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The Relationship Between Impedance, Programming and Word Recognition in a Large Clinical Dataset of Cochlear Implant Recipients

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Abstract

Cochlear implant programming typically involves measuring electrode impedance, selecting a speech processing strategy and fitting the dynamic range of electrical stimulation. This study retrospectively analyzed a clinical dataset of adult cochlear implant recipients to understand how these variables relate to speech recognition. Data from 425 implanted post-lingually deafened ears with Advanced Bionics devices were analyzed. A linear mixed-effects model was used to infer how impedance, programming and patient factors were associated with monosyllabic word recognition scores measured in quiet. Additional analyses were conducted on subsets of data to examine the role of speech processing strategy on scores, and the time taken for the scores of unilaterally implanted patients to plateau. Variation in basal impedance was negatively associated with word score, suggesting importance in evaluating the profile of impedance. While there were small, negative bivariate correlations between programming level metrics and word scores, these relationships were not clearly supported by the model that accounted for other factors. Age at implantation was negatively associated with word score, and duration of implant experience was positively associated with word score, which could help to inform candidature and guide expectations. Electrode array type was also associated with word score. Word scores measured with traditional continuous interleaved sampling and current steering speech processing strategies were similar. The word scores of unilaterally implanted patients largely plateaued within 6-months of activation. However, there was individual variation which was not related to initially measured impedance and programming levels.

Keywords

electrical stimulation, electrode, retrospective, plateau, fitting

Introduction

Cochlear implants (CIs) are the primary intervention for listeners with severe to profound sensorineural hearing loss. CIs directly stimulate the auditory nerve, by delivering electrical currents to electrodes located along the tonotopic axis of the cochlea. Although the CI is the most successful sensory neuroprosthesis, speech recognition ability remains highly variable amongst adult CI recipients (Firszt et al., 2004; Gifford et al., 2008; Holden et al., 2013). CI programming typically consists of the routine measurement of electrode impedance, selecting a speech processing strategy and fitting the dynamic range of electrical stimulation according to listener feedback (or evoked potentials). It is of interest to understand how these variables relate to speech recognition to inform programming, guide counselling, and suggest device development.

Electrode impedance, a measure of intracochlear resistance, informs the flow of electrical current between electrodes (Dong et al., 2021). Impedance mediates voltage compliance limits and the current levels required to elicit auditory percepts. Electrodes with greater impedance require greater voltage to maintain the delivered charge,

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which drains battery. The structure and volume of tissue around the electrode contacts influences impedance (Tykocinski et al., 2001), suggesting that impedances, in part, reflect electrode-to-tissue status (Hughes et al., 2001; Hughes, 2012). Histopathological studies have demonstrated that neural survival and bone formation, reflected by impedance, can be related to programming (Kawano et al., 1998) and word recognition (Kamakura & Nadol, 2016). Impedance has been suggested as a basis for programming modifications to potentially improve speech recognition (e.g., adjusting pulse widths and programming levels, deactivating electrodes; Sanderson et al., 2019). However, evidence on the relationship between clinically measured impedance and speech recognition is neither substantive nor conclusive. Retrospective studies by de Graaff et al. (2020) using several models to analyze the data of 138 Cochlear CI recipients, and Prenzler et al. (2020) using bivariate correlations to analyze the data of 127 Med-El CI recipients, reported no relationship between impedance magnitude and speech recognition. However, de Graaff et al. (2020) did report that greater variation in impedance across the electrode array was associated with poorer speech recognition in both quiet and noise. It is therefore unclear whether clinically measured impedance is associated with speech recognition.

Following impedance measurement, the speech processing strategy is selected. The speech processing strategy determines the electric representation of the acoustic signal, temporally and spectrally. Most CIs use a version of the traditional continuous interleaved sampling strategy which stimulates one electrode at a time (Wilson et al., 1991). Spectral resolution, important for listening in noise (Shannon et al., 2004), is limited in CIs (Bierer, 2010). One factor likely contributing to spectral degradation in CIs is the wide spread of electrical current and channel interaction along the length of the cochlea (Bierer, 2010; Hughes & Stille, 2010). Current steering, where adjacent electrodes are stimulated simultaneously to create additional virtual channels (Firszt et al., 2007), has been investigated to improve spectral resolution. Current speech processing strategy options for Advanced Bionics (AB) devices include: HiResolution (HiRes), a continuous interleaved sampling strategy, with a maximum of 16 stimulation sites (Firszt, 2003); Fidelity 120, a current steering strategy, with a maximum of 120 possible stimulation sites (Advanced Bionics, 2009); Optima, another current steering strategy which applies current steering such that electrodes are always stimulated in pairs, improving battery efficiency (Advanced Bionics, 2012). Previous results on the speech recognition benefits of AB current steering strategies compared to continuous interleaved sampling strategies have been mixed. Some studies (Brendel et al., 2008; Firszt et al., 2009) have shown small current steering benefits in quiet and noise, although these may have been confounded by processor and learning effects. Others have shown no benefit (Donaldson et al., 2011; Reynolds & Gifford, 2019). It is unclear whether what has been shown in such smaller studies is reflected clinical datasets of patients who have had long-term, daily listening experience with these strategies.

After the speech processing strategy has been selected, the upper and lower stimulation levels of a CI, the dynamic range, are measured to minimum detectable and loudest comfortable auditory percepts. These programming levels, detection threshold levels and most comfortable levels (referred onwards as T-levels and M-levels, respectively), are commonly fit to tone or speech bursts and verified with the live voice of the clinician. Programming T-levels below threshold may cause soft sounds to be inaudible, while programming T-levels too high may cause ambient noise to be too loud (Busby & Arora, 2016; Wolfe & Schafer, 2015). Programming M-levels too high or too low can limit speech recognition and sound quality (Wolfe & Schafer, 2015). Laboratory studies have shown that mean T-levels with focused stimulation (Bierer & Faulkner, 2010; Pfingst et al., 2004; Long et al., 2014) and mean M-levels with the clinically available monopolar configuration correlate with speech recognition (Pfingst & Xu, 2005). Negative correlations between variation in T-levels and speech recognition (Pfingst et al., 2004; Pfingst & Xu, 2005) with the monopolar configuration, and more focused configurations (Bierer, 2010) have also been shown. These findings may reflect variation in electrode-to-neuron distance across the array, neural health, as well as bone and tissue growth. The current study examined whether these laboratory findings were evident in larger clinical datasets.

