 7T and 3T MRI qualities for visualizing anatomic inner ear structures. This investigation required the development of a high-resolution imaging protocol, which included improvements in contrast homogeneity and transmitting efficiency in the region of the inner ear. In Chapter 3, we present an automatic method for tracing the first and second turns of the cochlea in high detail on preoperative CT scans. This method is expected to provide insight into the large variations in cochlear morphology, which could have potential implications for cochlear implantation. In Chapter 4, two cochlear implant electrode designs, the straight HiFocus 1J and the pre-curved HiFocus MS, are compared, in terms of the angular insertion depth, the frequency mismatch, and speech perception outcomes. Chapter 5 describes a study that aimed to facilitate the detection of insertion traumas. In that study, spatially synchronized, pre- and postoperative mid-modiolus, cross-sectional CT and MR images were assessed for their value in detecting the intra-cochlear positions of individual electrode contacts in cochlear implants. Chapter 6 describes the application of this evaluation method. In that study, we evaluated the effects of insertion speed and surgical approach on the risk of insertion trauma in a population that received cochlear implants equipped with the HiFocus MS electrode array. Chapter 7 describes the conclusions from Chapters 2-6, a general discussion, and implications for future developments.

References

1. Vos T, Allen C, Arora M, et al. Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet*. 2016;388(10053):1545-1602. doi:10.1016/S0140-6736(16)31678-6
2. *World Health Organization*.
3. Cunningham LL, Tucci DL. Hearing loss in adults. *N Engl J Med*. 2017;377(25):2465-2473. doi:10.1056/NEJMra1616601
4. Eisenberg LS. The contributions of William F. House to the field of implantable auditory devices. *Hear Res*. 2015;322:52-56. doi:10.1016/j.heares.2014.08.003
5. Eisen MD. Djourno, eyries, and the first implanted electrical neural stimulator to restore hearing. *Otol Neurotol*. 2003;24(3):500-506. doi:10.1097/00129492-200305000-00025
6. Bilger RC, Black FO, Hopkinson NT ME. Implanted auditory prosthesis: an evaluation of subjects presently fitted with cochlear implants. *Trans Sect Otorhinolaryngol Am Acab Ophthalmol Otolaryngol*. 1977;84(4):677-682.
7. Chouard CH. The early days of the multi channel cochlear implant: Efforts and achievement in France. *Hear Res*. 2015;322:47-51. doi:10.1016/j.heares.2014.11.007
8. Clark GM. The multi-channel cochlear implant: Multi-disciplinary development of electrical stimulation of the cochlea and the resulting clinical benefit. *Hear Res*. 2015;322:4-13. doi:10.1016/j.heares.2014.08.002
9. van der Marel KS, Briaire JJ, Wolterbeek R, Snel-Bongers J, Verbist BM, Frijns JHM. Diversity in Cochlear Morphology and Its Influence on Cochlear Implant Electrode Position. *Ear Hear*. November 2013:1-12. doi:10.1097/01.aud.0000436256.06395.63
10. Rask-Andersen H, Liu W, Erixon E, et al. Human cochlea: anatomical characteristics and their relevance for cochlear implantation. *Anat Rec (Hoboken)*. 2012;295(11):1791-1811. doi:10.1002/ar.22599
11. Erixon E, Högstorp H, Wadin K, Rask-Andersen H. Variational anatomy of the human cochlea: implications for cochlear implantation. *Otol Neurotol*. 2009;30(1):14-22. doi:10.1097/MAO.0b013e31818a08e8
12. Harnsberger HR, Dart DJ, Parkin JL, Smoker WR, Osborn AG. Cochlear implant candidates: Assessment with CT and MR imaging. *Radiology*. 1987;164(1):53-57. doi:10.1148/radiology.164.1.3108956
13. Phelps PD, Proops DW. Imaging for cochlear implants. *J Laryngol Otol*. 1999;113(SUPPL. 24):21-23. doi:10.1017/S0022215100146043
14. Verbist BM. Imaging of sensorineural hearing loss: a pattern-based approach to diseases of the inner ear and cerebellopontine angle. *Insights Imaging*. 2012;3(2):139-153. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3314739&tool=pmcentrez&rendertype=abstract. Accessed October 11, 2012.
