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Cochlear Implant: Analysis of the Frequency-to-Place Mismatch with the Table-Based Software OTOPLAN® and Its Influence on Hearing Performance

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Keywords

Cochlear implant · Hearing performance · Frequency allocation · Cochlear length · OTOPLAN®

Abstract

Objective: The purpose of this study was to compare the originally applied frequency allocation of cochlear implant electrodes assigned by default at the time of activation with a more recent frequency allocation that is anatomy-based by a software called OTOPLAN®. Based on a computed tomography scan of the temporal bone, this software calculates the position of each electrode in the cochlea and its corresponding tonotopic frequency. We also evaluated whether patients with a significant mismatch between these two allocations present poorer speech intelligibility. ***Materials and Methods:*** Patients who underwent cochlear implantation from 2016 to 2021 at the University Hospital of Liege were included in this retrospective study. We used OTOPLAN® to calculate the tonotopic frequency allocation of each electrode according to its exact position in the cochlear duct. This anatomical frequency mapping was compared with the default frequency mapping at the time of cochlear implant activation. Finally, we compared the mismatch with the patients' auditory performance, represented by the Auditory Capacity Index (ACI). ***Results:*** Thirteen patients were included in the study. All patients had a mismatch between the two frequency maps, to a variable extent (200 Hz–1,100 Hz). Frequency shift was significantly inversely correlated with ACI and with the time needed to improve speech intelligibility. ***Conclusion:*** Our primary results show that patients with a larger mismatch between default frequency mapping and anatomically assigned frequency mapping experience poorer hearing performance and slower adaptation to a cochlear implant.

Introduction

The cochlear implant (CI) is the first artificial neurosensory organ and allows hearing rehabilitation for patients with profound deafness. Since its first use in 1976, the intent with the CI system has been to approximate the natural organization of the cochlea. The cochlea is organized in a tonotopic mode corresponding with the maximum displacement of the basilar membrane after a sound stimulation. This movement will be maximal at the apex of the cochlea for low-frequency sounds and at the base for high-frequency sounds. Therefore, the electrical stimuli delivered by the implant will be assigned to apical electrodes for low-frequency sounds and basal electrodes for high-frequency sounds.

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The hearing performance of a CI can be extremely inconsistent; however, this variation is not always explainable. We know that parameters such as patient age at the time of implantation, duration of hearing loss, preoperative speech intelligibility thresholds, and cognitive abilities influence post-implant hearing performance [1, 2]. Experience with and duration of CI use also play a role with progressive improvement in speech intelligibility thresholds within 3 years post-implantation [1]. With radiological and technological improvements, more recent studies have shown that factors influencing the neuron-electrode interface also affect hearing performance, such as the depth of electrode insertion, percentage of electrodes present in the vestibular ramp, amount of fluid surrounding the electrode, and the presence of scar tissue [2–5].

When the CI is activated, a standard allocation of auditory frequencies is applied in an arbitrary and identical manner for each patient, depending on the implant model. No electrode array is designed to reach the most apical regions of the cochlea, and given the extremely variable anatomy of the cochlea (30% variability, especially by sex [6–8]), this frequency assignment will inevitably differ from the natural tonotopy of the cochlea. The result is a mismatch between the default frequency assignment of an electrode and the actual frequency of the neurons it stimulates, known as the frequency-to-place mismatch. This issue may not be as relevant for prelingually deaf CI users, who developed their speech perception through the implant, as it would be for postlingually deaf CI users, who have used normal cochlear tonotopy since birth [9].

So far, anatomical data have been difficult to incorporate into a CI fitting because of the lack of tools for measuring the cochlear duct length (CDL) [10, 11]. The tablet-based software OTOPLAN®, developed in close collaboration between CASCINATION AG (Switzerland) and MED-EL (Austria), provides an intuitive and quick way to assess the temporal bone anatomy and helps otologists plan personalized cochlear implantation to achieve the best results for each patient. It identifies the modiolus, round window, and tonotopic location of each individual electrode contact based on a computed tomography (CT) scan of the temporal bone. Canfarotta et al. [12] confirmed the reliability of OTOPLAN® for estimating the cochlear duct length (CDL) and angular insertion depth of the electrodes. These measurements are based on a formula developed by Alexiades et al. [6], which in turn is based on the third equation of Escudé [7] and on the elliptic-circular approximation [6, 8, 10, 13]. The software determines the characteristic frequency of the stimulated neurons using the Greenwood function (Greenwood 1990) and provides a tonotopic setting for patients with CI. In this study, we investigated the influence of the frequency-to-place mismatch on the hearing performance of CI users by comparing the anatomical frequency mapping defined by OTOPLAN® with the default mapping at the time of CI activation.

