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

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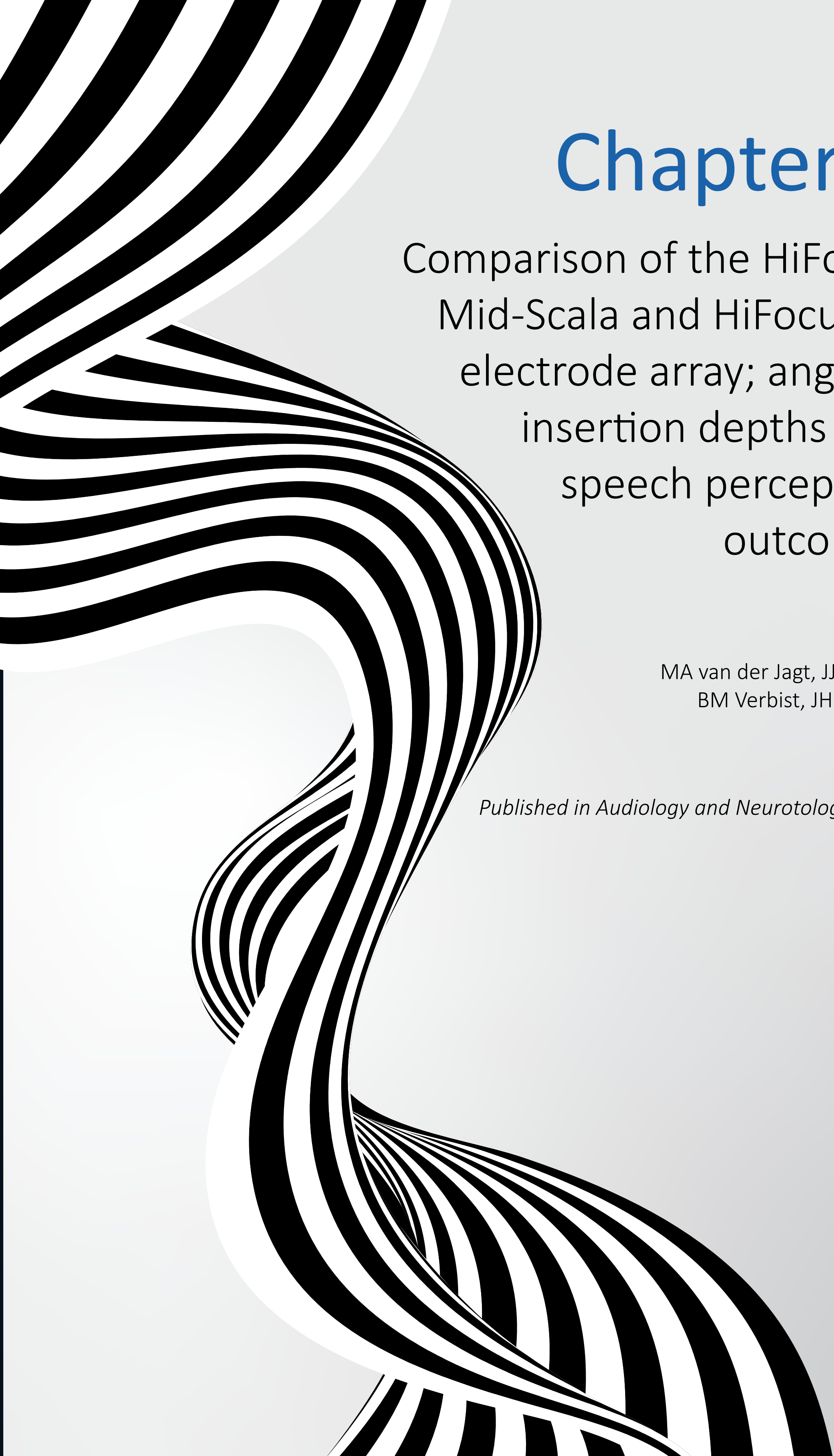

Chapter 4

Comparison of the HiFocus Mid-Scala and HiFocus 1J electrode array; angular insertion depths and speech perception outcomes

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Abstract

Recently the HiFocus Mid-Scala (MS) electrode array has been introduced onto the market. This pre-curved design with targeted mid-scalar intra-cochlear position pursues an atraumatic insertion and optimal distance for neural stimulation. In this study we prospectively examined the angular insertion depth achieved by and speech perception outcomes, till 6 months after implantation, resulting from the HiFocus MS electrode array and retrospectively compared these with the HiFocus 1J lateral wall electrode array. The mean angular insertion depth within the MS population (n = 96) was found at 470 degrees, 50 degrees shallower, but more consistent compared to the 1J electrode array (n = 110). Audiological evaluation within a subgroup including only post lingual, unilaterally implanted, adult CI recipients who were matched on preoperative speech perception scores and duration of deafness (MS = 32, 1J = 32), showed no difference in speech perception outcomes between the MS and 1J population. Furthermore, speech perception outcome was not affected by angular insertion depth or frequency mismatch.