15. Naganawa S, Nakashima T. Cutting edge of inner ear MRI. *Acta Otolaryngol Suppl*. 2009;(560):15-21. doi:10.1080/00016480902729819

16. Counter S a, Bjelke B, Borg E, Klason T, Chen Z, Duan ML. Magnetic resonance imaging of the membranous labyrinth during in vivo gadolinium (Gd-DTPA-BMA) uptake in the normal and lesioned cochlea. *Neuroreport*. 2000;11(18):3979-3983. http://www.ncbi.nlm.nih.gov/pubmed/11192613.
17. Sled JG, Pike GB. Standing-wave and RF penetration artifacts caused by elliptic geometry: an electrodynamic analysis of MRI. *Ieee Trans Med Imaging*. 1998;17(4):653-662.
18. Versluis MJ, Teeuwisse WM, Kan HE, van Buchem M a, Webb AG, van Osch MJ. Subject tolerance of 7 T MRI examinations. *J Magn Reson Imaging*. 2013;38:722-725. doi:10.1002/jmri.23904
19. Brink WM, van der Jagt AMA, Versluis MJ, Verbist BM, Webb AG. High Permittivity Dielectric Pads Improve High Spatial Resolution Magnetic Resonance Imaging of the Inner Ear at 7 T. *Invest Radiol*. 2014;00(00):1-7.
20. Verbist BM, Joemai RMS, Teeuwisse WM, Veldkamp WJH, Geleijns J, Frijns JHM. Evaluation of 4 multisection CT systems in postoperative imaging of a cochlear implant: a human cadaver and phantom study. *AJNR Am J Neuroradiol*. 2008;29(7):1382-1388. doi:10.3174/ajnr.A1108
21. Cass ND, Honce JM, O’Dell AL, Gubbels SP. First MRI with New Cochlear Implant with Rotatable Internal Magnet System and Proposal for Standardization of Reporting Magnet-Related Artifact Size. *Otol Neurotol*. 2019;40(7):883-891. doi:10.1097/MAO.0000000000002269
22. Mehanna AM, Gamaleldin OA, Fathalla MF. The misplaced cochlear implant electrode array. *Int J Pediatr Otorhinolaryngol*. 2019;117(October 2018):96-104. doi:10.1016/j.ijporl.2018.11.027
23. Başkent D, Shannon R V. Interactions between cochlear implant electrode insertion depth and frequency-place mapping. *J Acoust Soc Am*. 2005;117(3):1405.
24. O’Connell BP, Cakir A, Hunter JB, et al. Electrode Location and Angular Insertion Depth Are Predictors of Audiologic Outcomes in Cochlear Implantation. *Otol Neurotol*. 2016;37(8):1016-1023. doi:10.1097/MAO.0000000000001125
25. Biedron S, Prescher A, Ilgner J, Westhofen M. The internal dimensions of the cochlear scalae with special reference to cochlear electrode insertion trauma. *Otol Neurotol*. 2010;31(5):731-737. doi:10.1097/MAO.0b013e3181d27b5e
26. Gani M, Valentini G, Sigrist A, Kós M-I, Boëx C. Implications of deep electrode insertion on cochlear implant fitting. *J Assoc Res Otolaryngol*. 2007;8(1):69-83. doi:10.1007/s10162-006-0065-4
27. Heutink F, De Rijk SR, Verbist BM, Huinck WJ, Mylanus EAM. Angular Electrode Insertion Depth and Speech Perception in Adults with a Cochlear Implant: A Systematic Review. *Otol Neurotol*. 2019;40(7):900-910. doi:10.1097/MAO.0000000000002298
28. Holden LK, Firszt JB, Reeder RM, Uchanski RM, Dwyer NY, Holden TA. Factors affecting outcomes in cochlear implant recipients implanted with a perimodiolar electrode array located in scala tympani. *Otol Neurotol*. 2016;37(10):1662-1668. doi:10.1097/MAO.0000000000001241
29. Blamey P, Arndt P. Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. *Audiol Neurootol*. 1996;1:293-306.
30. Rubinstein JT, Parkinson WS, Tyler RS, Gantz BJ. Residual speech recognition and cochlear implant performance effects of implantation criteria. *Am J Otol*. 1999;20:445-452.