Materials and Methods

This retrospective study included patients with postlingual deafness implanted unilaterally with MEDEL CI from 2016 to 2021 at the University Hospital of Liege, a tertiary care center. The inclusion criteria were age ≥18 years and unilateral or bilateral postlingual hearing loss eligible for CI implantation in the deaf ear according to Belgian criteria. Exclusion criteria were age <18 years, prelingual deafness, loss to follow-up, cochlear malformations, contraindication for CT imaging, unavailable scans, poor-resolution scans, or incompatibility with the OTOPLAN® program.

All implants were activated and fitted with a processing strategy (FS4) using a standard frequency allocation map (logFS) distributed on active electrode contacts as prescribed by the manufacturer. All patients underwent a postoperative, high-resolution cone beam CT of the temporal bone, which was analyzed using OTOPLAN® (CE-certification number: G1 17 10 95657 003). The software applied automated assignment of anatomical landmarks without manual intervention (Fig. 1). With MAESTRO 9.0 anatomy-based fitting tools, an automated formula was used without manual intervention to determine a frequency allocation that followed the natural tonotopic map of the cochlea.

The default frequency assigned to each electrode at the time of fitting was compared with the frequency established by OTOPLAN®. The difference between these two values was calculated for each electrode for the frequencies corresponding to the speech spectrum (500–2,000 Hz), then averaged and presented as "average of frequency mismatch" (AFM).

Finally, the AFM was compared with the hearing results for patients as assessed by speech audiometry. We used the articulation function (AF) as an index of speech intelligibility, defined as the average speech discrimination score obtained at 40, 55, and 70 dB. The speech audiometries were performed in a soundproof booth, with the patient sitting 1 m from the sound source. We used the words of Fournier's dissyllabic list in French, pronounced to the patient through a loudspeaker. Measurements were recorded at 40–55 and 70 dB SPL to calculate the AF. All tests were performed in quiet and using the default frequency allocation.

Results

Patients

Thirteen patients were included in this retrospective study. Their demographics are shown in Table 1. Among the eight men and five women, the mean age of implantation was 57.76 years (range 39–75 years). All participants were French speaking. Eight patients were

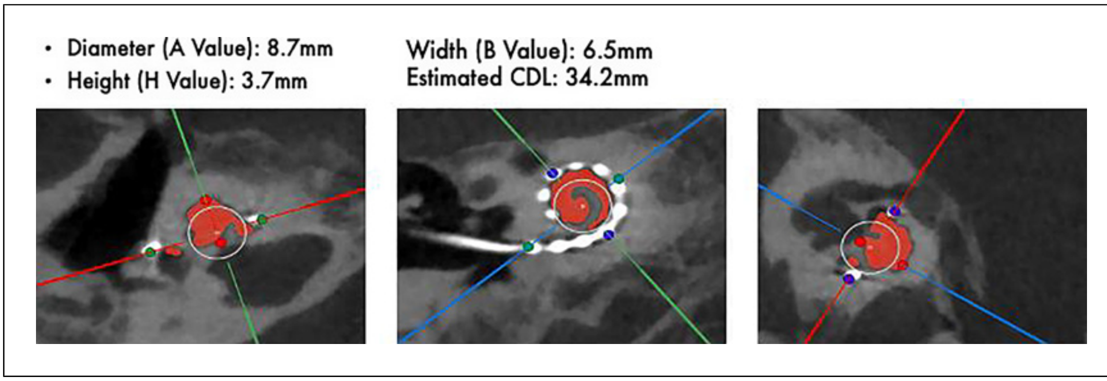

Fig. 1. CT analysis by OTOPLAN® to determine the diameter, height, and width of the cochlea for CDL estimation.