Relationships between programming levels and speech recognition in retrospective studies of clinical datasets have not necessarily reflected those shown in laboratory studies. Both van der Beek et al. (2015) and de Graaff et al. (2020) reported associations between mean T-levels and speech recognition for recipients of Cochlear and AB CIs. de Graaff et al. (2020) suggested that the negative relationship between mean T-levels and speech recognition was indicative of a poor electrode-neural interface (DeVries et al., 2016; Long et al., 2014), rather than suboptimal programming. No clear associations between M-levels (de Graaff et al., 2020), or variation in T- or M-levels across the electrode array (van der Beek et al., 2015), and word recognition were reported. The current study retrospectively analyzed a large clinical dataset, with a primary aim of elucidating how impedance and programming metrics relate to word recognition in post-lingually deafened adult CI recipients with AB devices. The second aim of the study was to examine the role of speech processing strategy on word recognition, analyzing a subset of patients who had experience with both HiRes and current steering strategies.

Understanding the longitudinal progression of speech recognition scores to reach maximum stable performance (i.e., to plateau) is valuable for guiding programming,

counselling, training, and the prescription of assistive listening devices. Previous studies have shown that while most adult CI recipients plateau in speech recognition performance within 12 months post-activation, the exact time taken to plateau can vary widely from patient-to-patient (Chang et al., 2010; Holden et al., 2013; Litovsky et al., 2006; Lenarz et al., 2012; Massa & Ruckenstein, 2014). It is unclear what factors are related to this variation, beyond some evidence on the duration of severe-to-profound hearing loss (Holden et al., 2013). The third aim of this study was to explore the time for word recognition to reach plateau within a clinical dataset of patients that had a varying number and frequency of word recognition measures. Logistic functions were fit to these data, to compare the time to reach plateau performance with the prospectively acquired longitudinal data of Holden and colleagues (2013). To do this, focus was placed on a subset of patients who had a sufficient number of word recognition scores measured over a defined period. This approach could be applied to clinical datasets and used to counsel patients about progress with their CI.

Patient factors, such as duration of deafness, age at implantation, and duration of CI experience (Blamey et al., 2013; Budenz et al., 2011; Derinsu et al., 2019; Dornhoffer et al., 2021; Green et al., 2007; Holden et al., 2013; Kim et al., 2018; Mosnier et al., 2014; van der Marel et al., 2015), have been shown to relate to speech recognition in clinical samples, although the relative strength of such relationships appears limited according to a meta-analysis of 1,095 patients (Zhao et al., 2020). The contribution of device and surgical factors to speech recognition, including electrode insertion, location and positioning has also been reported (Holden et al., 2013; O'Connell et al., 2016; Wanna et al., 2014). Certain patient and electrode array factors were available in the current clinical dataset. Such factors were included in analyses, to account for their contributions to word recognition relative to impedance and programming.

Methods

Data Collection

Data were collected at the Massachusetts Eye and Ear (MEE) Audiology clinic, extracted from two databases: the AB Soundwave programming software (Valencia, CA, USA) database at MEE, and the MEE audiology patient database. Data were merged between the databases using Microsoft SQL Server Management Studio (Redmond, WA, USA), exported into Excel 2013 (Microsoft, Redmond, WA, USA), and then imported into MATLAB R2015a (The Mathworks, Natick, MA, USA). This study was approved by the Institutional Review Board of the Partners Human Research Committee, Boston, Massachusetts (protocol number 2019P001158).

The AB database included 14,870 entries, with multiple entries (according to the appointment) for 833 implanted ears across 713 patients. The date of entries recorded in this dataset ranged from May 2003 to July 2018. Each entry included a unique de-identified patient ID, date of implantation, activation and test date, chronological age and ear tested. Entries also included electrode specific data (1–16) on activation status, impedance and programming levels. Impedance, date of test and ear tested values were automatically generated by the AB software each time the implant was connected to the software, while M- and T-levels were saved following adjustments. Duration of CI experience was calculated by subtracting the date of activation from the date of test. The range of data available for each patient in relation to their activation date varied: for some patients, the earliest data available were from the first post-activation follow-up, whereas for others, the earliest data from follow-up appointments several years post-activation (likely for patients who were implanted elsewhere but obtained follow-up care at MEE). If patients were implanted elsewhere, dates of implantation and activation data were gathered and input into the MEE patient database via communication with the implanting center, or the patient.

Data from the audiology patient database were extracted from the Audiometer Operating System (Franck & Hultman, 2020) used to collect and store patient and audiometric data. Each entry included a medical record number and implanted ear-specific data on etiology, age of onset of hearing loss, age of (first) implantation, Consonant-Nucleus-Consonant (CNC) phoneme and word scores. Age of onset of hearing loss (ranging from mild to profound) for individual ears was based on pure-tone thresholds. If pure-tone thresholds were unavailable, age of onset of hearing loss was estimated using a verbal case history, with probing questions on nature of onset (sudden or gradual). Duration of hearing loss was calculated by subtracting the age of onset of hearing loss from the date of activation. Note, the degree of hearing loss in age of onset (i.e., mild to profound) varied between ears, and therefore this measure is not equivalent to duration of "deafness". A unique de-identified patient ID was added to allow matching between the MEE audiology data and the AB database. Data from the MEE audiology database were appended to the entries from the AB database using the de-identified patient IDs and timestamps.

Two indices, for individual patients and ears were created to filter single entries. Entries were filtered by age at implantation ($\geq$18 years old), post-lingual deafness (age of onset of hearing loss in both ears was $\geq$3 years, and at minimum severe in degree), and from a most recent appointment, at least 5 months post-activation (the difference between the test date and activation date was $\geq$5 months). This yielded a final sample of 425 implanted ears across 384 individual patients, for follow-up appointments between July 2003 and July 2018.

Sample

The most recent data for 425 implanted ears from 384 post-lingually deaf patients were retrospectively analyzed. All patients were implanted with AB devices as adults. Patients were followed at MEE at least 5 months post-activation (i.e., patients had a minimum of 5 months of CI experience), for each implanted ear. The mean duration of hearing loss was 28.2 years ($SD = 16.5$ years; range = 0–78 years; three patients had unilateral hearing loss from birth). The mean age at implantation was 63.3 years ($SD = 14.1$; range = 24–93 years). The mean duration of CI experience was 4.2 years ($SD = 4.0$ years; range = 0.42–25.3 years).