Introduction

The capability of cochlear implants has dramatically evolved through developments in speech processing strategies, surgical techniques and electrode designs. These advances have led to major improvements in cochlear implant (CI) recipients' performance, although a great variability in outcome still exists. Multiple patient, implant and surgery related factors are proposed as contributing to this variability. These include duration of deafness, insertion depth, distance from the electrode contacts to the modiolus, scalar location and intra-cochlear trauma following insertion [Finley, and Skinner, 2008; Hughes, and Abbas, 2006; Adunka, and Kiefer, 2006; Holden et al., 2013]. Driven by the goal to further improve speech intelligibility of cochlear implant recipients, atraumatic surgery became an important aim as injury to intra-cochlear structures during insertion provokes a range of changes, leading to fibrosis, ossification and neural tissue loss[Carlson et al., 2011; James et al., 2005]. These changes, in turn, may inhibit the signal transmission by the CI. In addition, the degree of trauma is found to be heavily associated with the loss of residual hearing and clinical outcome [Adunka, and Kiefer, 2006; Gstoettner et al., 1997; Choi, and Oghalai, 2005; Carlson et al., 2011]. Therefore, implant features committed to reduce intra-cochlear damage, are being developed continually and are translated into advanced electrode array designs.

Such translation is found in the recently launched HiFocus Mid-Scala (MS) electrode array (Advanced Bionics, Valencia, CA). This implant design offers the smallest pre-curved design targeting a mid-scalar position. These features, together with the possibility of a round window (RW) insertion aim to support atraumatic surgery by avoidance of forces against the cochlear walls during insertion. In addition, a more ideal distance between the electrode contacts and the auditory neurons is aimed for with the targeted mid-scalar position. Earlier research has shown lower auditory brainstem response (ABR) thresholds in the case of a closer position of the array to the modiolus [Wackym et al., 2004; Pasanisi et al., 2002; Shepherd et al., 1993]. This results in the need for less current and in a more focused stimulation. To approximate this position, pre-curved arrays and positioners were developed. However, when the array is positioned along the inner cochlear wall, as in perimodiolar designs, the occurrence of cross-turn stimulation via the modiolus at the level of the 2nd or 3rd turn was demonstrated by Frijns et al. [Frijns et al., 2001; Wanna, George BGifford et al., 2014]. This suggests that anatomical difference between the basal and more upper turns requires a different approach to electrical stimulation [Frijns et al., 2001]. Their model predicts that a more approximate position of the basal electrode contacts leads to reduced current thresholds while retaining a good dynamic range, the difference between threshold and comfortable levels, and spatial selectivity. This hypothesis is translated into the geometry of the MS electrode array. Besides different intra-scalar position, differences in geometry of electrode arrays might also influence insertion depth. Combined with array length, this determines the range of stimulated frequencies. It is shown in earlier studies that deeply inserted electrode arrays results in increased intra-cochlear trauma and the loss in residual hearing[Adunka et al., 2006], limited stimulation of the basal frequencies[Finley, and Skinner, 2008] and confusion of the apical pitch due to neural interaction of the more densely located neural fibers in the apical regions in the cochlea[Gani et al., 2007]. On the other hand, other studies show that stimulation of the lower frequencies in the apical region of the cochlea are related to better speech perception outcomes[Hochmair et al., 2003; Yukawa et al., 2004], increased range of place pitches by stimulating a larger number of neural fibers[Landsberger, 2016], or reduced mismatch between the predicted and default frequencies by a further approximation of the normal frequency to place function of the cochlea[Landsberger et al., 2015]. Another study also showed that deeper inserted electrode arrays are not associated with scalar translocations[Wanna, George BGifford et al., 2014]. As a result of these divergent outcomes, and the use of different designs and sizes of electrode arrays in the discussed studies, the optimal insertion depth remains unclear.

Given the recent introduction of the HiFocus MS electrode array, studies reporting on speech perception outcome using this device are lacking. The aim of this present study was to report on the clinical outcomes of the new MS electrode array in terms of speech perception and angular insertion depth. To create a referential framework, these outcomes will be presented next to the outcomes of the HiFocus 1J electrode array.

Material and Methods

Patient population

For the evaluation angular insertion depth

Since the first implantation of the MS electrode array in June 2012, till October 2014, 96 patients with normal cochlear morphology were consecutively implanted with this CI electrode array design and were included to study angular insertion depth. For comparison, a similar-sized cohort of the last patients implanted with the 1J electrode was created by selecting all consecutively implanted 1J recipients from a partly overlapping period, viz. January 2010 till October 2014. This was considered to create groups with the least differences in selection criteria, surgical procedure, (experience of) surgeons and rehabilitation. This group counted 110 patients. Demographic characteristics of this patient population are described in table 1.

Table 1. Demographic characteristics

Total population (N = 206)		**N = 96**	**N = 110**	
Age at implantation	Mean, SD (years)	38.8, 29.2	47.4, 25.1	$p = 0.026$
Duration of deafness	Mean, SD (years)	16.0, 16.9	28.0, 20.5	$p = 0.001$
Preoperative phoneme scores*	Mean, SD (% correct)	48, 22	32, 23	$p < 0.001$
Population for speech perception analysis (N = 100)		**N = 52**	**N = 48**	
Age at implantation	Mean, SD (years)	61.6, 15.8	64.8, 11.9	*NS*
Duration of deafness	Mean, SD (years)	12.3, 12.3	24.8, 16.6	$p < 0.001$
Preoperative phoneme scores*	Mean, SD (% correct)	53.7, 19.6	40.7, 21.4	$P = 0.005$
Matched population for speech perception analysis (N = 64)		**N = 32**	**N = 32**	
Age at implantation	Mean, SD (years)	59.6, 17.4	64.9, 14.0	*NS*
Duration of deafness	Mean, SD (years)	13.9, 13.0	17.7, 13.8	*NS*
Preoperative phoneme scores*	Mean, SD (% correct)	52, 20	43, 20	*NS*

