Factors Influencing Speech Perception in Adults With a Cochlear Implant

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Objectives: The primary objective of this study is to identify the biographic, audiologic, and electrode position factors that influence speech perception performance in adult cochlear implant (CI) recipients implanted with a device from a single manufacturer. The secondary objective is to investigate the independent association of the type of electrode (precurved or straight) with speech perception.

Design: In a cross-sectional study design, speech perception measures and ultrahigh-resolution computed tomography scans were performed in 129 experienced CI recipients with a postlingual onset of hearing loss. Data were collected between December 2016 and January 2018 in the Radboud University Medical Center, Nijmegen, the Netherlands. The participants received either a precurved electrode (N = 85) or a straight electrode (N = 44), all from the same manufacturer. The biographic variables evaluated were age at implantation, level of education, and years of hearing loss. The audiometric factors explored were preoperative and postoperative pure-tone average residual hearing and preoperative speech perception score. The electrode position factors analyzed, as measured from images obtained with the ultrahigh-resolution computed tomography scan, were the scalar location, angular insertion depth of the basal and apical electrode contacts, and the wrapping factor (i.e., electrode-to-modiolus distance), as well as the type of electrode used. These 11 variables were tested for their effect on three speech perception outcomes: consonant–vowel–consonant words in quiet tests at 50 dB SPL (CVC50) and 65 dB SPL (CVC65), and the digits-in-noise test.

Results: A lower age at implantation was correlated with a higher CVC50 phoneme score in the straight electrode group. Other biographic variables did not correlate with speech perception. Furthermore, participants implanted with a precurved electrode and who had poor preoperative hearing thresholds performed better in all speech perception outcomes than the participants implanted with a straight electrode and relatively better preoperative hearing thresholds. After correcting for biographic factors, audiometric variables, and scalar location, we showed that the precurved electrode led to an 11.8 percentage points (95% confidence interval: 1.4–20.4%; $p = 0.03$) higher perception score for the CVC50 phonemes compared with the straight electrode. Furthermore, contrary to our initial expectations, the preservation of residual hearing with the straight electrode was poor, as the median preoperative and the postoperative residual hearing thresholds for the straight electrode were 88 and 122 dB, respectively.

Conclusions: Cochlear implantation with a precurved electrode results in a significantly higher speech perception outcome, independent of biographic factors, audiometric factors, and scalar location.

Key words: Cochlear implant, Electrode position, Explanatory factors, Imaging, Speech perception.

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INTRODUCTION

Since the first cochlear implant (CI) in 1973, the overall speech perception performance with a CI has increased as a result of technical, surgical, and audiologic improvements, such as the optimization of the speech processor program (Holden et al. 2011). However, performance still varies across CI recipients. As a result, the factors explaining speech perception with a CI have been discussed in an extensive number of studies over the past three decades.

The factors of interest affecting the variation in contemporary CI speech perception can be divided into three categories: biographical factors, audiometric factors, and electrode (positional) factors. Rapid developments in the CI field means that the influence of these factors on speech perception could be constantly changing, as shown by Blamey et al. (1996, 2013). Blamey et al. studied the influence of several biographic and audiologic factors on speech perception in two multicenter studies using the same study method (N = 800 in 1996 and N = 2251 in 2013). Compared with the results of the 1996 study, the authors showed less of an influence for biographic and audiologic factors (i.e., age at implantation, age at onset of deafness, duration of deafness, etiology of hearing loss, and CI experience) on speech perception in the 2013 study, explaining 21 and 10% of the variation in speech perception, respectively. This decrease was attributed to less stringent CI patient selection criteria and the improved clinical management of hearing loss and cochlear implantation in 2013 (Blamey et al. 2013).

Since their initial introduction, CIs have been developed from devices that only provide sound to deaf patients into devices that also improve speech perception in patients with moderate to severe hearing loss. In the last two decades, early implantation, when there still is some functional residual hearing, has been shown to positively affect the postoperative speech perception performance with CI (Friedland et al. 2003; Gomaa et al. 2003; Francis et al. 2004; Snel-Bongers et al. 2018; Huinck et al. 2019). As a result, the preservation of residual hearing

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became an important goal, both to reduce intracochlear damage but also because residual hearing can, in some CI recipients, be used in a combined electric–acoustic stimulation. Following this, postoperative imaging has become more important for checking the relationship between the electrode position post-implantation and the residual hearing. Several postoperative imaging studies have shown that translocation from the desired scala tympani (ST) to the scala vestibuli (SV) causes a higher loss of residual hearing and reduced speech perception (Holden et al. 2013; Wanna et al. 2014; O'Connell et al. 2016a,c; Chakravorti et al. 2019). Recently, the influence of electrode positional factors on speech perception has gained more interest, with studies exploring the effect of scalar location, insertion depth (Skinner et al. 2002; Holden et al. 2013; van der Marel et al. 2015; Heutink et al. 2019), and "electrode-to-modiolus" distance (Frijns et al. 2001; van der Beek et al. 2005; Holden et al. 2013; Holden et al. 2016). In 2012, Lazard et al. (2012) used Blamey et al. (2013) data and added several additional factors: gender, years of education, preoperative hearing aid use, preoperative pure-tone average (PTA) of the implanted ear, PTA of the best ear, preoperative speech score in quiet conditions, surgical approach, CI device brand, angular insertion depth, and percentage of active electrodes. Besides the five factors that Blamey et al. (2013) found to be significantly correlated with speech perception, Lazard et al. (2012) also observed an impact for the PTA of the best ear, the CI device brand, the percentage of active electrodes, and preoperative hearing aid use.

Blamey's and Lazard's multicenter studies significantly contributed to our understanding of the factors influencing cochlear implantation. The large number of subjects in multicenter studies means a high statistical power can be reached; however, multicenter research into CI has the disadvantage of introducing data heterogeneity caused by various clinical approaches and study methodologies (e.g., population, electrode selection, surgical approach, and audiometric measurements). Considering this limitation, Holden et al. (2013) conducted a single-center study with a relatively large number of participants implanted between 2003 and 2008 (N = 114). In addition to most of the biographic and audiometric factors described before, Holden et al. also found cognition and electrode position factors (scalar location, insertion depth, and electrode-to-modiolus proximity) to be correlated with CI performance, which was in line with the outcomes of other studies (Heydebrand et al. 2007; Pisoni et al. 2018). In Holden et al.'s study, however, the age at implantation and the cognitive function were found to be correlated, and after the authors reanalyzed the data controlling for the age at implantation, no significant correlation was found between cognition and speech perception. Several factors (electrode scalar position, angular insertion depth of the most basal electrode, CI sound field threshold, insertion depth in millimeters, duration of severe to profound deafness, and wrapping factor [WF]) remained significantly correlated with speech perception, however.

In current CI research, there might also be a risk of confounding variables when multiple CI systems and/or multiple electrode types are included in one study. Electrode type could introduce selection bias because the choice of electrode type is based on clinic-specific preoperative decision criteria (e.g., residual hearing, cochlear anatomy, and the surgeon's preference; Heutink et al. 2019). The potential correlations between the "electrode choice" criteria and the speech perception outcome may obscure the true correlation between electrode type and speech perception. Moreover, when analyzing multiple electrode designs in one study, the correlation between the electrode position and speech perception may be affected by electrode type-specific factors, the influence of which cannot be determined using different CI brands as they may be substantially different, for example, the number of contacts (Dhanasingh & Jolly 2017).

