The Effect of Stimulation Rate on Speech Performance in Quiet and Noisy Situations in Post-lingual Cochlear Implant Adult Recipients: A Literature Review

Mohammad M. Shadid

SAERA. School of Advanced Education Research and Accreditation

ABSTRACT

Stimulation rate is an important parameter that experienced audiologists usually pay attention to in order to improve how electrical pulses stimulate the auditory nerve fibres. Theoretically, faster stimulation rates may enhance temporal information sent to the nerve fibres, therefore better speech perception specially in noise is expected. However, this has not been confirmed in the literature. The aim of this review is to highlight the effect of different stimulation rates on post-lingual cochlear implant adult recipients' performance in quiet and noisy situations.

Methods: sixteen papers highlighted the effect of altering the stimulation rate on speech perception of post lingual adult Cochlear Implant users. However, only ten of them published between 2005 and 2019 matched our inclusion criteria, and therefore, were studied and analysed.

Results: it appears that mid rates showed better speech perception outcomes with Cochlear recipients when compared to low or high rates. However, MedEl & AB recipients showed better speech perception outcomes with high rates strategies with a preference to use sequential stimulation over the paired type particularly with AB users.

Conclusion: it's believed that what we know about the benefits of faster stimulation rates did not show in real clinical practice. The majority of CI users prefer mid stimulation rates. A slight and insignificant evidence have been reported on benefits of fast stimulation rates when listening to speech in the presence of background noise.

Keywords: *Cochlear Implant CI, Speech perception, Stimulation rate, Pulses per second per electrode pps/e, Current levels, Coding strategies*

INTRODUCTION

Background

Cochlear Implantation (CI) has been proven to be the best hearing solution for people with moderate to severe and profound sensory hearing losses. According to WHO (2021), there are more than 430 million people currently suffer from some degree of hearing loss and need intervention. A significant percentage of those people have permanent severe to profound SNHL and are considered CI candidates. However, according to several CI manufacturers' reports, the number of active CI recipients currently does not exceed one million.

Numerous researchers looked at the performance predictions of CI users and studied different factors that contribute to their hearing performance. This included speech recognition and understanding in both quiet and noisy environments in addition to patients' overall satisfaction.

Factors that contribute to CI success vary widely. For instance, one of the most important factors that impacts hearing performance of post lingual adults is the duration of deafness. The shorter the duration of deafness is, the better the overall outcomes are. Other factors for example but not limited to are rehabilitation structure in addition to family and friends support, cognitive abilities and optimizing programing parameters.

Holden et al. (2013) identified several factors contributing to better speech recognition in CI users. This included age at implantation, the duration of hearing loss and the duration of hearing aid use.

Additionally, the depth of electrode array insertion and electrode positioning differences were investigated, for example, the number of electrodes in Scala vestibuli as opposed to those in Scala tympani. Moreover, the positioning of electrode arrays closer to the modiolus wall was positively correlated with outcomes. Cognitive abilities were significantly and positively related to the outcomes. Unsurprisingly, age at implantation and cognition were highly correlated.

Another element which makes a difference on hearing performance is the audiologist experience and knowledge of programing electrical parameters such as lower threshold levels and maximum comfort levels, pulse width, stimulation rate, mode of electrical stimulation, number of active electrodes and the selected coding strategy. We should know that speech perception and overall performance outcomes may differ among cochlear implant recipients due to map optimization and the selected coding strategy (Pasanisi et al., 2002; Psarros et al., 2002; Skinner et al., 2002a, b; Plant et al., 2002).

There are thousands of cochlear implant clinicians worldwide with different backgrounds working with cochlear implant recipients. Those clinicians deal differently with these parameters due to different university programs, training access, experience and most importantly different cochlear implant programing standards in each country. Vaerenberg et al. (2014) conducted a survey which aimed to scan the cochlear implant programing protocols and methodologies in multiple countries around the globe. The main conclusion was that although cochlear implant programing training was provided primarily by the CI manufacturers, there were no standardized

methodologies to follow by clinicians. This in turn reflected on the CI recipients' outcomes depending on the clinician's experience.