* Using a standard Dutch speech audiometric test of the Dutch Society of Audiology, consisting of phonetically balanced monosyllabic (CVC) phoneme lists.[22]

For the evaluation of speech perception outcome

Evaluation of speech perception outcomes was performed within a subgroup including 100 post lingual, adult CI recipients whom were unilaterally implanted. Reimplanted patients were excluded from the analysis. As shown in Table 1, initially significant differences in preoperative speech perception and duration of deafness were present between the MS and 1J population. An explanation for these differences are the expanding implant criteria in our centre, evolved over the past few years, coinciding with a change of standard array for implantation from 1J to MS since 2013. To limit differences in demographic characteristics that might affect speech perception, the MS and 1J population were matched on duration of deafness, age at implantation and preoperative phoneme scores. This resulted in two groups of 32 patients. It should be noted that not all patients data at all follow-up measurements were available. Demographic characteristics of this subpopulation are specified in table 1. All patients participated in the standard intense rehabilitation procedure [van der Beek et al., 2005].

Electrode designs

The MS electrode array was launched in 2013 and includes a pre-curved array designed for mid-scalar position. It contains 16 electrode contacts arranged on a 0.9 mm pitch. The dimensions of each contact surface are 0.43 by 0.39 mm. The total length of the array from basal contact to the tip is 15.0 mm. The distance from tip to the proximal blue marker that indicates a full insertion is 18 mm. The cross-sectional diameter varies from approximately 0.5 mm at the most apical contact to approximately 0.7 mm at the most basal contact. In this study, all MS insertions were performed using the insertion tool, which comes with the implant. Either a pure round window (RW, n = 30) or extended RW (n = 65) insertion was performed. In case of an extended round window approach the RW is enlarged in anterior-inferior direction. Information about the surgical approach is extracted from surgical procedure reports.

The 1J electrode array, introduced in 2003, is a less pre-curved array, designed for outer wall positioning. It contains 16 electrode contacts, spaced 1.1 mm apart, leading to a total length of the array from basal contact to the tip of 17 mm. There is an additional 3 mm length from the most basal contact to the marker contact, indicating a full insertion is 20 mm. The dimensions of each contact surface are 0.5 by 0.4 mm. The cross-sectional diameter of the array varies from approximately 0.4 mm at the most apical contact to approximately 0.8 mm at the most basal contact. All 1J electrode arrays were implanted through an extended RW approach, as the dimension of this design is not compatible with a pure RW approach. Electronic functionality is identical for both devices.

Radiological evaluation

All 206 patients underwent pre- and post-operative MSCT scans (Aquilion; Toshiba Medical Systems, Otowara, Japan) according the standard work-up for cochlear implant patients at our institution. Subsequently multiplanar reconstructions (MPRs) were made from these scans [Verbist et al., 2005]. To study angular insertion depths, MPRs from each patient were analysed by applying a three-dimensional coordinate system as described by Verbist et al. [Verbist et al., 2010]. Based on this coordinate system, the angular location of the RW was determined at the pre-operative CT scan and applied to the post-operative CT scan. Subsequently, the angle of the most apical electrode was defined as the angular insertion depth. The angular depth of all contacts in the array was used to calculate the frequency mismatch as described in detail in two earlier studies[van der Marel et al., 2015][Kalkman et al., 2014]. This mismatch indicates the difference between the frequency-to-place map as programmed in the implant system and the actual pitch associated with the electrode contact position, derived from the angular depth of each electrode contact, according to the tonotopical organization of the nerve fibers as described by Greenwood et al., combined with histological data from Stakhovskaya et al. [Greenwood, 1990][Stakhovskaya et al., 2007]. The overall frequency mismatch (ΔF) in each patient in semitones (equal to a twelfth of an octaves) was obtained by calculating the difference (Δfi) between f_{MF} (i) and f_{SG} (θ_i) in semitones with:

$$\Delta f_i = 12 \times {}^2\log f_{MF}(i) - 12 \times {}^2\log f_{SG}(\theta_i),$$

In this formula, f_{MF} (i) represents the center frequencies obtained from the filter map assigned to the implant's channel by the manufacturer, for each contact number i (1 through 16). The predicted place pitch at the spiral ganglion for each electrode contact i, based on their angular position is indicated by (f_{SG} (θ_i)). From this, the root mean square (RMS) is calculated with:

$$\Delta \mathrm{F} = \sqrt{\frac{1}{\mathrm{N}} \sum_{i=1}^{N} \Delta f_i^2} \,.$$

These calculations were carried out by an in-house designed post-processing program written in Matlab (Mathworks, Novi, MI, USA). Also the number of electrode contacts that are active in the map are incorporated in the calculation of the degree of mismatch. The Matlab program was also used to assess the distance of each electrode contact to the inner wall, to the center of the modiolus, and to asses cochlear size. For this last purpose, the outer and inner wall distances to the center of the modiolus along 4 radial lines were measured. The accumulated radial distances at 0 and 180 degrees from the center of the RW indicate the largest cochlear diameter, named diameter A. The accumulated radial distances at 90 and 270 degrees from the RW indicate the smaller diameter, named diameter B[Escudé et al., 2006].