Fifteen etiology groups, identified by audiologists or physicians, were represented in the sample. The groups were: unknown, for no identifiable etiology (n = 136); childhood, for patients diagnosed with hearing loss before the age of 18, with no identifiable etiology (n = 67); sudden sensorineural hearing loss (n = 50); noise induced hearing loss (n = 44); presbycusis (n = 35); Meniere's disease (n = 33); otosclerosis (n = 24); ototoxicity (n = 14); radiation (n = 7); enlarged vestibular aqueduct (n = 4); Usher syndrome (n = 4); meningitis (n = 3); temporal bone fracture (n = 2); maternal rubella (n = 1); Susac syndrome (n = 1).

Of the 425 ears analyzed, 206 were left-implanted, and 219 were right-implanted. Of those, 342 were from unilaterally implanted patients, and 83 ears were from 42 bilaterally implanted patients (one of these patient's ears was not included in the sample due to a lack of follow-up data). Patients were implanted with one of four types of HiFocus electrode arrays: the HiFocus I/II (n = 48), HiFocus 1J (n = 161), HiFocus Helix (n = 79), or HiFocus Mid-Scala (n = 137) arrays. HiFocus I/II and Helix arrays are designed for closer perimodiolar placement in the cochlea. The 1J array is designed for outer wall positioning. The Mid-Scala array is designed for medial mid-scalar placement. Each array consisted of sixteen electrode contacts. Across the sample, 82 ears (19.3%) had at least one electrode deactivated. Most deactivated electrodes were in the base of the cochlea. Sixty ears (14.1%) had electrode 16 deactivated, and 36 ears (8.5%) had electrode 15 deactivated. Thirty-two ears (7.5%) had both electrodes 15 and 16 deactivated. Less than 22 ears (5.2%) had a single electrode from 1 to 14 deactivated. Devices were programmed with one of three HiRes speech processing strategies: the original HiRes (n = 28), Fidelity 120 (n = 98) or Optima (n = 299). Most ears were programmed with the most recent current steering strategies (Fidelity 120 or Optima). Although there were two possible stimulation strategies in devices, sequential and paired, standard practice at MEE was to program devices with sequential stimulation (Buechner et al., 2005). Four-hundred and nineteen ears (98.6%) had sequential stimulation, while six ears (1.4%) ears had paired stimulation.

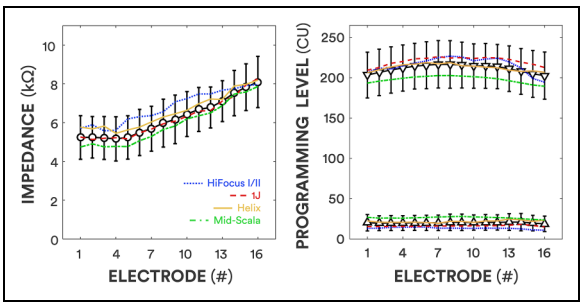

Figure 1. Line plots with error brs showing mean impedance (left panel) and programming levels (right panel) across the electrode array. In the programming levels plot, the upward-pointing triangles refer to T-levels, while the downward-pointing triangles refer to M-levels. Error bars denote ± 1 standard deviation. Mean impedance and programming levels for the following electrode array types are overlaid: the dotted blue line refers to those from HiFocus I/II arrays; the dashed red line refers to those from 1J arrays; the solid yellow line refers to those from Helix arrays; and the dashed-dotted green line refers to those from Mid-Scala arrays.

Follow-up Appointment Measures

Patients attended MEE audiology clinics for appointments between July 2003 and July 2018. Appointments occurred at the main MEE building in Boston, or at nearby suburban clinics, thus, this study is considered single centered. Audiologists followed a standard MEE clinical protocol. The recommended time scale for follow-up appointments was 1 week, 1, 3, 6 and 12-months post-activation, then annually. The exact dates depended on patient progression and availability, hence the operational 5-month cutoff for this study. Furthermore, the median time for CNC word scores in Holden et al. (2013) to plateau was around 5 months. Follow-up appointments typically included speech testing, impedance and M-level re-measurement and counselling.

Electrode impedance was measured in monopolar mode for each electrode (1–16) using the AB programming software. A fixed, low-level current was applied to each electrode, with the voltage measured between the active and return electrodes. The voltage and the current level were used to calculate impedance. Figure 1 (left panel) shows mean impedance across the electrode array. Impedance measured at basal electrodes (electrodes 9–16; $M = 7.0$ kΩ; $SD = 1.9$ kΩ) was greater than at apical electrodes (electrodes 1–8; $M = 5.4$ kΩ; $SD = 2.0$ kΩ; $t(423) = 22.7$, $p = 1.7 \times 10^{-75}$). Therefore, impedances were separated in analyses between these sites. Two metrics were used to assess impedance variation: ± 1 standard deviation (SD) across active electrodes, and across-site variation (ASV), the mean of the absolute difference between each active electrode in the array and its active adjacent neighboring electrodes. The mean SD in impedance was 0.95 kΩ and 1.21 kΩ across apical and basal regions of the electrode array, respectively. The mean

ASV in impedance was 0.10 kΩ and 0.28 kΩ across apical and basal regions of the electrode array, respectively.