Table 1. Patient demographics

Patient	Age, years	Sex	Age at implantation, years	Etiology of deafness – right side	Etiology of deafness – left side	Other otologic symptoms	Implant type – electrode array
P1	51	M	45	Sudden hearing loss	Sudden hearing loss	None	MEDEL – FLEX 28
P2	52	M	49	Intralabyrinthine neurinoma	/	Tinnitus	MEDEL – FLEX 24
P3	55	F	50	Unknown	Unknown	None	MEDEL – FLEX 28
P4	47	M	44	/	Sudden hearing loss	None	MEDEL – FLEX 24
P5	66	F	65	Cochlear otosclerosis	Cochlear otosclerosis	Dizziness	MEDEL – FLEX 24
P6	67	M	63	Unknown	Ménière disease	Tinnitus and vertigo	MEDEL – FLEX 24
P7	46	F	40	Hereditary	Hereditary	None	MEDEL – FLEX 24
P8	70	M	68	Unknown	Unknown	Tinnitus	MEDEL – FLEX 24
P9	77	M	75	Unknown	Unknown	None	MEDEL – FLEX 24
P10	79	F	75	Sudden hearing loss	Neurinoma with radiotherapy	Tinnitus and vertigo	MEDEL – FLEX 24
P11	41	M	39	/	Trauma	None	MEDEL – FLEX 24
P12	79	F	73	Hereditary	Hereditary	None	MEDEL – FLEX 28
P13	69	M	65	Unknown	Unknown	Tinnitus	MEDEL – FLEX 28

implanted in the right ear and five in the left ear. No postoperative complications were observed. Implantation with a round window approach was performed for 12 patients, and the remaining patient was implanted using a cochleostomy approach. A MEDEL FLEX 24 (24 mm) electrode array was used for 9 patients, and 4 patients were implanted with the FLEX 28 (28 mm). Complete insertion of the electrode array was observed in 11 patients. Two patients had one extra cochlear electrode (number 12 in both cases). Subsequently, these electrodes were deactivated in accordance with the manufacturer's recommendations.

Average of Frequency Mismatch

The main objective of this retrospective study was to evaluate the outcome of speech intelligibility as a function of the difference between the default frequency mapping for each electrode and the frequency fitted by the software OTOPLAN®. All patients (100%) had a frequency mismatch of at least 200 Hz, and the average mismatch was 608.84 Hz. Five patients (38.46%) had a mismatch of <500 Hz (<500 Hz group), 4 patients (30.7%) had a mismatch of ≥500–1,000 Hz (≥500–1,000 Hz group), and 3 patients (23%) had a mismatch of ≥1,000 Hz (≥1,000 Hz group).

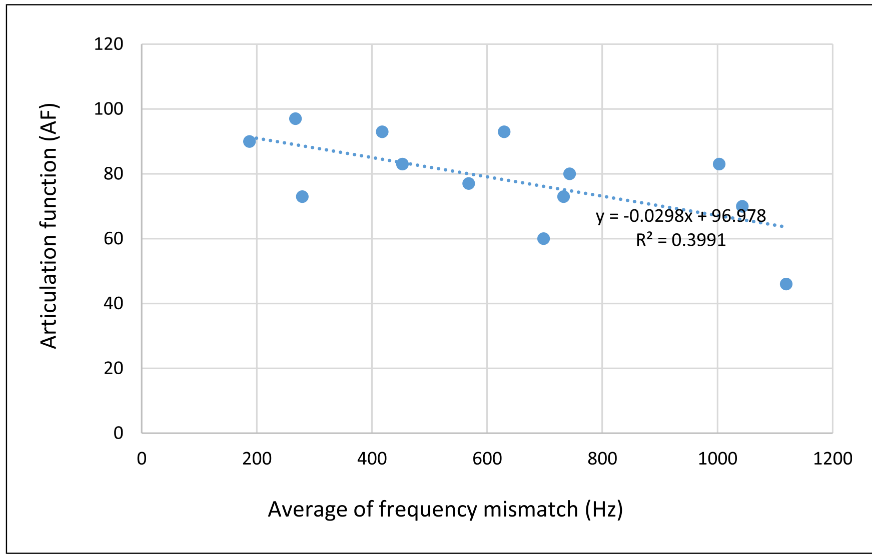

Fig. 2. A significant negative linear correlation (blue dotted line) between AF (*Y* axis) and average of frequency mismatch (*X* axis) for each patient.

Articulation Function

The relationship between AFM and AF was analyzed. AF was 75–99% in the >500 Hz group, 60–95% in the ≥500–1,000 Hz group, and 82–45% in the ≥1,000 Hz group. Average frequency mismatch correlated strongly (R^2 = 0.3991) with speech intelligibility as measured by the articulation function (p = 0.0206) (Fig. 2).

Speed of AF Acquisition

Speech intelligibility acquisition speed was evaluated in the context of average frequency mismatch using the slope reflecting the number of weeks after CI activation relative to the AF (Fig. 3). Values for these two factors showed a statistically significant negative correlation (p = 0.0286). The increase in the difference between the tonotopic frequency as defined by OTOPLAN® and the fitted frequency strongly and inversely correlated with the decreasing slope of the acquisition of speech intelligibly. Overall, the closer the match was between the adjusted and predicted frequencies, the faster speech intelligibility is acquired after CI activation.