Evaluation of speech perception

Speech perception was assessed using the standard Dutch speech test of the Dutch Society of Audiology. Four lists of 11 monosyllabic (CVC) words were administered per speech level and the number of phonemes and words correct was determined. Patients were tested in quiet at speech levels of 65 and 75 dB SPL, over which the average score was calculated and used for analysis. When the average phoneme score in quiet was higher than 50%, patients were also tested in noise at a speech level of 65 dB. Speech scores in noise were assessed at a signal to noise ratio (SNR) of +10 dB and +5 dB. The assessments took place 1 week, 2 weeks, 1 month, 3 and 6 months after implantation. Speech scores in noise at 6 months after implantation are presented in our study. Table 2 shows the number of patients available per assessment.

Table 2. Number of patients available per follow-up measurement in quiet and both noise conditions.

	1 week	2 weeks	1 month	3 months	6 months
Phonemes MS					
Quiet	32	31	32	31	28
Noise +10 dB			27	27	27
Noise +5 dB			23	25	24
Phonemes 1J					
Quiet	32	32	31	30	25
Noise +10 dB			22	28	24
Noise +5 dB			20	24	21
Words MS					
Quiet	31	30	31	30	27
Noise +10 dB			26	26	26
Noise +5 dB			22	24	24
Words 1J					
Quiet	32	32	31	30	25
Noise +10 dB			22	28	24
Noise +5 dB			20	24	21

Statistical analysis

Statistical analyses were performed using SPSS (version 20, IBM, Armonk, New York). To study the difference in angular insertion depth between the MS and 1J population, an independent T-test was used. Subsequently, a linear mixed model analysis was used that incorporates the effect of cochlear size as possible factors of influence on the depth of insertion. The effect of surgical approach on angular insertion depth in the MS population was studied using an independent T-test. To study the difference in angular depth and distance to the inner wall of each individual electrode contact an independent T-test was used. For the analysis of speech perception at 5 (in silence) and 1 (in noise) phoneme and word measurements post implantation, the MS and 1J population were matched on duration of deafness and preoperative speech perception scores. The differences in phonemes and words, both in silence and in noise, were studied with an independent T-test. Eventually, a linear mixed model was used to study the individual and possibly combined effects of (1) implant design, (2) angular insertion depth, (3) frequency mismatch (4) age at implantation (5) preoperative speech perception scores and (6) duration of deafness on speech perception outcome within the matched population. A p-value < 0.05 was considered to indicate a statistically significant difference.

Results

Angular insertion depth

Figure 1 shows the distribution of the angular insertion depth in the two groups. The 96 MS patients showed a mean angular insertion depth of 422° with a standard deviation of 29°. The 110 1J patients showed a mean angular insertion depth of 478°, with a larger standard deviation of 66°. The 56° shallower angular insertion depth and 37° smaller standard deviation of the MS electrode array represent significant differences with the 1J population, both with a p-value < 0.001. The shallower insertion depth and narrower distribution of the pre-curved HiFocus MS array is clearly visible in Figure 1. The mean angular insertion depth within the matched population was 424° (SD 24°) for the MS and 469° (SD 69°) for the 1J recipients ($p < 0.001$).

Surgical approach, either a pure or extended round window approach, did not influence angular insertion depth of the MS population (p = NS). Cochlear size did have a significant effect on angular insertion depth in the 1J population only. An increase of 1 mm of diameter A, results in a shallower angular insertion depth of 44° ($p = 0.010$). Insertion depth in the MS population was not affected by cochlear size (p = NS).