M-levels were measured using "Live Voice", "Speech Burst" or "Tone Burst" stimulation (Advanced Bionics, 2003), or a combination, depending on the audiologist's judgment. M-levels could be measured for individual electrodes or for up to four electrodes simultaneously to balance loudness. Following this, M-levels were checked for comfort with the live voice of the audiologist as the stimulus and fine-tuned according to patient feedback. In AB devices, T-levels are preset to 10% of M-levels for each electrode, although occasionally audiologists will set the T-levels to zero or measure them behaviorally. In the current sample, 243 ears (57.2%) had T-levels set to 10% of M-levels, and 94 ears (22.1%) had T-levels set to 0 clinical units (CU). Forty-six ears (10.8%) had T-levels set to over 15% of their respective M-levels. Figure 1 (right panel) shows mean programming levels across the electrode array. Programming levels are reported in CU, which are scaled charge units used in AB clinical programming software. CU was calculated using pulse peak amplitude current and pulse widths extracted from the programming database, along with a scaling constant (Advanced Bionics, 2003; L. Litvak, Advanced Bionics, personal communication, November 8, 2019). CU are linearly proportional to charge delivered in a single phase of a biphasic pulse. Mean T-levels measured at basal electrodes ($M = 21.0$ CU) were similar to those measured at apical electrodes ($M = 20.0$ CU; $t(420) = 1.71$, $p = 0.06$). Furthermore, mean M-levels measured at basal electrodes ($M = 211.9$ CU) were similar to those measured at apical electrodes ($M = 212.7$ CU; $t(424) = 0.83$, $p = 0.41$). Therefore, T- and M-levels were grouped across the electrode array in analyses. As with impedance, two metrics were used to assess programming level variation: ± 1 SD across electrodes, and the mean absolute difference between adjacent electrodes (ASV). The mean T-level was across ears 20.5 CU ($SD = 18.7$ CU), the mean SD in T-level across the electrode array was 2.7 CU, and the mean ASV in T-level across the electrode array was 0.14 CU. The mean M-level across ears was 211.3 CU ($SD = 59.0$ CU), the mean SD in M-level across the electrode array was 10.4 CU, and the mean ASV in M-level was 0.47 CU. Mean T- and M-level were positively correlated ($r = 0.24$; $p = 4.1 \times 10^{-7}$).

Table 1. Pearson Correlation Coefficients for Relationships Between Continuous Fixed-effects Candidates and Word Recognition Score (RAU).

Fixed-effects candidate	r	p
Apical impedance (kΩ)		
Mean	−0.03	.483
SD	−0.13	.008
ASV	−0.01	.796
Basal impedance (kΩ)		
Mean	−0.10	.050
SD	−0.14	.003
ASV	−0.09	.057
M-level (CU)		
Mean	−0.13	.006
SD	−0.13	.009
ASV	−0.13	.009
T-level (CU)		
Mean	−0.06	.224
SD	−0.11	.031
ASV	−0.09	.055
Age at implantation (years)	−0.22	4.8×10^{-6}
Duration of CI experience (years)	0.08	.089
Duration of hearing loss (years)	−0.08	.084

Speech recognition in quiet was measured with the open-set CNC monosyllabic word test (Peterson & Lehiste, 1962). Stimuli were presented at 65 dB HL from a single loudspeaker at 0° azimuth, 1 meter from the patient. To collect ear-specific data, a single device was tested sequentially. Contralateral ears with residual hearing were plugged with a foam ear plug or masked using continuous speech-shaped noise. The test consists of 10 lists, each of 50 words, spoken by a single, male-talker with a mid-western American dialect. A total of three lists were tested: one for each ear, and one for bilateral presentation. Phoneme and word recognition were scored for each ear tested.

Analyses

Analyses were conducted in MATLAB. CNC scores in percent correct were transformed into rationalized arcsine units (RAU; Studebaker, 1985), as they were non-normal based on the Kolmogorov-Smirnov test ($D(425) = 0.076$, $p = 0.01$). CNC scores in percent correct are reported as medians given their non-normality.

A linear mixed-effects model was used to infer factors related to word recognition scores (word scores; fit using the fitlme function in MATLAB). A single model with word score as the response variable was constructed as these scores were strongly correlated with phoneme scores ($r = 0.96$, $p = 1.8 \times 10^{-227}$). There were seventeen fixed-effect candidates for the model, consisting of fifteen continuous variables and two categorical factors. The continuous variables were means, SDs, and ASVs for apical impedance, basal impedance, T-level, and M-level, and age at implantation, duration of CI experience and duration of hearing loss. The categorical factors were etiology with fifteen levels, and electrode array type with four levels. These levels were dummy coded. The mean performing etiology group (otosclerosis, 52.9 RAU) and the 1J electrode array group (50.7 RAU) were assigned as reference groups for comparisons. α was corrected for these multiple comparisons using the Holm-Bonferroni method (Holm, 1979).

Pearson correlation coefficients were used to assess relationships between continuous fixed-effect candidates and word scores. Correlations between fixed-effect candidates

and word scores with $p > 0.25$ were excluded from the model. Pearson correlation coefficients were also used to assess if collinearity between fixed-effect candidates exceeded $r > 0.7$ (Dormann et al., 2013). Table 1 shows correlation coefficients and p-values for relationships between the fixed-effect candidates and word scores. All p-values were <0.25, apart from mean and ASV in apical impedance. The only violation of collinearity was between mean apical and basal impedance ($r = 0.73$; $p = 2.5 \times 10^{-70}$). Given this collinearity, and lack of correlation with word score, mean and ASV in apical impedance were not included in the model as fixed effects.

The fifteen fixed effects in the model were: SDs in apical impedance, means, SDs and ASV in basal impedance, M-level and T-level, age at implantation, duration of CI experience, duration of hearing loss, electrode array type and etiology. The random effect in the model was subject ID (bilaterally implanted ears from the same patient had identical subject IDs). The model was fit using restricted maximum likelihood parameter estimates, and residuals were visually inspected for linearity and normality.

To explore the role of processing strategy on word recognition, a paired t-test analysis was conducted on the most recent word scores of a subset of 57 ears (42 ears from unilaterally implanted patients, 15 ears from 8 bilaterally implanted patients). Ears in this subset had scores measured with both the HiRes strategy and one of the current steering strategies (Fidelity 120 or Optima). These ears had a mean age at implantation of 61.9 years ($SD = 13.8$ years), similar to the rest of the sample ($t(423) = 0.29$, $p = 0.77$). All ears here had a minimum of 1 month's experience with each strategy at the time of testing. On average, ears had more experience with either the Fidelity 120 or Optima strategies ($M = 64.5$ months) than with the HiRes ($M = 31.8$ months)