Discussion

The principal aim of this study was to compare the default frequencies assigned to CI electrodes at the time of fitting with those based on the cochlear anatomy in OTOPLAN®. As expected, we demonstrated a systematic mismatch between these frequencies, as previously reported in several studies [9, 10, 14, 15]. The average of the mismatch was 608.84 Hz, and the magnitude of mismatch was variable, leading us to establish three groups for analysis (<500 Hz; ≥500–1,000 Hz; ≥1,000 Hz).

The secondary outcome was to compare this mismatch with the speech intelligibility reflected by the AF. We found that the group with the smallest mismatches (<500 Hz) had the best AF. Conversely, those with the greatest mismatch (≥1,000 Hz) had the worst AF. The strong negative correlation between these two factors was statistically significant (R = 0.3991).

Mertens et al. [10], which also used OTOPLAN® to calculate tonotopic frequencies, reported a similar correlation between frequency-to-place mismatch and hearing performance impairment. They showed that the mismatch was more important at the apex of the cochlea than in the base, as demonstrated in other studies [16]. This effect may be explained by the increasing difficulty of maintaining the tonotopy of the cochlea with increasing distance from its base. More importantly, these authors observed that the relationship between frequency shift and speech intelligibility deterioration disappeared 12 months after CI activation. This finding highlights the plasticity of the brain in adapting to a tonotopic frequency shift over time. Indeed, the experience of CI users is of a progressive adaptation to this discrepancy and an improvement in speech comprehension after several months of use [15–17].

Brain plasticity in this context seems to be limited to small frequency shifts, however, and is extremely variable among CI users. In addition, frequency-to-place mismatch increases the time required for CI adaptation, as Venail et al. [15] reported. They compared the frequency-to-place mismatch with the time required to reach 70–80% of

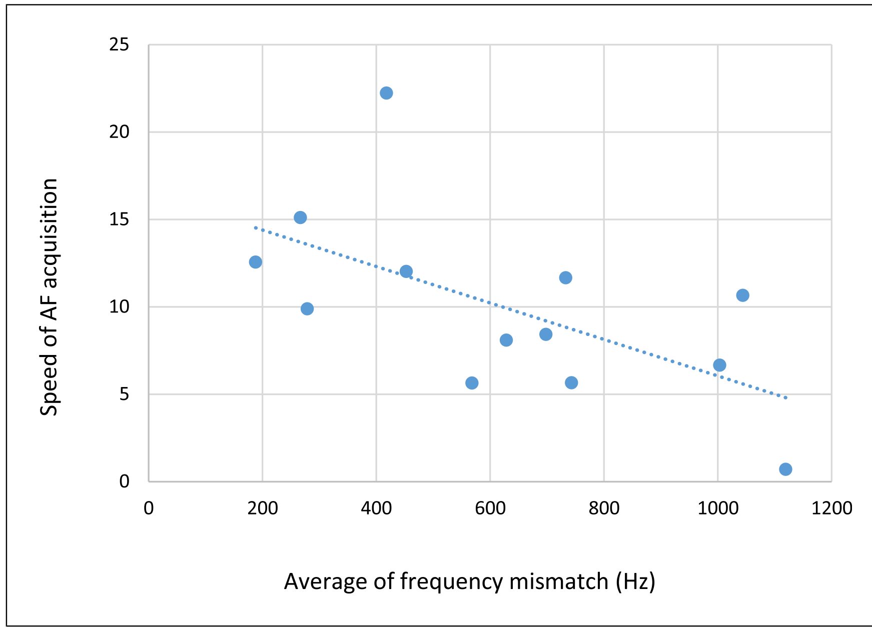

Fig. 3. A significant negative linear correlation (blue dotted line) between speed of AF (*Y* axis) acquisition and the average of frequency mismatch (*X* axis) for each patient.

maximum speech intelligibility and demonstrated a linear relationship between these two parameters [15]. This pattern is consistent with our results showing that patients with the largest AFM had the slowest AF acquisition. In addition, the subjects in our study had 1–6 years of experience with their CI but still showed a negative correlation between AFM and AF. This indicates that while adaptation does exist, it still failed to completely compensate for the negative consequences of frequency mismatch on speech perception, at least in our study cohort.