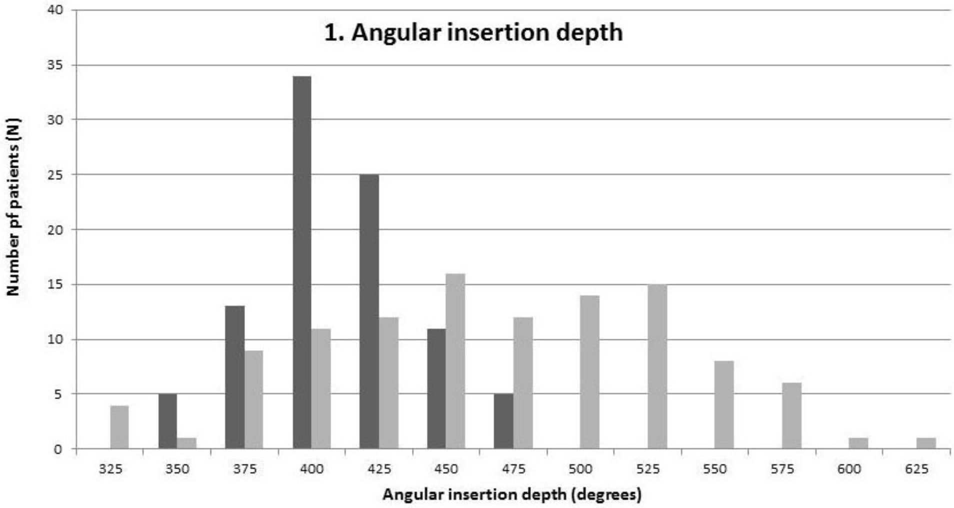
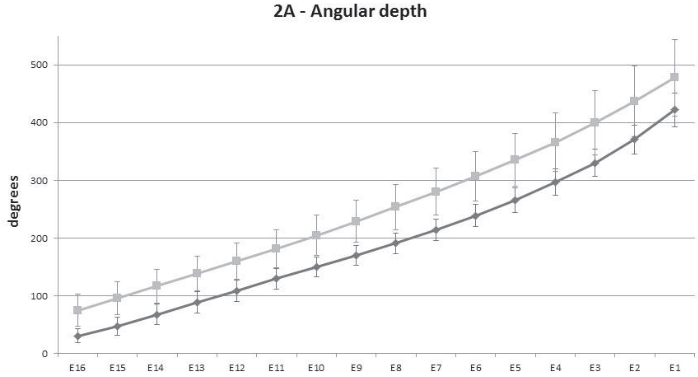
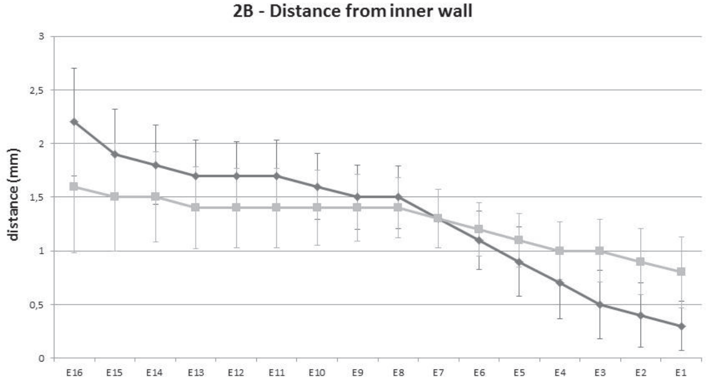


Figure 1. Angular insertion depth of the HiFocus MS (dark grey, n = 96) and HiFocus 1J (light grey, n = 110) and groups.

Intra-cochlear position

Figure 2A shows the mean angular depths of each individual electrode contact of the MS (dark grey) and 1J (light grey) electrode arrays. For each electrode contact the angular depth is significantly different between the MS and 1J electrode arrays (all $p < 0.001$). Figure 2B shows the mean distance from the electrode contacts to the inner wall for the MS (dark grey) and 1J (light grey) electrode array. The distance of electrode contact 8 and 7 were not significant different from each other, the distances of all the other contacts were (p-value ranged from <0.001 till 0.008). Figure 2C is shown to illustrate the difference in intra-cochlear position in terms of angular depth and distance to the inner wall and center of the modiolus of each individual electrode contact. It is shown that the basal electrode contacts of the MS electrode array cover higher frequencies compared to the 1J electrode array and are positioned in close proximity with the inner wall at the basal region.





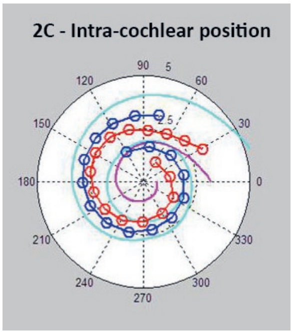


Figure 2A: Mean angular distance from each electrode contact (horizontal axis) for the HiFocus MS (dark grey) and HiFocus 1J (light grey) groups.

Figure 2B: Mean radial distance from each electrode contact (horizontal axis) to the inner wall for the HiFocus MS (dark grey) and HiFocus 1J (light grey) groups.

Figure 2C: The intra-cochlear position of the HiFocus MS (red) and HiFocus 1J (blue) electrode array, displayed within the outer (light blue) and inner (pink) wall of an average sized cochlea.

Frequency mismatch

Figure 3 shows the frequency mismatch in semitones plotted against the corresponding angular insertion depth of each individual patient. The mean frequency mismatch (ΔF) of the MS population of 10.3 semitones (SD 2.2) is significantly ($p < 0.001$) higher than in the 1J population which shows a frequency mismatch of 4.8 semitones (SD 3.0). It is clearly demonstrated that the higher frequency mismatch of the MS population is related to the shallower insertion observed with the MS electrode array. Within the matched population the mean frequency mismatch in the MS population is 9.58 semitones (SD 1.95). In the 1J population the mean frequency mismatch is 5.23 (SD 3.17) ($p < 0.001$).