The present study investigates the factors influencing the CI outcome using a cross-sectional study design. The population represents a homogeneous group of adult CI recipients with a postlingual onset of hearing loss, implanted between 2010 and 2016 at the Radboud University Medical Center (Radboudumc), Nijmegen, the Netherlands. The included patients received either a precurved or straight electrode made by a single CI manufacturer.

Objectives

The primary objective of this study was to identify the biographic, audiologic, and electrode position factors that influence the speech perception performance in adult CI recipients implanted with a device from a single manufacturer. The secondary objective was to investigate the independent association of the type of electrode with speech perception.

MATERIAL AND METHODS

Study Design

This cross-sectional study was conducted between December 2016 and January 2018 at Radboudumc (Nijmegen, the Netherlands) and approved by the Institutional Review Board (Medical Ethics Committee Arnhem-Nijmegen; NL510071.091.14). All participants signed their informed consent. Eleven biographic, audiometric, and electrode-position variables were evaluated in a cohort of CI recipients (N = 129), in terms of their effect on speech perception under quiet and noisy conditions (Table 1). The biographic and preimplantation data were retrospectively collected from the electronic patient files, whereas the postimplantation ultrahigh-resolution computed tomography scan (UHR-CT) and audiometric tests were prospectively collected. The moment at which the study variables and outcome measurements were taken is referred to as the Study Variables and Outcome Evaluation (SVOE). The time between the surgery and the SVOE ranged from 14 to 92 months due to the selected time window of inclusion: CI recipients who were implanted between 2010 and 2016 were invited to participate in this study.

Participants

All participants were diagnosed with a bilateral postlingual onset of hearing loss, defined as the onset of severe or profound hearing loss (SPHL), after the age of 5 years. Participants had at least 1 year of experience with their CI before SVOE (mean 3.8 years; SD 1.7; range 1.2–7.7 years). Patients with a prelingual onset of hearing loss, a congenital or acquired mental disorder, congenital or acquired anomalies of the vestibulocochlear system identified in preoperative imaging (CT or magnetic resonance imaging), or fewer than 12 months of experience with CI were not included in this study. In total, 211 patients met the inclusion criteria and received information about the study, of whom 129 agreed to participate and signed informed consent. The exact reasons not to participate or respond to the invitation

TABLE 1. Descriptive data, presented per group (the total group of all participants, the group of participants with the precurved electrode and the group of participants with the straight electrode

	Independent Variables*				
	Biographical factors	All (n = 129)	Precurved (n = 85)	Straight (n = 44)	*p*†
1	Age at implantation (yrs)	62.6 (13)	62.6 (12)	62.6 (14)	0.995
2	Level of education (cat.)	18% ≥ BSc	16% ≥ BSc	20% ≥ BSc	0.58
3	Years of hearing loss (yrs)	25 (0–72)	25 (0–72)	25 (6–58)	0.26
	Audiological factors				
4	Preoperative CVC—phoneme score (%)	9 (0–68)	0 (0–60)	29 (0–68)	<0.001
5	Preoperative PTA3 (dB)	100 (62–130)	108 (78–130)	88 (62–122)	<0.001
6	Postoperative PTA3 (dB)	130 (85–130)	130 (102–130)	122 (85–130)	<0.001
	Electrode positional factors				
7	Electrode type (cat.)	66% precurved 34% straight			
8	Scalar trajectory‡ (cat.)	48% all ST 22% all SV 30% Trans.	44% all ST 32% all SV 24% Trans.	56% all ST 2% all SV 42% Trans.	<0.001
9	Angle of insertion basal contact§ (°)	19.4 (16)	25.9 (13)	7.2 (13)	<0.001
10	Angle of insertion apical contact§ (°)	372.8 (46)	386.2 (47)	347.6 (30)	<0.001
11	Wrapping Factor§¶	0.73 (0.59–0.92)	0.66 (0.05)	0.85 (0.03)	<0.001
	Dependent outcomes	All	Precurved	Straight	*p*
1	CVC50‖ (%)	63 (0–92)	65 (23–92)	61 (0–90)	0.03
2	CVC65 (%)	81 (33–100)	83 (45–100)	81 (33–100)	0.12
3	DIN** (dB SNR)	−1.3 (−7.2 to 14.3)	−2.5 (−7.2 to 12.7)	0.1 (−6.5 to 14.3)	0.02

The tested level of significance for the differences between the precurved and the straight electrode groups is indicated with a p value; the statistical test used was dependent on the type of variables and are provided‡.

**Mean values (with standard deviation in brackets) are presented for normally distributed variables (variables 1, 9, and 10 for all data, and variable 11 for the data on precurved and straight electrode), Median values (with range in brackets) are presented for not normally distributed variables (variables 3, 4, 5, and 6 for all data, and variable 11 for the data on all participants; and for all data on outcomes 1,2 and 3), and proportions of the sample are presented for categorical variables (variables 2, 7 and 8).*

†Differences in continuous independent variables and dependent outcomes were compared between the precurved and straight electrode groups using t-test (if normally distributed) or Mann–Whitney test (if not normally distributed), and differences in categorical variables were compared using chi-square test.

‡the quality of 6 UHR-CT scan was too poor (due to movement artifacts) to score variable 8.

§the quality of 5 UHR-CT scans was too poor (due to movement artifacts) to score variables 9 to 11.

¶Wrapping Factor was calculated only in participants with ST position; 59 participants had a ST position in all groups, of which 35 had a precurved electrode and 24 a straight electrode.

‖Outcome measurement of CVC50 was missing in five participants.

***Outcome measurement of DIN test was missing in four participants.*

BSc, Bachelor of Science; Cat., categorical; CVC, consonant–vowel–consonant; CVC50, CVC phoneme score in quiet at 50 dB; CVC65, CVC phoneme score in quiet at 65 dB; DIN, digits-in-noise test; PTA3, pure-tone average (in dB) over frequencies 0.5, 1, and 2 kHz; SNR, signal–noise ratio; ST, scala tympani; SV, scala vestibuli; Trans., translocation.

were not evaluated for each patient, but most recipients refrained either due to (1) the effort and time involved or (2) the radiation dose of the UHR-CT. None of the 82 participants who did not participate had failed devices nor complicated procedures in which they differed from the study population. Table 1 summarizes the biographic, audiometric, and electrode (position) data and study outcomes of the 129 participants.