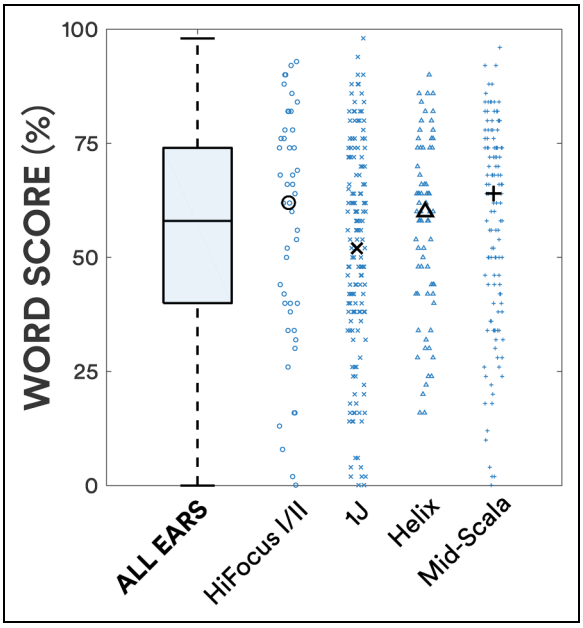

Figure 2. Boxplot of word scores across the sample. The solid horizontal line within the box denotes the median. Whiskers extend to the most extreme values within 1.5 × the interquartile range. The jittered columns of circles, crosses, triangles, and pluses to the right of the boxplot denote individual scores measured with HiFocus I/II, 1J, Helix and Mid-Scala electrode arrays, respectively. Black markers denote medians.

Table 2. Results From the Linear Mixed-effects Model With Word Recognition Score (RAU) as the Response Variable. *P*-values Were Calculated Using Satterthwaite Approximations. The Model Included Random Effects for Subject ID.

Fixed effects					
	Estimate (β)	*SE*	*95% CI*	*t*	*p*
Intercept	84.08	11.09	62.27–105.88	7.58	2.3×10^{-13}
Apical impedance (kΩ)					
SD	−3.23	1.86	−6.89–0.43	−1.73	.084
Basal impedance (kΩ)					
Mean	−0.70	0.66	−2.01–0.60	−1.06	.289
SD	−3.50	1.64	−6.94 – −1.51	−2.13	.034
ASV	−1.51	2.73	−6.88–3.86	−0.55	.580
M-level (CU)					
Mean	−0.02	0.02	−0.06–0.02	−0.92	.357
SD	−0.17	0.11	−0.39–0.05	−1.49	.136
ASV	−0.84	0.48	−1.78–0.10	−1.76	.078
T-level (CU)					
Mean	−0.07	0.08	−0.24–0.09	−0.91	.363
SD	0.08	0.21	−0.35–0.51	0.36	.716
ASV	0.07	0.97	−1.84–1.98	0.07	.947
Age at implantation (years)	−0.38	0.09	−0.55 - −0.22	−4.49	9.0×10^{-6}
Duration of CI experience (years)	0.74	0.30	0.14–1.33	2.43	.015
Duration of hearing loss (years)	−0.06	0.07	−0.20–0.08	−0.83	.407
Electrode array type	2.29	0.69	0.93–3.65	3.31	.001
Etiology	−0.27	0.22	−0.70–0.16	−1.22	.223
Random effects					
		Variance		SD	
Subject ID		17.54		4.18	

strategies. Nine ears (15.7%) here had paired HiRes stimulation strategies, all other ears had sequential stimulation strategies.

To assess the time for word scores to reach plateau, logistic functions were individually fit to the longitudinal scores of a subset of 88 unilaterally implanted patients. The patients in this subset had a mean age at implantation of 66.1 years (SD = 12.1 years), slightly older than the rest of the sample ($t(423) = 2.1$, $p = 0.03$). Each patient here had a minimum of four scores measured over time, with at least one of the scores measured within 3-months of activation, and another of the scores measured following 12-months post-activation. Of this subset, 73 patients (83%) had scores measured over a period greater than 24 months, and 60 patients (68%) had six or more scores measured over time. The final scores of this subset ($M = 58.4$ RAU; $SD = 18.7$ RAU), were not significantly different to the rest of the sample ($M = 53.8$ RAU; $SD = 24.3$ RAU; $t(423) = 1.6$, $p = 0.10$). Logistic functions were fit to scores (Holden et al., 2013), and the plateau score was estimated as the upper horizontal asymptote. Plateau time was estimated as the first date on the function within 5% of the plateau score: the mean SD for the variation in scores measured over each patient's plateau was 5.7%. A multiple linear regression model was used to infer factors related to plateau times (using the fitlm function in MATLAB). The model had ten explanatory variables. This included means and SDs in basal impedance, apical impedance, T-level and M-level, all measured at the patient's first follow-up appointment. Patient factors of age at implantation and duration of hearing loss were also included as explanatory variables.

Table 3. Results From the Linear Mixed-effects Model of the Categorical Fixed Effects Interactions Between Electrode Array Type, and Etiology Groups With Word Recognition Score (RAU) as the Response Variable. *P*-Values Were Calculated Using Satterthwaite Approximations. The Model Included Random Effects for Subject ID. SNHL Refers to Sensorineural Hearing Loss.

Categorical fixed effects interactions					
	Estimate (β)	*SE*	*95% CI*	*t*	*p*
Electrode array type (reference group: 1J)					
HiFocus I/II	5.34	3.90	−2.33–13.02	1.37	.172
Helix	3.60	3.19	−2.69–9.89	1.12	.261
Mid-Scala	11.22	2.96	5.39–17.05	3.78	1.7×10^{-4}
Etiology (reference group: otosclerosis)					
Childhood	−1.68	5.62	−12.72–9.37	−0.30	.765
Enlarged vestibular aqueduct	−28.04	12.03	−51.68 – −4.40	−2.33	.020
Maternal rubella	−20.08	22.01	−63.36–23.20	−0.91	.362
Meniere's	7.08	6.24	−5.20–19.35	1.13	.257
Meningitis	−20.88	13.89	−48.20–6.43	−1.53	.133
Noise induced hearing loss	0.04	5.85	−11.46–11.56	0.01	.993
Ototoxicity	−7.19	7.93	−22.79–8.41	−0.91	.365
Presbyacusis	−0.83	6.32	−13.27–11.60	−0.13	.895
Radiation	4.03	10.85	−17.30–25.36	0.37	.710
Sudden SNHL	1.14	5.79	−10.25–12.52	0.19	.845
Susac syndrome	8.88	22.09	−34.55–52.32	0.40	.689
Temporal bone fracture	30.69	16.15	−1.06–62.45	1.90	.058
Unknown	4.68	5.09	−5.32–14.68	0.92	.358
Usher syndrome	6.18	12.99	−19.34–31.73	0.48	.634