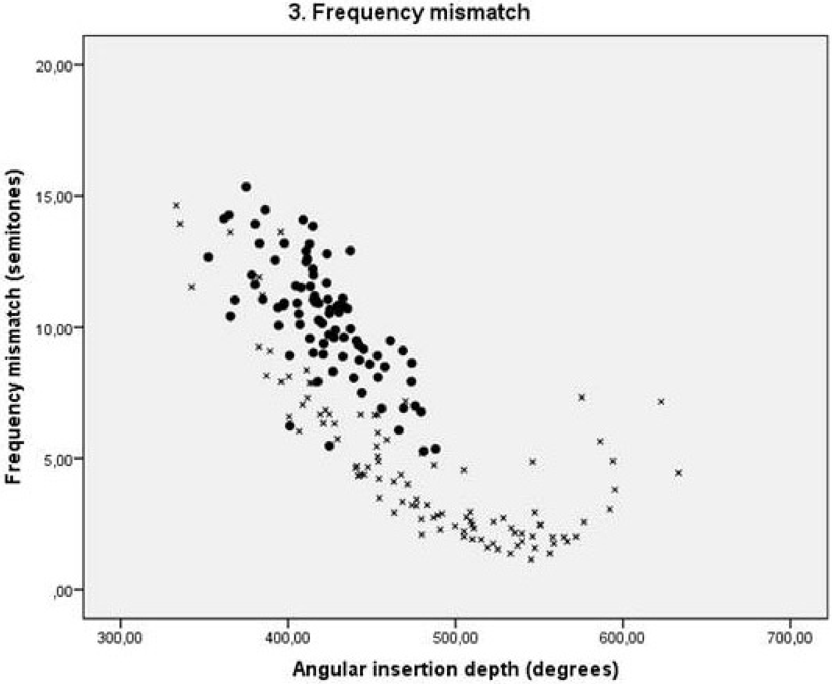
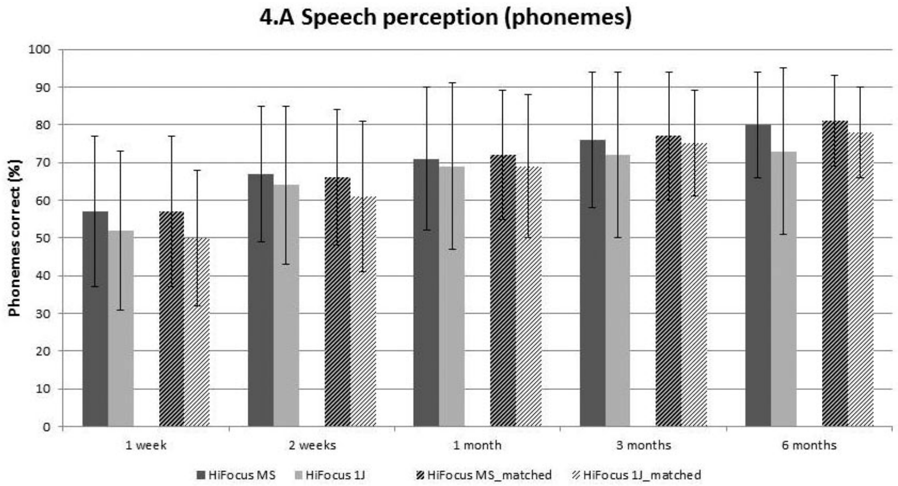


Figure 3. Frequency mismatch in semitones plotted against angular insertion depth of the HiFocus MS (dots) and HiFocus 1J (crosses) groups.

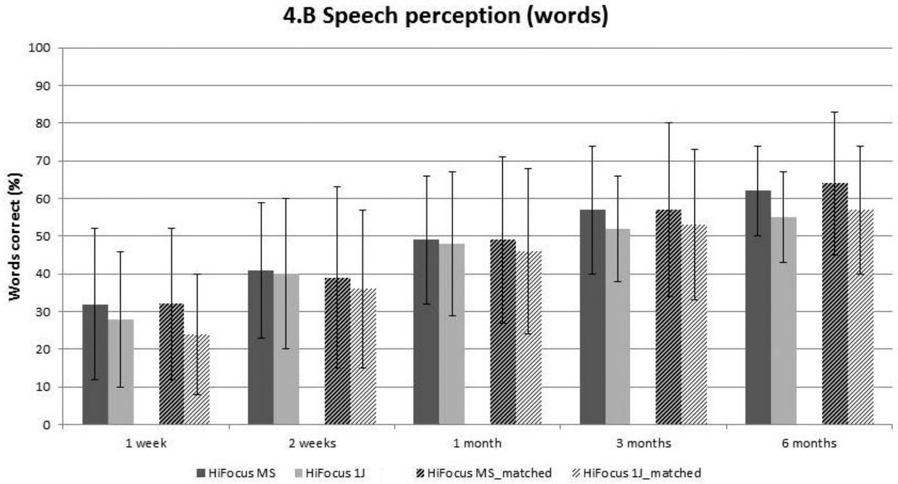
Speech perception scores

The results from the evaluation of speech perception at 5 intervals after implantation is showed in Figure 4. The bars in Figure 4A show the mean phoneme scores in quiet of both the unmatched (plain) and matched (shaded) MS and 1J population. In Figure 4B the mean word scores in quiet are presented of both the unmatched (plain) and matched (shaded) population. The scores of the unmatched population are presented to show the results as clinically represented in our population of implanted patients. The scores of the matched group are used for statistical analysis. During the follow-up period, both groups show an increase in performance on the speech tests. Although there is a tendency for higher scores with the MS group, no significant difference in speech perception at all 10 measurements is present between the two groups. Figure 5 shows the phoneme and word scores after 6 months in quiet and in +10 and +5 dB SNR test conditions. No significant difference in phoneme or word scores at 6 months in quiet and at +10 dB and +5 dB SNR were found.