Sixty-three males and 66 females with an average age at implantation of 62.6 (SD 12.7; range 27–85) years were included in the study. The highest achieved level of education, ranked according to the Dutch educational system, was recorded for all participants. An educational level of a Bachelor of Science (BSc) or higher was defined as a "high level of education," and had been attained by 23 of the 129 participants. The average duration between the onset of hearing loss and implantation was 26.7 (SD 15.3; range 0–72) years. Due to the lack of audiologic data in the referred patients, the duration of SPHL was mostly unknown. As the retrospective recall of start of SPHL is prone to bias, the duration of SPHL was not evaluated. The etiologies of hearing loss were: hereditary–unspecified (25); sudden deafness (8); autosomal dominant nonsyndromic hearing loss—that is, DFNA-9 (13) and DFNA-22 (1); autosomal recessive nonsyndromic hearing loss—that is, DFNB-3 (1); trauma (3); Meniere's disease (2); Usher syndrome (4); ototoxic medication (2); maternal rubella (2); mumps infection (1); otosclerosis (5); and unknown (60). The preoperative PTA at 500, 1000, and 2000 Hz (PTA3) and the postoperative PTA3, measured at SVOE were analyzed. If a participant experienced a vibrotactile sensation at any frequency before the audiometric threshold was found, the threshold of the stimulated frequency was recorded as a missing value. If a participant had no response at the maximum stimulated frequency, the threshold was set to 130 dB. The preoperative speech perception phoneme score of the CI ear, used as the independent variable, was measured using the consonant–vowel–consonant (CVC) words in quiet test at 65 dB SPL in the best aided condition using a hearing aid. Patients that had ceased using a hearing aid in the ear to be implanted were tested with a clinic hearing aid. The contralateral ear was plugged.

Surgery and CI Details

All 129 participants were unilaterally implanted by one of the four CI surgeons at the Radboudumc CI Center. Each surgeon implanted between 24 and 38 participants. In terms of the preoperative PTA3 threshold, 98 participants were implanted in the poorer ear (mean difference between the best ear and the implanted poorer ear was 16.8 dB), five participants showed an exactly symmetric preoperative hearing loss, and 26 participants were implanted in the best ear (mean difference between the implanted best ear and the poorer ear was 13.9 dB). Implantation in the best ear was considered when there was a risk of vestibular function loss when implanting the poorer ear with significant residual vestibular function, or when the poorer ear was expected to have less hearing opportunities with CI. Sixty-six participants were implanted in the right ear and 63 were implanted in the left ear. All participants were implanted with a CI system from Cochlear Ltd. (Sydney, Australia), of whom 85 participants were implanted with a precurved electrode [the Cochlear Contour advanced (CI512/CI24RE)] and 44 were implanted with a straight electrode [the Cochlear slim straight electrode (CI422/522)]. The choice of electrode was based on the local selection criteria used in the Radboudumc CI Center between 2010 and 2016. In general, patients with (functional) residual hearing received a straight electrode and patients without residual hearing received a precurved electrode, based on the assumption that the less traumatic insertion of the straight electrode better preserved the residual hearing. No strict definition or cutoff point was used for (functional) residual hearing, and the choice of electrode type was made by the CI team clinician in consensus with the patient in view of the reported functionality of the ear by the patient, the presence of vestibular function, and the preoperative audiometry. This resulted in two groups of participants based on electrode type, with different median values in the preoperative thresholds and speech perception but with overlapping ranges (Table 1). The precurved electrode was inserted via a cochleostomy approach (n = 85), while the straight electrode was inserted using the round window approach (n = 35). If the round window membrane could not be clearly identified, the straight electrode had to be inserted via a cochleostomy approach (n = 9). The location for the cochleostomy was anterior and inferior to the round window. In all participants, the standard mastoidectomy and facial recess approach was used to expose the round window. All patients underwent a complete insertion of the electrode array during surgery.

Fitting Protocol

After implantation, all participants attended the standard clinical rehabilitation program of the Radboudumc CI Center. The CI processor was fitted by experienced CI audiologists, all of whom used the local standard fitting protocol. This protocol is based on the conventional threshold and comfort levels established for each electrode, following the manufacturer's guidance.

The loudness of complex speech-like sounds was assessed by presenting the vowels [ʊː], [ɑː], and [iː], and the consonants [tʃ] and [s], through a loudspeaker. The participants responded by pointing at a seven-item loudness scale from "nothing" to "too loud." Together, these sounds covered the speech spectrum. Each sound was presented nine times without pause and, therefore, allowed a loudness summation across electrodes and summation over a time span similar to that of a short sentence. Each sound was spectrally filtered to minimize the spectral overlap between sounds, which ensured that aberrant responses were traceable to specific electrodes and could be adjusted as the clinician deemed fit. Presentation at 75 dB SPL was used to assess the occurrence of discomfort; sounds presented at 65 dB SPL were expected to be of moderate loudness. All participants had the same generation of CI processor (Nucleus 6; Cochlear Ltd., Sydney, Australia). The default processing strategy was ACE, with a stimulation rate of 900 pps.

Imaging Details and Electrode Position Variables of Interest

A UHR-CT (Aquilion Precision; Canon Medical Systems, Otawara, Japan) scan was taken at the time of SVOE to be able to measure the electrode-position variables. The imaging was conducted in one sequential (volume) scan with the following settings: 160 × 0.25 collimation, 120 kVp, 80 mA, and a 1.5-s rotation time. The images were reconstructed with a filtered back projection in bone kernel (FC81) from images with a 0.25-mm slice thickness with 0.125-mm intervals, a 90-mm field of view, and using a 1024 × 1024 matrix. Oblique multiplane reconstruction (MPR) images were obtained through the cochlea, parallel to the basal turn of the cochlea. For image processing, the images were magnified to 500% and centered on the vestibulocochlear system. The window width and level were adjusted until both cochlear walls and the individual electrode contacts were visualized.

The UHR-CT MPRs were used to measure the four electrode position variables of interest for all participants. The scalar location of all 22 contacts along the electrode array was reviewed in midmodiolar sections. Every contact was scored as either (1) located in the ST, (2) located in the SV, or (3) located in an undefined position inside the cochlea. The independent variable scalar trajectory was categorically defined as (1) all contacts in ST, (2) all contacts in SV, or (3) contacts translocated between ST and SV. Examples of electrode contacts with different scalar positions are presented in Figure 1.

For all 22 contacts along the electrode array, the angular insertion depth was measured. An angular measurement of the insertion depth was made by indicating the center of the round window and the modiolus on a multiplanar reconstruction along the basal turn of the cochlea. Next, a 0° reference line between the modiolus and the middle of the round window, as well as a line between the contact from which the angular insertion depth has to be measured and the modiolus, are drawn. The angular insertion depth is the angle between these two lines. The method of measurement used to measure the angle of insertion is shown in detail in Figure 2. The independent variables of interest were defined as the angle of insertion of the most basal (AOI1) and apical (AOI22) contacts.

The last independent electrode-position variable of interest was the WF, shown in Figure 3. The WF was defined as the proximity of the electrode array relative to the modiolus, and was calculated and compared only in participants with a ST-located CI (N = 59; Holden et al. 2013). The WF is calculated as: $\mathrm{WF} = \dfrac{L\mathrm{Electrode}}{L\mathrm{Lateral\ Wall}}$

The length of the lateral wall (*L*Lateral Wall) and the length of the electrode (*L*Electrode) were measured (in millimeters) by first defining the center of the round window and the modiolus. Then, two lines were drawn; one to indicate the onset, a "starting point line" perpendicular to the first contacts on the