Results

Figure 2 shows a boxplot of word scores across the sample. The median word score was 58.0% (IQR = 40.0–74.0%; range = 0–98.0%). Table 2 shows the results of the linear mixed-effects model with word score as the response variable. The coefficients indicate how a single unit increase in a particular fixed effect changes word score, assuming that all other fixed effects are fixed. The SD in basal impedance was negatively associated with word score, such that a 1 kΩ increase in basal impedance SD was associated with a 3.50 RAU ($SE = 1.64$) decrease in word score ($p = 0.034$). Duration of CI experience was positively associated with word score. A year of CI experience was associated with a 0.74 RAU ($SE = 0.30$) increase in word score ($p = 0.015$). Age at implantation was negatively associated with word score. A year increase in age at implantation was associated with a 0.38 RAU ($SE = 0.09$) decrease in word score ($p = 9.0 \times 10^{-6}$). There was an effect of electrode array type ($\beta = 2.29$; $SE = 0.69$; $p = 0.001$). Table 3 shows the results of the interactions for electrode array type and etiology groups. The Mid-Scala array was associated with an 11.22 RAU (SE = 2.96) increase in word score compared to the 1J array ($p = 1.7 \times 10^{-4}$). The p-values for etiology group comparisons exceeded α when adjusted for multiplicity.

A subset of 57 ears had experience with both HiRes and current steering strategies, and a paired samples t-test was used to examine whether scores with these strategies differed. Word scores measured with the current steering strategies ($M = 52.7$ RAU, $SD = 23.2$ RAU) were not significantly

different to scores measured with the HiRes strategies ($M = 51.2$ RAU, $SD = 23.0$ RAU; $t(56) = 0.59$, $p = 0.55$). Word scores between strategies were positively correlated ($r = 0.71$; $p = 6.5 \times 10^{-10}$).

A subset of 88 unilaterally implanted patients had their word scores analyzed longitudinally to estimate the time for performance to plateau. Figure 3 shows the data of three patients with similar plateau scores, but varying plateau times, to demonstrate the analysis. Figure 4 shows a histogram of plateau times. The mean plateau time was 7.5 months ($SD = 10.7$ months): performance typically plateaued well before a year post-activation. The range in plateau time was 0.2–44.7 months: for some patients, performance did not improve substantially beyond that initially measured, while for other patients, scores did not plateau until approximately 4-years post-activation. Plateau times were highly positively skewed: the median plateau time was 2.9 months (IQR = 0.9–9.0 months). Sixty-one ears (69.3%) plateaued within 6-months of activation. The median plateau score was 61.2% (IQR = 46.8–71.3%). Plateau time and score were not correlated ($r = 0.11$; $p = 0.32$). A multiple linear regression analysis was used to examine factors related to plateau time. Table 4 shows the results of this analysis. There was little evidence to suggest that any of the impedance, programming, or patient factors were associated with plateau time.

Discussion

The current study retrospectively analyzed clinical data from post-lingually deafened adults implanted with AB CIs. The study aimed to investigate whether impedance and programming level metrics were related to word recognition. The study also explored the role of speech processing strategy on word recognition. Finally, a longitudinal analysis was conducted to examine the time taken for speech recognition to plateau, and related impedance and programming factors were investigated.

The difference between apical and basal impedance magnitude is in line with previous study (Sanderson et al., 2019), and is likely related to increased fibrosis, osteogenesis and poorer neural survival in the base, the region closest to the site of insertion (Fayad et al., 2009). The median CNC scores and variation are similar to those reported in large clinical datasets of post-lingually deafened adult implant recipients (de Graaff et al., 2020; Holden et al., 2013). Even after 5-months of experience, some patients still failed to correctly recognize any words. Word score decreased with increasing SD in basal impedance, but not mean impedance, concordant with de Graaff et al.'s (2020) retrospective study of CI recipients with Cochlear devices. This finding supports de Graaff et al.'s (2020) suggestion that clinicians should attend to the profile of impedance. This correlation may be related to bone formation in the basal region of the cochlea (Fayad et al., 2009); Kamakura and Nadol (2016) reported that CNC word score was negatively correlated with new bone volume in implanted cochleae. This finding may be also associated with greater electrode-to-modiolus distance reflected by higher basal impedance (Kawano et al., 1998).

There was little evidence to suggest that mean T-levels were related to word scores. This is contrary to work by van der Beek et al. (2015) and de Graaff et al. (2020), who showed that participants with greater T-levels tended to have poorer speech recognition scores. Differences in findings between clinical studies may be due in part to varying clinical practice between centers (e.g., manually setting T-levels), and differences between devices and programming software (e.g., automatically setting T-levels based on M-levels in AB software). Pfingst and Xu (2005) reported a negative correlation between the variation in monopolar T-levels and speech recognition, supported by bivariate correlations here. However, this relationship was not supported from the results of the model, in line with van der Beek et al. (2015) and de Graaff et al. (2020). There were small, negative bivariate correlations between mean, SD and ASV in M-level and word scores. Pfingst and Xu (2005) reported a negative bivariate correlation between ASV of bipolar M-levels and speech recognition as in the current results, and a positive correlation between mean M-levels and speech recognition, differing to the current correlations. However, these current M-level metrics were not clearly associated with word score when accounting for other factors in the linear mixed-effects model, as in the large clinical samples studied by van der Beek et al. (2015) and de Graaff et al. (2020). A possible reason as to why the findings from laboratory studies by Pfingst and colleagues (2004; 2005) were not clearly reflected in the current and prior retrospective clinical datasets (de Graaff et al., 2020; van der Beek et al., 2015), is that Pfingst and colleagues (2004; 2005) used the method of adjustment technique to measure T- and M-levels, including randomized test orders, which would differ to the noisier setting of programming levels in the clinic (particularly considering that many T-levels were preset or set to zero). Furthermore, the speech recognition testing in studies by Pfingst and colleagues (2004, 2005) – including consonant recognition, vowel recognition, and sentence recognition in background noise – was far more comprehensive than that in the clinical assessment.