To evaluate the effect of implant design, angular insertion depth and frequency mismatch on speech perception in the matched groups, a linear mixed model analysis was performed. Additional factors that were included in the model are preoperative speech perception scores, age at implantation and duration of deafness. Implant design, angular insertion depth, frequency mismatch and age at implantation showed no significant effect on final speech perception outcomes. However, both preoperative speech perception score ($p = 0.002$) and duration of deafness ($p < 0.001$) did significantly affect speech perception outcome. For each increased percentage preoperative phoneme score, the speech perception outcome after implantation, corrected for all repeated measurements in both silence and noise, was increased by 0.16%. For each additional year in duration of deafness, the speech perception outcome score was 0.40% lower.



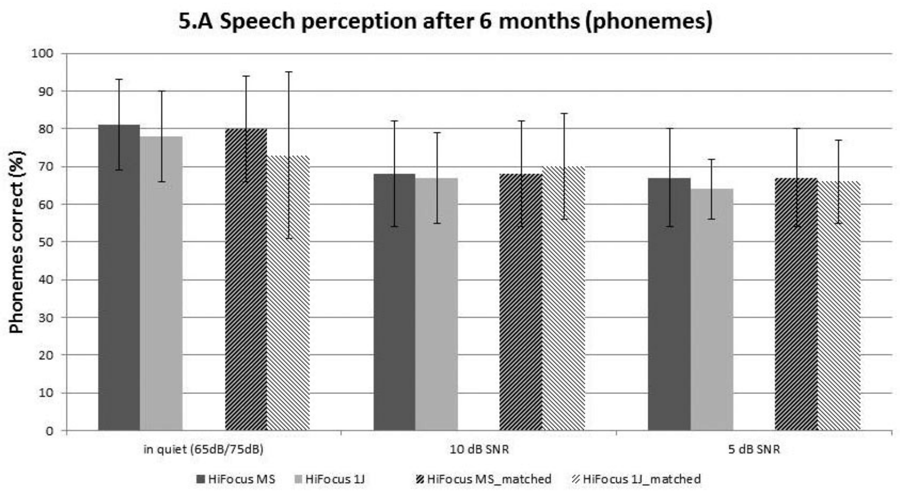
4.A Speech perception (phonemes)



4.B Speech perception (words)

Figure 4A: Mean phoneme scores at 5 follow-up intervals after implantation for the HiFocus MS (dark grey) and HiFocus 1J (light grey). The scores of the unmatched group is presented as plain bars and the scores of the matched group is presented as shaded bars.

Figure 4B: Mean word scores at 5 follow-up intervals after implantation for the HiFocus MS (dark grey) and HiFocus 1J (light grey). The scores of the unmatched group is presented as plain bars and the scores of the matched group is presented as shaded bars.



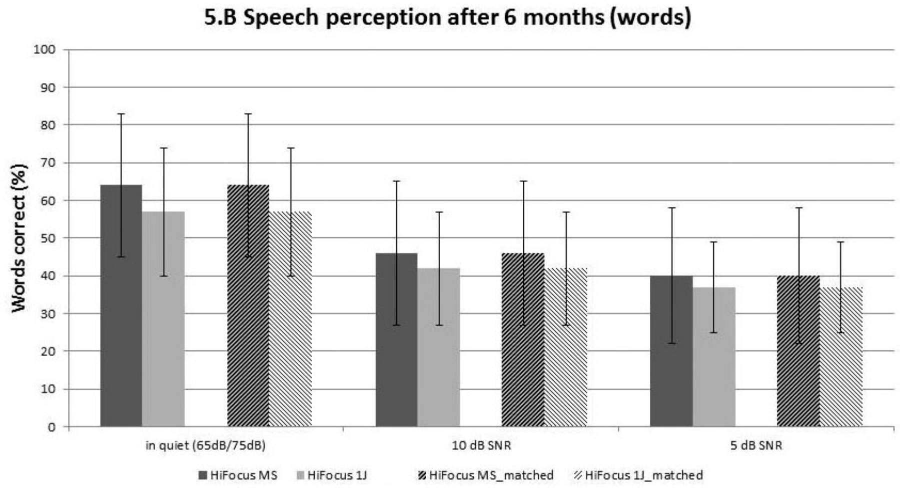


Figure 5A: Mean phoneme scores at 6 months after implantation in quiet, and at +10 dB SNR and +5 dB SNR noise conditions.

Figure 5B: Mean word scores at 6 months after implantation in quiet, and at +10 dB SNR and +5 dB SNR noise conditions.

Discussion

This study is the first to report on the clinical outcome of the new precurved HiFocus MS electrode array. Results regarding angular insertion depth and speech perception outcomes up until 6 months after implantation are reported and set against outcomes of the straight HiFocus 1J electrode array. Our study found a shallower but more consistent angular insertion depth for the MS implanted patients, resulting in a larger frequency mismatch. In addition, cochlear size and surgical approach did not affect angular insertion depth in the MS population. Speech perception outcomes were studied in two groups matched on duration of deafness and preoperative speech perception scores. This analysis showed that up till 6 months after implantation, the population implanted with an MS electrode array performs similarly to the 1J population, however, there is a trend toward better performance within the MS population. Additionally, a linear mixed model analysis showed that neither angular insertion depth, frequency mismatch or electrode design affected speech performance outcome. The baseline parameters duration of deafness and preoperative phoneme scores turned both out to significantly affect speech perception outcomes, corroborating findings in previous research [Holden et al., 2013; Rubinstein et al., 1999; Blamey, and Arndt, 1996; Green et al., 2007].