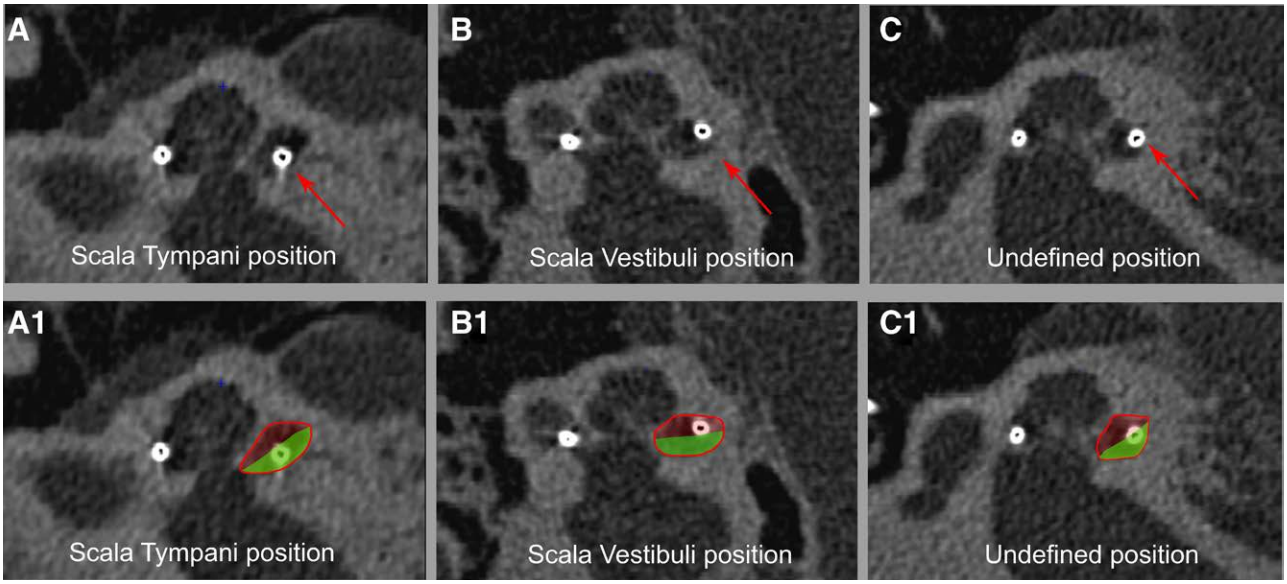

Fig. 1. Method for measuring scalar location using mid-modiolar sections of an ultrahigh-resolution computed tomography (UHR-CT) scan. Examples of electrode contacts in different scalar positions: A1–C1, The scala tympani (ST) is roughly denoted by the green area, and the scala vestibuli (SV) is roughly indicated as the red area. The scala media is not visible. Dependent of the location of the electrode contact, the position was defined as contact in ST position (A and A1), SV position (B and B1), or undefined (C and C1). An undefined position, defined as a contact located between the two scalas, was only found if the electrode translocated from one scala to the other. The independent variable scalar trajectory was categorically defined as (1) all contacts in ST; (2) all contacts in SV; or (3) translocation between ST and SV.

electrode, and the "endpoint line," drawn between the modiolus and the contact located at 360° or, if below 360°, the most apical contact. This resulted in a score between 0 and 1, with 0 indicating the closest possible proximity to the modiolus and 1 reflecting the closest possible proximity to the lateral wall of the cochlea.

Speech Perception Outcome Measurements

Three speech perception outcome measurements, measured at SVOE, were used as dependent outcome variables: the CVC words in quiet test at 50 dB SPL (CVC50) and at 65 dB SPL (CVC65) and the digits-in-noise (DIN) test. The CVC test is the standard speech perception test used by the Dutch Society of Audiology, consisting of phonetically balanced CVC word lists. The CVC test was presented at 50 dB SPL and 65 dB SPL using a loudspeaker 1 m in front of the participant, who was positioned in a quiet soundproof booth, and the average phoneme score of three CVC lists was calculated. The DIN test (Smits et al. 2013) consists of 24 pairs of three consecutively presented digits (a digit triplet) with background noise. If the digit triplet is repeated correctly, the signal-to-noise ratio (SNR) of the next digit triplet is lowered until the participant makes an error. If a digit triplet is not heard or incorrectly repeated, the SNR of the next digit triplet is increased until the participant hears and repeats it correctly. The score of the DIN test (in dB SNR) represents the 50% speech recognition threshold of the DIN test (dependent outcome DIN). In this study, the DIN was presented in a small soundproof case, developed for CI-audiometric testing, called the OtoCube (Otocube Limited, Geertruidenberg, the Netherlands). Speech perception testing with the Otocube gives

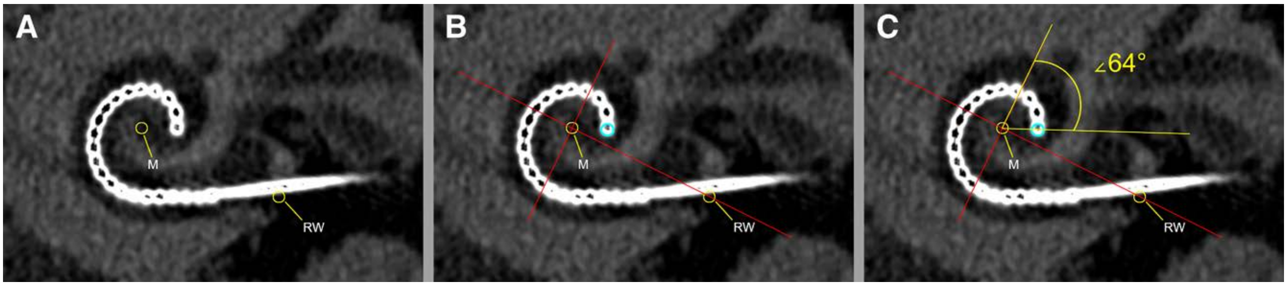

Fig. 2. Method for the measurement of the angular insertion depth from a multiplanar reconstruction along the basal turn of the cochlea (A, B, and C) in an ultrahigh-resolution computed tomography (UHR-CT) scan. A, An angular measurement of the insertion depth can be made by indicating the center of the round window (RW) and the modiolus (M). B, A 0° reference line was drawn between the modiolus (M) and the middle of the RW, and a perpendicular line was drawn from the M on the 0° reference line is drawn (red cross). The contact for which the angular insertion depth is to be measured is indicated (turquoise circle); in this case this is the most apical contact. C, An angle was drawn (in yellow) from the modiolus over the 270° reference line, and onto the most apical point of the electrode array (turquoise circle). In this example, the angular insertion depth of the most apical electrode contact is 334° (the sum of the three quadrants, equal to 270°, plus the measured yellow angle of 64°). The independent variables of interest were defined as the angle of insertion for the most basal (AOI1) and apical (AOI22) contacts.