Word score increased with CI experience, as in Blamey et al. (1996, 2013). Peripherally, greater numbers of spiral ganglion neurons may contribute to this; electrical stimulation may protect spiral ganglion neurons (Leake et al., 1991, 1999). Central factors including auditory processing, plasticity and learning may also underlie this association (Moore & Shannon, 2009; Petersen et al., 2013; Rouger et al., 2012). Word score decreased as age at implantation increased, as previously reported (Blamey et al., 1996; Blamey et al., 2013; Holden et al., 2013; Roberts et al., 2013). Senescent decline in a combination of peripheral and central factors, including spiral ganglion cell count (Nadol et al., 1989), slower cortical reorganization (Lazard

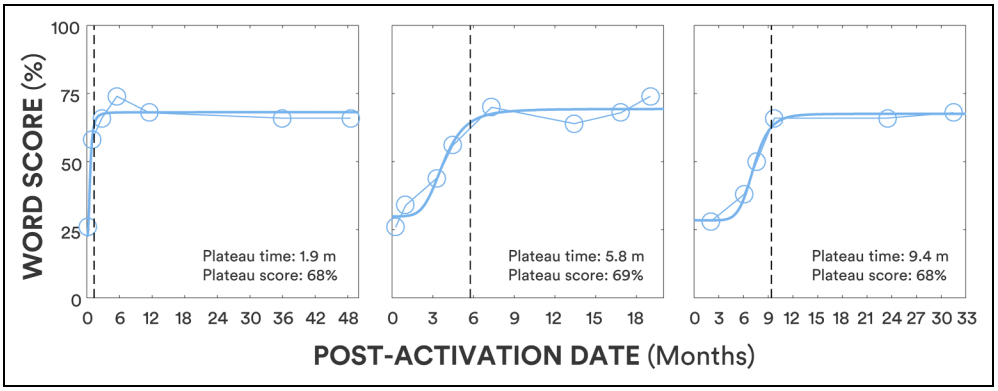

Figure 3. Longitudinal word scores and estimated plateau times for three patients with similar plateau scores. The circles denote the measured word scores, and the vertical dashed lines denote the plateau time estimates. The curved lines denote the logistic functions.

et al., 2011) and poorer cognitive ability (Holden et al., 2013) with higher implanted age, may explain this association. In contrast, duration of hearing loss was not clearly associated with word score. This may be due to the challenge of accurately estimating the age of onset of hearing loss, and the current inability to explicitly define "duration of deafness" (at least severe to profound in degree), as opposed to "hearing loss" (the degree of which varied from mild to profound in the measured age of onset of hearing loss). This lack of clear association between duration of hearing loss and word recognition may also be attributed to clinical advancements, such as, improved hearing-aid technology and advancing implant criteria; for example, in 2016 MEE began implanting patients with unilateral and asymmetric hearing loss where the better ear had mild hearing loss. In line with this reasoning, Blamey et al. (2013) reported a weaker association between duration of severe to profound hearing loss and speech recognition than in their previous retrospective study (Blamey et al., 1996). This weaker association was interpreted by Blamey et al., as possibly being influenced by clinical developments.

Etiology underlies many pathophysiological processes in the cochleae of CI recipients. However, previous analyses on clinical datasets have demonstrated few clear differences in speech perception between etiology groups. Blamey et al. (1996) reported that only meningitis and Meniere's disease patients had speech perception scores which differed from the average. In their follow-up study (Blamey et al., 2013), only genetic, Meniere's disease, and auditory neuropathy spectrum disorder patients had scores which differed from the average. The lack of association in the current study may be related to the variation in group sample sizes, that most etiologies in the were unknown, and that other factors were more influential than etiology. While Nadol et al. (1989) reported etiology as a significant determinant of spiral ganglion cell count, many counts did not differ between etiology groups. There is, however, evidence of differences in psychophysical abilities between etiology groups when etiology is clarified with genetic testing or imaging (Jahn et al., 2020).

Ears implanted with the Mid-Scala electrode array, introduced in 2013, had better word scores than those with the less pre-curved 1J array, introduced in 2003. van der Jagt et al. (2016) compared speech recognition in patients implanted with these arrays, matched for duration of deafness and pre-operative performance. They reported that while patients performed similarly up until the first 6-months post-activation, there was a trend for better performance with the Mid-Scala array, in line with the current results.

This study compared word scores between the continuous interleaved sampling HiRes strategy and current steering Fidelity 120 and Optima strategies for ears that had real-world experience with both. This analysis showed no difference in scores between the strategies. While it may be that the monosyllabic word recognition task is insufficiently sensitive to capture potential real-world benefits of current steering, previous study (Donaldson et al., 2011; Reynolds & Gifford, 2019) has shown little benefit of said strategies in a selection of psychophysical, speech and music perception tasks. In the current analysis, ears had at least 1-month of experience with each strategy, but Donaldson et al. (2011) suggested that 5-months of experience with the current steering strategies may be needed to attain maximum benefit. Forty-two ears had 5-months or more experience with both strategies in the current subset, and when analyzing their scores after 5-months, the results remain: the word scores measured with the current steering strategies ($M = 54.6$ RAU, $SD = 22.0$ RAU) were not different to those measured with the HiRes strategies ($M = 53.8$ RAU, $SD = 22.2$ RAU; $t(41) = 0.27$, $p = 0.784$).

Word scores were analyzed longitudinally for a subset of unilaterally implanted patients. The greatest improvement in scores was attained within a year post-activation, most patients plateauing within 6-months of activation. However, there was considerable individual variation; some patients' scores did not improve much beyond their initial

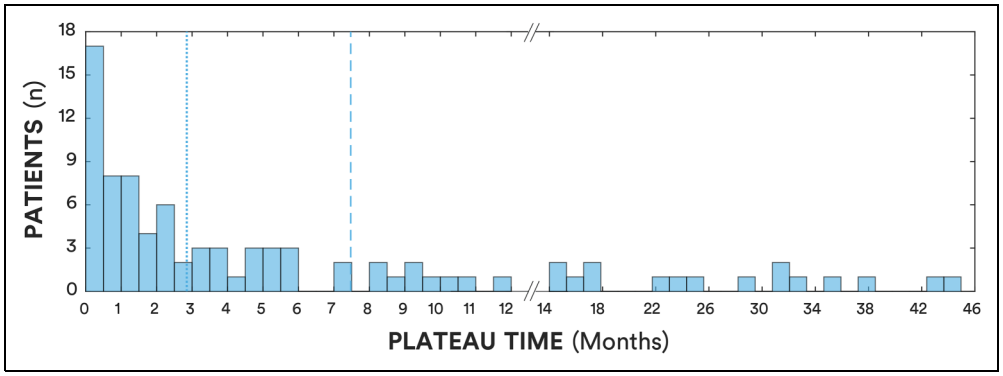

Figure 4. Histogram of plateau times. The vertical dashed and dotted lines refer to mean and median plateau times, respectively.