Two earlier studies on the MS electrode array are published, showing similar angular insertion depths. One includes a temporal bone study by Hassepass et al., where they analyzed angular insertion depth and intra-cochlear trauma using rotational tomography for the MS electrode array in 20 temporal bones [Hassepass et al., 2014]. A mean angular insertion depth of 406º from the center of the RW was reported. Atraumatic insertion (Grade 0 trauma) was shown in 18 of 19 scala tympani (ST) inserted temporal bones: less trauma than reported in previous temporal bone studies [Rebscher et al., 2008; Wardrop et al., 2005]. A second temporal bone study by Frisch et al. investigated implant position and depth of insertion using micro-CT in 8 temporal bones [Frisch et al., 2015]. A mean angular insertion depth of 429.6º was reported, with 1 implant (12.5%) showing a translocation to the scala vestibuli. This last study distinguished between insertions through the RW or a cochleostomy, showing a deeper insertions with RW insertions. In our population, either a pure or extended RW approach was used. Between these two approaches, no significant difference in angular insertion depth was found.

Previous studies focusing on insertion depth alone and in relation to speech perception outcomes show conflicting results. Consistent with our results, no correlation between insertion depth and speech perception outcome was reported by Van der Marel et al. who studied the effect of multiple variables related to implant position in a group of 203 patients who received an AB cochlear implant[Marel et al., 2015].In accordance with our finding of the lack of a correlation between angular insertion depth and speech perception outcomes, Finley et al. reported no correlation between the angular insertion depth of the apical electrode and speech perception in 14 AB CI-recipients. Nevertheless, they did found a correlation between angular insertion depth of the most basal electrode and speech perception. However, this was no longer significant after controlling for age, probably due to their limited population size [Finley, and Skinner, 2008]. Skinner et al. did find a correlation between insertion depth and word scores, but the average depth of insertion for that group of Nucleus-22 recipients was 333 degrees, significantly shallower compared to our population. [Skinner et al., 2002]. Their results show that very shallow insertions hinder speech recognition, whereas, insertions in which all electrodes are inserted into the cochlea or insertions that are to the intended design depth of the array, benefit speech recognition. Furthermore, Holden et al. did not find correlation between speech perception and angular insertion depth of the most apical electrode in a group of 144 CI patients, of whom 19 received an Advanced Bionics CI system [Holden et al., 2013]. However, the angular depth of the most basal electrode was significantly correlated to performance in this study. They state that the most basal electrode position is the best descriptor of the degree of over insertion and is therefore more reliable to study the correlation between performance and angular insertion depth. Yukawa et al. used multiple regression analysis to investigate the effect of insertion depth on speech perception in 26 patients implanted with a Nucleus-22 or Nucleus-24 CI with a straight array and indicated insertion depth as a positive predictive value for speech perception [Yukawa et al., 2004]. They used Cohen's method on a modified Stenver's view radiograph [Cohen et al., 1996], and reported also shallower insertions compared to our population, with their mean angular depth being 357.7 (SD 63.2).

We demonstrated that the angular insertion depth of the MS electrode array is relatively constant and less susceptible to variations in cochlear dimensions. Perhaps also contributing to this increased stability is the use of the tool which increases the control over the basal electrode contacts. With the HiFocus 1J, almost 80% of angular insertion depth variance can be predicted by surgical insertion distance [van der Marel et al., 2015]. Due to the precurved design, electrode migration is also expected to be less likely to occur [van der Marel et al., 2012]. Nevertheless, one patient implanted with an MS electrode array was rescanned due to a drop in performance (from 93% to 71% phonemes correct) accompanied by increasing T-levels for the basal electrodes (average increase of 30 current units (CU)). The new scan showed a retraction of approximately 4 mm, corresponding to 50 angular degrees, slightly over 3 electrode contact distances. Despite this retraction, all active contacts were in an intra-cochlear position, and performance could partially be restored by reprogramming the device. This patient is the only one of approximately 130 patients implanted with an MS electrode array in our institution with this finding. A previous study carried out by Van der Marel et al. described a migration rate of 29% (10/35) in patients implanted with a HiFocus 1 or HiFocus 1J array, of whom 2 experienced a drop in speech perception [van der Marel et al., 2012]. A more recent study of Mittman et al., studying electrode migration of perimodiolar electrode arrays, showed a migration rate of 26% (7/27) [Mittmann et al., 2015]. This migrational behaviour might obscure the correlation analysis on insertion depth and speech perception outcome, as insertion depth at the moment of evaluating speech perception could potentially be more shallow than calculated from the postoperative CT-scan obtained 1 day after implantation.

In summary, this first report on the clinical outcome of the HiFocus Mid-Scala electrode array shows favourable speech perception outcomes comparable to patients implanted with a 1J electrode array, despite significant differences in angular insertion depth and related increased frequency mismatch. We found that the angular insertion depth is more consistent with the MS electrode array and that insertion depth in the MS population was not affected by cochlear size, contrarily to the 1J population, or surgical approach. In other words, differences in electrode design and related intra-cochlear position did not have an effect on the performance of CI recipients. Perhaps, inherent limitations of electrical stimulation might restrict improving speech perception after cochlear implantation. Further improvements of technical capabilities, or different techniques such as injection of neural growths, might potentially push the ability of CI systems further towards optimal hearing rehabilitation.

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