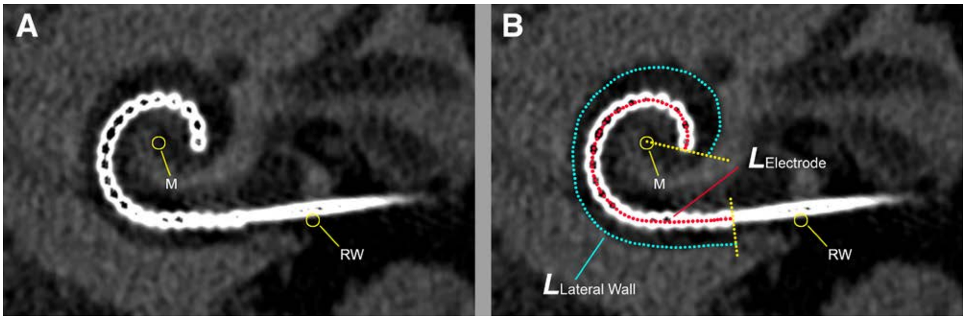

Fig. 3. Method for measuring the wrapping factor (WF) on a multiplanar reconstruction along the basal turn of the cochlea (A and B) in an ultrahigh-resolution computed tomography (UHR-CT) scan. WF was defined as the proximity of the electrode array relative to the modiolus, and was calculated and compared only in participants with a ST-located CI (Holden et al. 2013). WF is calculated as: $\mathrm{WF} = \frac{L\mathrm{Electrode}}{L\mathrm{Lateral\ Wall}}$ The length of the lateral wall (*L*Lateral Wall) and the length of the electrode (*L*Electrode) were measured (in millimeters) by first defining the center of the round window (RW) and the modiolus (M). Then, two lines were drawn; one to indicate the onset, a "starting point line" perpendicular to the first contacts on the electrode, and the "endpoint line," drawn between the M and the contact located at 360° or, if below 360°, the most apical contact. This resulted in a score between 0 and 1, with 0 indicating the closest possible proximity to the M and 1 reflecting the closest possible proximity to the lateral wall of the cochlea.

similar results to soundbooth testing (De Matos Magalhaes et al. 2014). Using the Otocube, the CI processor of the participant is connected to the CI coil with an extended wire. The processor is placed inside this soundproof case, while the coil remains connected to the CI implant in the participant's head. In the soundproof case, a speaker orientated in front of the processor presents both the background noise and the digit triplets (signal) of the DIN test. A DIN score above a +15 dB SNR is considered unreliable because the adaptive procedure does not work properly at these levels and, therefore, results above +15 dB do not reflect the ability to recognize speech in noise (Kaandorp et al. 2015). In the present study, three participants had a score >15 dB SNR and were therefore not included in the DIN-test analysis. Under all conditions, participants were tested using the speech processor program, volume, and sensitivity settings they used in everyday life. If the participant was using a hearing aid in the contralateral ear, this device was removed. In all participants, the contralateral ear was plugged before audiometric testing.

Statistical Approach

Data were presented for all participants (as is common in the literature), and for groups by electrode type: (1) "precurved group," that is, the participants with a precurved electrode and (2) "straight group," that is, the participants with a straight electrode. Study characteristics were summarized using the mean (SD) for normally distributed variables or the median (range) for non-normally distributed variables. Categorical variables were summarized in percentages.

Differences in continuous independent variables and dependent outcomes were compared between the precurved and straight electrode groups using a t-test (if normally distributed) or a Mann–Whitney test (if non-normally distributed). Differences in categorical variables were compared using a chi-square test. To assess the relationships between continuous independent variables and dependent outcomes, Spearman's correlation coefficient was calculated. A Mann–Whitney U test or Kruskal–Wallis test was used to assess differences in the level of dependent outcomes across the levels of categorical independent variables.

A multivariable linear regression analysis was used to assess the relationship between the independent variable of interest, that is, electrode type, and the dependent speech perception outcome. A squared outcome transformation was used to normalize the skewed data for the CVC50 and CVC65 outcomes, and a log transformation was used for the DIN test. The model assumptions were assessed by examining the distribution of residuals. For all statistical tests, a p value of ≤ 0.05 was used as the level of significance.

RESULTS

In Table 1, the descriptive data for all participants and both electrode-type groups (precurved and straight) are presented. The biographical factors did not differ between the two electrode-type groups; however, all audiological factors were significantly poorer in the precurved group compared with the straight group ($p < 0.001$). Additionally, all electrode position factors showed significant differences between the precurved and straight electrode groups ($p < 0.001$). In particular, the ranges of the proximity to the modiolus, that is, the WF, observed in both groups barely overlapped. On average, the precurved electrodes were positioned 11.1% deeper inside the cochlea and were 22.4% closer to the modiolus than the straight electrodes. The partial extrusion of one or more of the most basal contacts on the electrode array was seen in 13 participants. In the precurved group, one participant had four electrode contacts outside the cochlea. In the straight group, eight participants had one contact outside the cochlea, three participants had three contacts outside the cochlea, and one participant had four contacts outside the cochlea. These partial extrusions did not cause a statistically significant difference in the speech perception of the affected participants relative to those without an extrusion. With respect to the scalar position, 56% of the straight electrodes and 44% of the precurved electrodes were positioned in the ST. A complete SV position was found more often for the precurved electrode (32%) compared with the straight electrode (2%; one participant, whose straight electrode was, like all precurved electrodes, inserted through a cochleostomy approach). Translocation between the ST and SV along the trajectory of the electrode array occurred in 24% of the participants with a precurved electrode and in 42% of the participants with a straight electrode.

Speech perception was higher in the precurved electrode group than in the straight electrode group. The median CVC50 phoneme score for all participants was 63% (0–92%); however, the scores were significantly different ($p = 0.03$) for the precurved and straight groups [65% (23–92%) and 61% (0–90%), respectively]. The median CVC65 phoneme score was 83% (45–100%) in the precurved group and 81% (33–100%) in the straight electrode group ($p = 0.12$). The median DIN score was –2.5 dB SNR (–7.2 to 12.7 dB SNR) in the precurved electrode group and 0.1 dB SNR (–6.5 to 14.3 dB SNR) in the straight electrode group ($p = 0.02$). All three outcome measures, CVC50, CVC65, and DIN, significantly correlated with each other ($p \leq 0.003$); scatter plots and Pearson's correlations between the three outcome measures are presented in Supplemental Digital Content A, http://links.lww.com/EANDH/A739. Overall, the results of the CVC50, CVC65 (Table B1, Supplemental Digital Content B, http://links.lww.com/EANDH/A739), and DIN tests (Table B2, Supplemental Digital Content B, http://links.lww.com/EANDH/A739) showed the same trends in the influence of independent variables on speech perception; however, the results were most distinct in the CVC50 outcome.

In Table 2, univariate Spearman correlations between the CVC50 outcome and the 10 independent factors are reported (see Table 1 for the differences between electrode type). Besides the factor "electrode type," the age at implantation, preoperative PTA3, and the angle of insertion of the basal and apical electrode contacts were significantly correlated with the CVC50 phoneme score for the group containing all participants. In the precurved group, however, none of the independent factors showed a significant correlation with CVC50. In the straight group, only the age at implantation was significantly correlated with CVC50 (Spearman $\rho = -0.4$; $p = 0.01$). The correlation coefficient of the preoperative CVC phoneme score for the straight group was higher than that of the group comprising all participants (Table 2). While a higher incidence of translocations was observed in the straight electrode group than in the precurved electrode group (respectively, 42% and 24%), a correlation between the scalar location and the CVC50 outcome was not seen (Table 2).