31. Dijk JE, van Olphen AF, Langereis MC, Mens LHM, Brokx JPL, Smoorenburg GF. Predictors of cochlear implant performance. *Audiology*. 1999;38:109-116.

32. Van Der Beek FB, Briaire JJ, Van Der Marel KS, Verbist BM, Frijns JHM. Intracochlear position of cochlear implants determined using CT scanning versus fitting levels: Higher threshold levels at basal turn. *Audiol Neurotol*. 2016;21(1):54-67. doi:10.1159/000442513
33. Heutink F, Verbist BM, van der Woude, W-J, et al. Factors Influencing Speech Perception in Adults With a Cochlear Implant. *Ear Hear*. 2021;Publish Ahead of Print:1-12. doi:10.1097/aud.0000000000000988
34. Snel-Bongers J, Netten AP, Boermans PPBM, Rotteveel LJC, Briaire JJ, Frijns JHM. Evidence-based inclusion criteria for cochlear implantation in patients with postlingual deafness. *Ear Hear*. 2018;39(5):1008-1014. doi:10.1097/AUD.0000000000000568
35. van der Straaten TFK, Briaire JJ, Vickers D, Boermans PPBM, Frijns JHM. Selection Criteria for Cochlear Implantation in the United Kingdom and Flanders: Toward a Less Restrictive Standard. *Ear Hear*. 2020;42(1):68-75. doi:10.1097/AUD.0000000000000901
36. von Ilberg C, Kiefer J, Tillein J et al. Electric-Acoustic Stimulation of the Auditory System. *ORL J Otorhinolaryngol Relat Spec*. 1999;(61):334-340.
37. Gstoettner WK, van de Heyning P, O'Connor AF, et al. Electric acoustic stimulation of the auditory system: results of a multi-centre investigation. *Acta Otolaryngol*. 2008;128(9):968-975.
38. E. Lehnhardt. Intracochlear placement of cochlear implant electrodes in soft surgery technique. *HNO*. 1993;41(7):356-359.
39. Hinojosa R, Marion M. Histopathology of Profound Sensorineural Deafness. *Ann N Y Acad Sci*. 1983;405(1):459-484. doi:10.1111/j.1749-6632.1983.tb31662.x
40. Carlson ML, Driscoll CLW, Gifford RH, et al. Implications of minimizing trauma during conventional cochlear implantation. *Otol Neurotol*. 2011;32(6):962-968. doi:10.1097/MAO.0b013e3182204526
41. Skinner MW, Holden T a., Whiting BR, et al. In Vivo Estimates of the Position of Advanced Bionics Electrode Arrays in the Human Cochlea. *Ann Otol Rhinol Laryngol*. 2007;116(4):2-24. doi:10.1177/000348940711600401
42. Finley CC, Skinner MW. Role of electrode placement as a contributor to variability in cochlear implant outcomes. *Otol Neurotol*. 2008;29(7):920-928.
43. Schuman T a, Noble JH, Wright CG, Wanna GB, Dawant B, Labadie RF. Anatomic verification of a novel method for precise intrascalar localization of cochlear implant electrodes in adult temporal bones using clinically available computed tomography. *Laryngoscope*. 2010;120(11):2277-2283. doi:10.1002/lary.21104
44. Hoskison E, Mitchell S, Coulson C, Hoskison E, Mitchell S, Coulson C. Systematic review : Radiological and histological evidence of cochlear implant insertion trauma in adult patients Systematic review : Radiological and histological evidence of cochlear implant insertion trauma in adult patients. 2017;0100(June). doi:10.1080/14670100.2017.1330735
45. Shepherd RK, Hatsushika S, Clark GM. Electrical stimulation of the auditory nerve: the effect of electrode position on neural excitation. *Hear Res*. 1993;66(1):108-120.
46. Aschendorff A, Kubalek R, Turowski B, et al. Quality control after cochlear implant surgery by means of rotational tomography. *Otol Neurotol*. 2005;26(1):34-37. http://www.ncbi.nlm.nih.gov/pubmed/15699717.