measurement, while others took years to improve and plateau. This is consistent with previous research on performance in post-lingually deafened, unilateral CI recipients (Cusumano et al., 2017; Hamzavi et al., 2003; Holden et al., 2013). Holden et al. (2013) reported a mean CNC word score rise time (time to reach 90% of final score) of 6.3 months measured prospectively with post-lingually deaf adults with AB implants, similar to the current mean word score plateau time of 7.5 months. Calculating plateau time slightly earlier as rise time, 10% to plateau score (Holden et al., 2013), the mean plateau time becomes 5.2 months. The similarity in results between the controlled, prospective measurement in Holden et al. (2013), who measured a minimum of 12 scores, and the current retrospective analysis, demonstrates the potential of analyzing clinical data with a varying number of scores and frequencies between measurements. However, while many rise times occurred within the first few months of activation like plateau times, they were not as positively skewed: the median rise time in Holden et al. (2013) was 5.3 months, compared to the current median plateau time of 2.9 months. This skew may be related to methodological limitations. Fifteen patients (17%) did not have word scores measured beyond 24 months, and therefore it is possible that they improved beyond this 24-month period. However, when excluding these fifteen participants, the mean (7.9 months) and median (2.2 months) plateau times change little. There was no clear evidence to suggest that the variation in plateau time was explained by impedance, programming or patient factors. Unrepresented factors, such as the hearing status of the contralateral ear, cognitive ability, or auditory training may account for variation. Future research could examine such data with more distinct audiological characteristics (e.g., postlingually deaf compared to congenitally deaf, bimodal listeners compared to bilaterally implanted) to explore factors beyond those tested here. Plateau time and score were not correlated, suggesting that patients who plateau earlier do not necessarily have better long-term speech recognition outcomes.

Table 4. Results From the Multiple Linear Regression With Word Score Plateau Time (Months) as the Response Variable.

Explanatory variables				
	Estimate (β)	*SE*	*t*	*p*
Intercept	−6.69	10.58	−0.63	.529
Apical impedance (kΩ)				
Mean	0.34	1.05	0.32	.747
SD	3.18	2.88	1.11	.272
Basal impedance (kΩ)				
Mean	0.45	1.26	0.36	.722
SD	0.85	2.88	0.29	.768
M-level (CU)				
Mean	−0.01	0.02	−0.39	.698
SD	−0.05	0.14	−0.33	.739
T-level (CU)				
Mean	−0.17	0.13	−1.33	.739
SD	−0.09	0.68	−0.13	.900
Age at implantation (years)	0.17	0.10	1.68	.098
Duration of hearing loss (years)	−0.02	0.08	−0.31	.758
R^2		0.13		
Adjusted R^2		0.0171		
F		1.15		
P-value		0.337		

The retrospective study of clinical datasets has inherent limitations (Dillard et al., 2020). Although the clinicians adhered to defined MEE protocols, the data collection was not as controlled or systematic as it would be in a prospective research design. Much of the current data was manually entered, which is prone to systematic or random miscoding errors. Some data here is inherently vague. For example, the largest etiology group was unknown, and even reported etiologies are largely speculative without confirmation from assessments such as imaging or genetic testing. The data here were collected over 15 years and are therefore prone to cohort effects. For example, surgical, audiological and device developments are likely to contribute to variation in the data.

The current study analyzed implanted ears in isolation. Although the measures here were ear specific, there will be a contribution from the contralateral ear, the status of which (pre-, per- and post-activation) was unknown here. For example, Lazard et al. (2012) reported a positive effect of hearing aids pre-implantation. Therefore, the full hearing status of the contralateral ear is likely to explain some variation in the speech scores (Derinsu et al., 2019). There is evidence of a bimodal benefit for speech recognition (Dunn et al., 2005; Gifford et al., 2015), so bimodal patients could perform worse when the implanted ear is tested alone, although such benefits may be unclear in clinical tests (Gifford & Dorman, 2019).

The present results could be useful for clinical practice. The relationships between impedance variation and word scores suggest value in evaluating the impedance profile across the electrode array, rather than just the overall magnitude of impedance. Clinicians could counsel patient expectations on speech perception in the case of high impedance variation, and conduct integrity tests on the device. More research is required to understand the perceptual consequences of erratic impedance profiles. Further study is also warranted to examine whether variation in programming levels across the electrode array are an indication of cochlear damage which leads to poorer speech recognition, or whether programming levels with high variation itself leads to poorer speech recognition. This may lead to further insights on how to make programming adjustments, such as electrode deactivations, to benefit speech perception. The current results suggest a benefit to early implantation, and that improvements in speech recognition can be expected over time. These findings can be used to guide patient expectations. The plateau times demonstrate that most unilaterally implanted patients can expect their word scores to reach maximum performance within 6-months post-activation. However, it should be noted that several patients took over a year to plateau. Although it is unclear just how well monosyllabic word tests represent real-world hearing ability, these findings can be used in counselling, particularly in managing patient expectations.

Conclusions

This study examined the relationship between impedance, programming and word recognition scores in a large clinical dataset of AB CI recipients. Greater variation in basal impedance was associated with poorer word recognition, supporting prior suggestion that clinicians should attend to the profile of impedance. Bivariate correlations showed that increases in mean M-levels, and increases in the variation of T- and M-levels, were associated with small decreases in word recognition. However, these findings were not clearly reflected in the model accounting for other factors. As in previous research, greater age at implantation was associated with poorer word recognition, and greater CI experience was associated with better word recognition. Ears implanted with the Mid-Scala electrode array had better word scores than those implanted with the 1J array. Word scores measured with continuous interleaved sampling and current steering speech processing strategies were similar, in line with previous research. A longitudinal analysis suggested that unilaterally implanted patients tend to plateau in word recognition performance well within 6-months post-activation. There was, however, considerable variation in plateau time, and little evidence to suggest that this variation was related to initially measured impedance or programming levels.

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