A multivariable linear regression model was conducted to investigate the extent to which the favorable CVC50 speech perception outcome in the precurved group was independent of the influence of biographic variables, audiometric variables, and scalar electrode location. The model presented in Table 3 shows that the CVC50 phoneme score is 11.8 percentage points (95% CI: 1.4–20.4%; $p = 0.03$) higher with a precurved electrode than with a straight electrode, independent of the influence of age at implantation, level of education, years of hearing loss, preoperative CVC phoneme score, preoperative PTA3, postoperative PTA3, and scalar trajectory. This trend of an independent higher speech perception outcome for the precurved electrode was similar for the CVC65 (Table B1, Supplemental Digital Content B, http://links.lww.com/EANDH/A739) and DIN tests (Table B2, Supplemental Digital Content B, http://links.lww.com/EANDH/A739). The proportion of variance explained by the multivariable model on CVC50 (Table 3) was 11%, and the degrees of freedom were 9, 110, and 119, respectively, for the model, the residual, and the total. Nine participants with missing data were excluded from the model; four were excluded due to the inability to score the scalar location from poor-quality CT scans resulting from movement artifacts, three were excluded due to missing CVC50 outcome measurements, and two were excluded for both reasons. The multivariable linear regression model in Table 3 did not show apparent violation of the assumption regarding the distribution of residuals (Figure C1, Supplemental Digital Content C, http://links.lww.com/EANDH/A739).

Sensitivity Analysis of the Multivariable Model

In the present study, speech perception was measured after at least 12 months to ensure that participants were in a phase of stable speech perception. The average time from CI implantation to the SVOE ranged from 14 to 92 (mean 45.5; SD 20.7) months. The correlation between the time from CI to the SVOE and the outcomes was evaluated (Figure A1, Supplemental Digital Content A, http://links.lww.com/EANDH/A739). The time between the CI and the SVOE showed a weak correlation with CVC50 ($r = 0.19$; $p = 0.04$); however, there was no correlation with CVC65 ($r = 0.06$; $p = 0.5$) or DIN ($r = -0.09$; $p = 0.3$). The correlation between the time from CI to the SVOE and the CVC50 was insignificant if participants with a CI more recently than 18 months previously were excluded. As a sensitivity analysis, a multivariable linear regression model was conducted on the CVC50, excluding the participants for whom the time from CI to SVOE was less than 18 months (Table C1, Supplemental Digital Content C, http://links.lww.com/EANDH/A739). Like the original model, this model showed the same significant influence of electrode type on CVC50 independent of the other variables of interest (Table 3). This confirmed that the time from CI to SVOE was not a significant factor in the present study.

DISCUSSION

The primary objective of this study was to identify the biographic, audiologic, and electrode position factors that influence the speech perception performance in adult CI recipients implanted with devices from a single manufacturer. The secondary objective was to investigate the independent association of the type of electrode with speech perception.

We found that participants implanted with a precurved electrode and who had poor preoperative hearing thresholds performed better with their CI on all speech perception outcomes than those participants implanted with a straight electrode and with relatively better preoperative hearing thresholds (Table 1). The average absolute CVC50 score was 4 percentage points higher in the group with the precurved electrodes than for those implanted with the straight electrodes ($p = 0.03$). For speech perception in a noisy background, evaluated using the DIN test, the absolute difference was –2.6 dB SNR in favor of the precurved electrode ($p = 0.02$). This is an important result, as hearing in noisy situations is challenging for CI users; for example, a 1-dB improvement in SNR was shown to correspond to a 10 percentage point improvement in speech understanding in quiet conditions (Litovsky et al. 2006; Soli & Wong 2008).

After correction for the influence of biographic, audiometric, and scalar position factors, the independent positive effect of the precurved electrode on the CVC50 outcome was found to be 11.8% (95% CI: 1.4–20.4%; $p = 0.03$), as determined using a multivariate model. This effect size is almost three times higher than the 4% absolute difference in CVC50 outcome between the

TABLE 2. Univariate correlations for independent variables of interest with CVC50 in all precurved electrode and straight electrode participant groups

		Spearman ρ (*p*)		
	Continuous variables	All	Precurved	Straight
1	Age at implantation*	**−0.21/0.02**	−0.12/0.28	**−0.40/0.01**
3	Years of hearing loss*	0.06/0.53	0.06/0.61	0.04/0.81
4	Preoperative CVC—phoneme score*	0.01/0.94	0.07/0.55	0.21/0.18
5	Preoperative PTA3*	**0.20/0.04**	0.14/0.21	−0.05/0.74
6	Postoperative PTA3*	0.07/0.46	0.003/0.98	−0.04/0.79
9	Angle of insertion basal contact†	**0.22/0.02**	0.04/0.74	−0.003/0.98
10	Angle of insertion apical contact†	**0.23/0.01**	0.05/0.67	0.16/0.33
11	Wrapping factor‡	−0.21/0.11	0.20/0.24	0.003/0.99
	Categorical variables	*p* of Mann—Whitney/Krusskall–Wallis test§		
2	Level of education (cat.)*	0.53	0.98	0.26
8	Scalar trajectory (cat.)¶	0.90	0.61	0.35

**One hundred twenty-four participants had complete measurements of both CVC50 and variables 1–6, of which 82 participants had a precurved electrode and 42 participants had a straight electrode.*

†One hundred twenty-one participants had complete measurements of both CVC50 and variables 9, 10, and 11, of which 81 had a precurved electrode and 41 participants had a straight electrode.

‡Fifty-seven participants had complete measurements of both CVC55 and variable 11, and had a Scala Tympani position, of which 35 had a precurved electrode and 22 had a straight electrode.

§The Mann–Whitney test was performed for variable 2, and the Krusskall–Wallis test was performed for variable 8.

¶One hundred twenty participants had complete measurements of both CVC50 and variable 8 of which 79 had a precurved electrode and 41 participants had a straight electrode.

BSc, Bachelor of Science; CVC, consonant–vowel–consonant; PTA3, pure-tone average (in dB) over frequencies 0.5, 1, and 2 kHz.

TABLE 3. Multivariate linear regression on dependent outcome CVC50 in all participants with complete measurements (n = 120)

	Independent Variable	Coefficient	95% Confidence Interval		*p*
1	Age at implantation	−0.30	−0.67	0.07	0.11
2	Level of education (cat.)				
	<BSc	Ref.			
	≥BSc	0.15	−10.04	10.28	0.98
3	Years of hearing loss	−0.01	−0.30	0.28	0.93
4	Preoperative CVC—phoneme score*	0.14	−0.16	0.44	0.35
5	Preoperative PTA3	0.17	−0.20	0.54	0.37
6	Postoperative PTA3	−0.19	−0.65	0.26	0.40
7	Electrode type				
	Precurved	Ref.			
	Straight	−11.79	−20.42	−1.39	0.03
8	Scalar trajectory (cat.)				
	All scala tympani	Ref.			
	All scala vestibuli	−1.00	−11.26	9.66	0.87
	Translocation	−0.53	−9.70	8.84	0.92

Participants with missing data were excluded from the model (n = 9); four were excluded due to inability to score scalar location because of poor-quality CT scan due to movement artifacts, three were excluded due to missing CVC50 outcome measurement, and two were excluded for both reasons. The proportion of variance explained by the model in this table was 11%, the degrees of freedom were 9, 110, and 119, respectively, for the model, the residual and the total.

**This is 1 factor (Pre-operative CVC-phoneme score). The significance is just like with all other factors in final column of the table (p = 0.35).*

BSc, Bachelor of Science; CVC, consonant–vowel–consonant; PTA3, pure-tone average (in dB) over.

two electrode groups (Table 1), indicating that the pre-implantation factors (in particular, the audiometric factors) probably obscured the real added value of using a precurved electrode over a straight electrode. Similar to the CVC50 outcome, the effect size for the electrode type in the multivariable model was greater than the absolute differences between the two electrode type groups in terms of the DIN outcome and the CVC65 outcome (Tables B2 and B1, Supplemental Digital Content B, http://links.lww.com/EANDH/A739).