Strategies to reduce this mismatch are promising and in a constant state of development. Landsberger et al. [9] showed that this mismatch could be reduced by using longer electrode arrays or increasing the insertion depth. In this way, the frequency distribution would be closer to the natural tonotopy of the cochlea. Canfarotta et al. [14] corroborated these results in a larger patient cohort, also using OTOPLAN®. This group used the angular insertion depth to estimate the offset from the spiral ganglion and applied the Greenwood function to define the frequency mismatch. They confirmed that this mismatch could be reduced with deeper insertions and that the correlation between frequency-to-place mismatch and speech intelligibility was strongest at 1,000–2,000 Hz. Surprisingly, they also found a high degree of mismatch variability between patients carrying the same electrode array, once again demonstrating the vast anatomical variability of cochlear anatomy.

The great variability of the CDL and the lack of a standardized method are the main difficulties in calculating the mismatch [8, 18, 19]. Some studies use maps from the spiral ganglion or the organ of Corti, and some studies calculate these values based on standard X-rays [9] of the cochlea, temporal bone CT, or cone beam CT [15]. These images often present metallic artefacts, and the cochlear landmarks can be difficult to identify, requiring a certain technical and operator-dependent expertise.

Although another study by Canfarotta et al. [12] demonstrated excellent reproducibility of anatomical value identification across varying OTOPLAN® program users, subjective evaluation biases are possible, and CT analysis was time-consuming with this older version. In the newest version of OTOPLAN®, an automated evaluation of the different anatomical structures is applied, reducing potential subjective errors and processing time of each CT. The strength of our study is its use of the latest version of OTOPLAN® in combination with the MAESTRO 9.0 anatomy-based fitting tool, which is fully automated and may reduce measurement errors.

Di Mario et al. [11] also used the latest version of OTOPLAN® with the MAESTRO 9.0 tool and proposing frequency reallocation once the anatomical mapping had been established. They performed pure-tone and speech audiometry in 10 CI recipients after the patients had undergone a new anatomical frequency fitting. The speech recognition threshold was significantly lower after reallocation. These results demonstrate that the frequency-to-place mismatch has a real clinical impact on auditory performance for patients, especially when brain plasticity does not as easily facilitate adaptation to the mismatch (e.g., in elderly patients) [11]. In contrast, Lambricks et al. [16] recently published the ELEPHANT study, a single-blinded randomized controlled trial with 14 CI recipients who were given a new anatomical frequency setting for comparison with a default setting. Recipients were randomized to switch to one of two processors for 3 months. Unexpectedly, 12 of the 14 patients preferred the standard frequency allocation setting to the anatomically based setting, and their speech intelligibility was also better with the standard fitting. The authors proposed two hypotheses for these findings. First, in anatomy-based fitting, the representation of frequencies shifts towards the high frequencies. With this factor, a patient's preference for standard fitting might arise from insufficient representation of low frequencies in the anatomical fitting. Second, the number of active electrodes differed between the two modes, with three fewer electrodes enabled in the anatomy-based compared with the standard map.

Thus, the comparison with these two studies is difficult because of a completely different methodology and design. In our study, we found a significant negative correlation between pitch-place mismatch and hearing performance, but rapidity in gaining speech intelligibility. Our results also showed a small frequency mismatch (<500 Hz) in one-third of cases, with excellent hearing results with the default fitting. This finding suggests that reallocation to anatomical mapping is not necessary in all CI patients.

Conclusion

Using the latest version of OTOPLAN®, our study showed a strong negative correlation between the default and anatomically established frequency mismatch and speech intelligibility. We also showed a correlation between the speed of speech intelligibility acquisition and this mismatch. Our results are consistent with those of other studies [9, 10, 14, 15] regarding the necessity of reducing frequency-to-place mismatch to improve hearing performance in CI users and encourages further research in the field of personalized fitting strategies.

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Statement of Ethics

This study protocol was reviewed and the need for approval and the need for informed consent for participants were waived by Comité d'Ethique Hospitalo-Factultaire Universitaire de Liège (agreement number 707).

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Laura Dessard and Guillaume Gersdorff: study conceptualization and methodology, data collection, analysis and interpretation, and writing the original draft. Nicola Ivanovik, Masoud Zoca-Assadi, and Peter Nopp: study conceptualization and methodology, and draft review. Séverine Camby: data analysis, interpretation and illustration, draft review, and editing for the final manuscript. Philippe Lefebvre: study conceptualization and methodology, data analysis and interpretation, draft review, and editing for the final manuscript.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

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