In our clinic, the choice of electrode type depends on several factors, including audiometric parameters. As a result, the electrode type is a mediating factor in the known relationship between lower preoperative audiometric factors and an increased speech perception (Gomaa et al. 2003; Francis et al. 2004; Snel-Bongers et al. 2018; Huinck et al. 2019). As shown in Table 2, the univariate correlations in all patients indicate that audiometric variables have a significant positive relationship with speech perception, suggesting that poorer preoperative hearing results in better postoperative CI speech perception. This correlation is misleading, however, since this effect was caused by the fact that participants with limited or no residual hearing were implanted with the better-performing precurved electrode. Moreover, in the Spearman correlations, after stratification by electrode type, no correlations were found for the audiometric factors (Table 2), despite the variation in preoperative hearing within the electrode groups. The explanation for not finding a correlation between audiometric factors and speech perception in the stratified analysis could be that, in the precurved electrode group, the preimplantation residual hearing might have been too poor to positively affect the postoperative speech perception (Table 1 shows a median preoperative PTA3 of 108). In the straight electrode group, there was a positive trend (the correlation coefficient of the preoperative CVC phoneme score with the CVC50 outcome was higher than for the group containing all participants; Table 2); however, the number of participants might have been too low to detect a statistical significance (n = 44).

The positive effect of the precurved electrode is likely to be related to the different intracochlear electrode positions compared with the straight electrode. The precurved electrode is positioned significantly deeper inside the cochlea and significantly closer to the modiolus (Table 1). While it is valuable to determine the independent influence of these two factors (insertion depth and WF) on speech perception, these factors are inseparable from the electrode type and each other. The electrode type (which has either a straight or modiolus-hugging design) determines the WF and, to a lesser degree, the depth of insertion (an electrode of the same length with a close modiolus position is deeper than a with a lateral wall position). The correlation between the WF, position of the most apical electrode, and electrode type is demonstrated in a scatter plot in Figure 4. Whether the WF or the insertion depth is the main factor for improved speech perception using the precurved electrode cannot be statistically inferred from this study.

Theoretically, however, better speech perception due to a greater angular insertion depth may be the result of a larger coverage of the cochlear spiral ganglion cells by the electrode or by an improved frequency match between electric stimulation and natural frequency tonotopy (Skinner et al. 2002; Baskent & Shannon 2003, 2005). In this study, the absolute difference between the average angular insertion depth of the most apical electrode contact (AIO22) between the two electrode types was only 40° (Table 1). In theory, if only the angular insertion depth influenced speech perception, this 40° would have to explain the 11.8% higher speech perception scores. The ranges of the AIO22 within the electrode type are 264° and 144°, respectively, for the precurved and straight electrodes. Considering that in the stratified univariable analysis within these electrode types, no correlations were found between the AOI22 and speech perception (Table 2), suggest that deeper insertion does not explain the higher speech perception scores in the recipients of the precurved electrodes. This is consistent with the results of a number of other studies evaluating the influence of angular insertion depth on the speech perception outcome (Holden et al. 2013; van der Marel et al. 2015; Heutink et al. 2019).

The theory that a small WF positively influences speech perception is based on the improved electrophysiological properties that a small electrode-to-modiolus distance provides. A perimodiolar position has been shown to lead to lower stimulation thresholds, the reduced spread of excitation, and, therefore, to the stimulation of a more specific region of spiral ganglion cells (Frijns et al. 2002; Mens et al. 2003; van der Beek et al. 2005; Hughes & Abbas 2006; Todt et al. 2008; Hughes & Stille 2010). It is likely that these electrophysiological properties are the explanatory factors underpinning the significantly better performance of the precurved electrodes in this study. Moreover, other studies (Frijns et al.

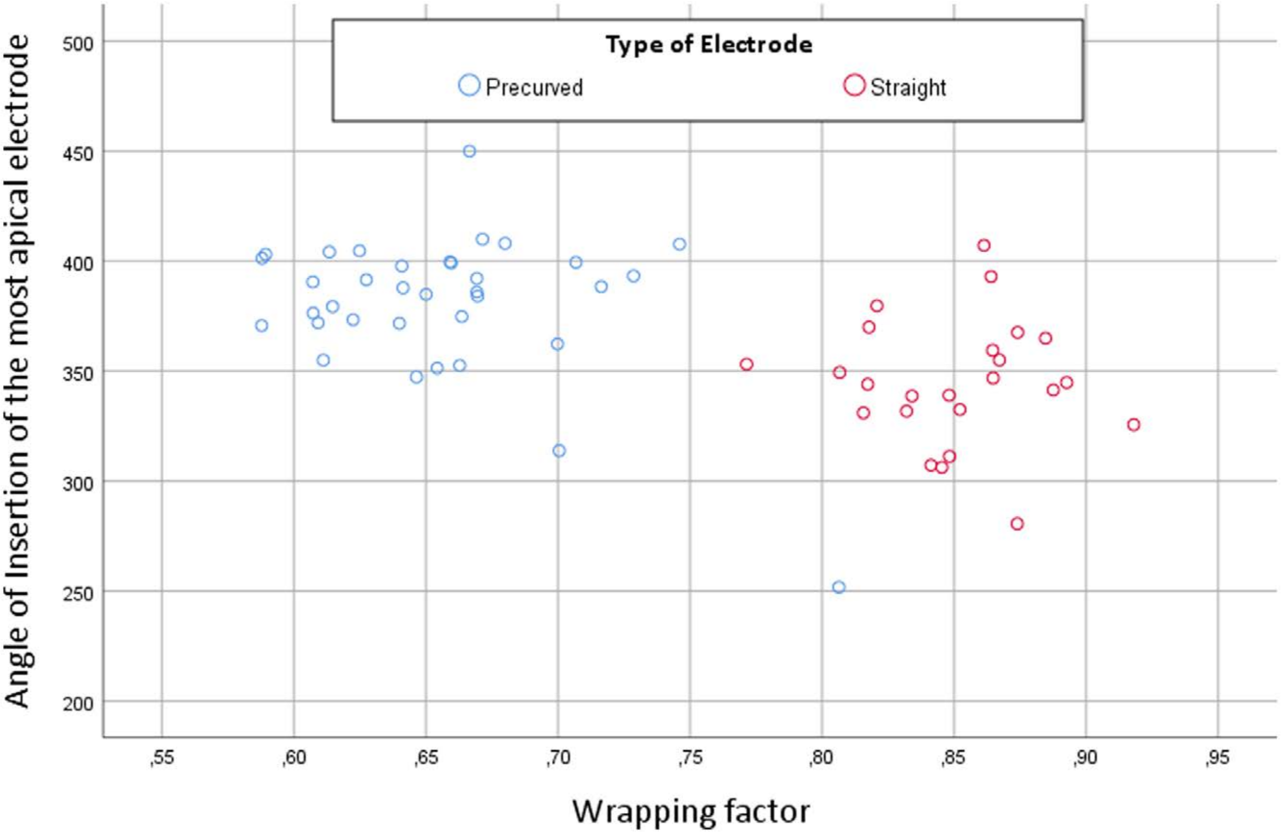

Fig. 4. A scatter plot between the wrapping factor and the angle of insertion of the most apical electrode contact (AOI22), in which individual cases are marked by type of electrode, indicating the influence of electrode type on the electrode position.

2001; van der Beek et al. 2005; Holden et al. 2013; Holden et al. 2016) also demonstrated a positive influence on speech perception when the electrode array was in close proximity to the modiolus.

A number of other studies (Bacciu et al. 2004; Fitzgerald et al. 2007; Gordin et al. 2009; Doshi et al. 2015; O'Connell et al. 2016a,b; Park et al. 2017) compared speech perception in precurved and straight electrodes; however, the results of these studies are somewhat divisive. Park et al. (2017) found that children who were bilaterally implanted with a precurved and a straight electrode had significantly better speech perception in the ear with the precurved electrode. Four studies in adults reported significantly higher speech perception for the precurved electrodes (Bacciu et al. 2004; van der Beek et al. 2005; Gordin et al. 2009; Holder et al. 2019), whereas four other adult studies found no difference between electron types (Fitzgerald et al. 2007; Doshi et al. 2015; O'Connell et al. 2016a; Fabie et al. 2018). One study reported better speech perception scores for straight electrodes (O'Connell et al. 2016b). The reason for the variation between these studies is unknown; however, observational studies investigating cochlear implantation are prone to different forms of bias, potentially causing these differences in findings. The physiological process of converting sound to electricity and stimulating the auditory nerve into comprehensive speech perception is complex, and many patient-specific factors can influence long-term speech perception. Moreover, every CI implant center has specific clinical procedures, leading to differences in the indication of participants, in choices for CI systems and electrode types, and in surgical techniques. As shown in this study, these clinical choices and differences can cause selection (present study) or information and confounding bias, which is not accounted for in a univariable analysis. Therefore, the clinical differences in combination with the observational design of most CI studies most likely explain the variation between findings in the current CI literature.

One example of a strong confounding factor, which has been addressed in the present study, is the influence of the type of electrode and its correlation with factors related to it, such as electrode insertion and placement. Because CI surgeons strive for structure and therefore the preservation of residual hearing, the electrode choice is usually based on clinical decision parameters (e.g., audiometric parameters), and thus may influence the results of all recent nonrandomized CI research. Moreover, the covariance between electrode type and electrode position factors in the present article showed that the electrode type mainly determines the position of the electrode inside the cochlea; thus, the electrode position is only partly influenced by other factors such as the variation in surgical approach and cochlear anatomy (van der Marel et al. 2014, 2016). This indicates that the analysis of electrode position factors in a group of participants with multiple types of electrodes is merely analyzing the differences between the types of electrodes and not the variation in electrode position. Considering this potential influence, one may wonder about the possible bias in studies analyzing multiple CI systems incorporating several CI clinics. Based on these findings, it is important that future nonrandomized studies investigating factors affecting CI outcomes should take into account that the electrode type has an effect on the three position factors (angular insertion depth, scalar location, and WF) and that the clinician's choice of a specific electrode type is likely to be dependent on the patient's (audiologic) profile. In hindsight, the rationale for implanting participants who retained a certain degree of residual hearing with a straight electrode seemed to be incorrect. In the current study, we observed that (1) the overall results when using the precurved electrode were better than the results with the straight electrode and (2) adults who received a straight electrode eventually lost, to a great extent, their residual hearing postimplantation. The overall preoperative and postoperative residual hearing for the straight electrode were 88 and 122 dB, respectively.

Compared with other studies (Holden et al. 2013; Wanna et al. 2014; O'Connell et al. 2016a,c; Chakravorti et al. 2019), we identified a high number of SV locations and translocations. Interestingly, however, the scalar trajectory did not significantly influence the speech perception performance (Tables 2 and 3). It is unclear why we did not observe a negative effect for a SV position or translocation, and future research should explore this.

Beside the electrode position and audiometric factors, the correlation between speech perception and the three included biographic factors (age at implantation, level of education, and years of hearing loss) was evaluated (Table 2). Regarding age at implantation, a univariate analysis suggested that higher speech perception scores would be detected in the younger participants than in the older participants. This was observed for the straight electrode but not the precurved electrode, which might be due to a potentially confounding correlation in which younger adults more commonly had higher preimplantation speech perception scores in straight electrode implants. Some studies found a positive effect for the age at implantation on speech perception (Blamey et al. 1996; Friedland et al. 2010; Blamey et al. 2013; Holden et al. 2013), while others found no effect (Leung et al. 2005; Budenz et al. 2011).

The reason why no correlation was found between the level of education and speech perception might be that the level of education, as defined in this study, did not reflect the level of cognitive functioning, which was previously shown to influence speech perception in CI (Heydebrand et al. 2007; Holden et al. 2013; Pisoni et al. 2018). Several studies also reported a negative effect for the duration of deafness (Blamey et al. 1996; Lazard et al. 2012; Blamey et al. 2013; Holden et al. 2013); however, we calculated the duration of hearing loss instead of the duration of deafness, and did not find a correlation. Studies investigating the duration of deafness often define it as the time since the start of SPHL, which is an average hearing level higher than 70 dB. In our clinic, however, we found that it often is quite difficult to pinpoint the exact onset of deafness in adults with a late onset of hearing loss. Most adults cannot recall this because their hearing loss happened slowly over time, and there is often a lack of audiometric history in referred patients. In addition, the retrospective recall of start of SPHL is prone to bias; therefore, duration of deafness was not evaluated here. The duration of hearing loss is easier to recall as it is often a more memorable event from the patient's perspective, and is therefore less prone to recall bias. Another potential reason for not finding an effect for the duration of hearing loss is the effect of the time frame in which studies are conducted. Blamey et al. (1996, 2013) showed that the influences of biographic and audiometric factors decrease over time. Because the indication criteria for adult CI candidates have become less stringent, today most adult CI candidates still have some residual hearing that is rehabilitated with hearing aids.

Strengths and Limitations

The present article is the first single-center study to identify factors that affect speech perception in a large, homogeneous group of patients implanted with a CI device from a single manufacturer, in which the data were stratified according to the type of electrode. The main limitation of this study is that it is observational and thus not randomized. The present study was designed to limit bias arising from the electrode type used, and any potential bias is considered in the statistical analysis and addressed in the discussion; however, not all factors that theoretically might influence speech perception have been measured (e.g., cognition and brain plasticity). Second, the variation of some of the independent factors investigated was limited in the present study (Table 1). Limited variation restricts the extent to which the conclusions can be generalized to patients fitted with different CI brands. The electrodes of some other CI models can extend up to 880° (De Seta et al. 2016), while the maximum angular insertion depth in our study was 498°. An effect of angular insertion depth above our maximum insertion depth cannot be ruled out. Finally, stratifying the analysis by the electrode type results in a reduced number of participants per group. This could have resulted in some of the statistically insignificant univariate correlations (Table 2), particularly in the audiometric analysis in the straight electrode group (n = 44).

CONCLUSION

In this study, cochlear implantation with a precurved electrode resulted in a significantly higher speech perception outcome, independent of biographic factors, audiometric factors, or scalar location. The clinical selection process for choosing the type of electrode can significantly influence correlations between speech perception and the biographic, audiometric, and electrode positional factors. Nevertheless, because the study was limited to two electrode types from one CI manufacturer, we gained insights into the importance of electrode choice.

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