Among the important parameters mentioned above, stimulation rate is one of the most important. It is defined as the number of pulses reaching one intra-cochlear electrodes per one second pps/e. There is another term related to all active electrodes receiving the train of pulses called Total Stimulation Rate, which can be derived from pulses per second received by each electrode multiplied by all active intracochlear electrodes.

In the electrical hearing world, the coding methodologies must combine both spectral and temporal resolutions in order to extract better speech information. The spectral information which represents mainly the frequency and pitch perception can be extracted based on the electrode array placement along the cochlea particularly in the Scala tympani following the cochlear tonotopic organization (High frequencies in the basal regions and low frequency in the more apical regions). While the temporal information which represents mainly the timing and envelope of the speech information can be extracted based on the stimulation rate.

Theoretically speaking, we need a fast rate to represent the acoustic signal electrically based on Nyquist theorem, which stated that to represent a digital signal the rate used should be twice the highest frequency. Moreover, McKay et al. (1994) added that CI systems need a stimulation rate that is four times the highest frequency to be extracted. However, neural fibers do not benefit from faster stimulation due to the refractory period which will affect the firing synchronization between these neural fibers as shown on animals' experiments (Dynes and Delgutte, 1992). In practice, CI recipients across all CI manufacturers have used multiple different rates from low (250-400 pps/e), mid (500-1200 pps/e) to high rates (>1200 pps/e) and yet there is no precise conclusion on whether high stimulation rates can provide any additional benefits on speech perception in both quiet and noisy situations.

Lastly, understanding the effects of stimulation rate on CI users' speech perception, specifically on the current levels, overall loudness perception in relation to increasing or decreasing stimulation rate, pitch perception changes specially when increasing the rate and also the relation between the stimulation rate and other electrical parameters are very crucial for any CI clinician before working with a CI recipient.

OBJECTIVES

The aim of this literature review is to spotlight multiple research that studied and discussed diverse effects of stimulation rate changes on the adult CI recipients' overall performance.

Studies have shown that different designs and technologies in the CI systems, coding methodologies as well as patients' etiologies play a role in clinicians' preferences on changing stimulation rate aiming to improve patients' outcomes and performance. Several studies have concluded that high stimulation rates exceeding approximately 1200pps/e won't benefit patients' outcomes and overall performance. On the other hand, Arora et al. (2009), Balkany et al. (2007) and others illustrated that speech recognition improved

when increasing stimulation rates from 250 400pps/e to a stimulation rate of 800pps/e. Nevertheless, going above to higher rates showed no significant improvements on overall performance as well as on speech recognition. On the other hand, Dunn, Tyler, Witt & Gantz., (2006) suggested that increasing the rates above and beyond 2000pps/e gave consistent and better improvement in speech recognition.

The effect of increasing stimulation rate on speech recognition in quiet, speech recognition in noise and overall subjective satisfaction for a CI recipient will be studied deeply by shedding the light on several studies in order to provide a sufficient answer to the following primary questions:

a- Does faster stimulation rate for a CI recipient provides performance? better hearing
b- How much faster stimulation rate can be provided?
c- What are the outcomes that a CI clinician should expect when changing the rate in the Map parameters and on the patient perception?

As a secondary aim, this review will discuss different circumstances related to stimulation rate parameter trying to provide a robust clinical guidance to CI clinicians dealing with programing parameter with different CI technologies as well as those who deal with different complex CI patients such as Long-Term Deafness, Auditory Neuropathy Spectrum Disorder (ANSD), Auditory Nerve Deficiency and Cochlear Malformation cases.

MATERIAL AND METHODS

Methodology

This review will investigate several studies that investigated the effects of different stimulation rates used with post-lingual CI recipients. The research sources used in the search are (Google Scholar, ResearchGate, PubMed, PMC, Academia and other research sources) using multiple key words such as (CI, cochlear implants, Speech perception, Stimulation rate, Pulses per second per electrode, overall outcome). Thirty related articles were found. However, most of these articles were related to specific CI manufactures, a few articles involved different CI manufacturers. Papers investigating stimulation rate only were included. Table number one shows the Sixteen articles grouped by CI manufacturers.

Table 1. *Total number of research found divided into CI manufacturer and subject numbers*

CI Manufacturer	Number of research found
Advanced Bionics AB	2
Cochlear LTD	11
MedEl	2
AB, Cochlear & MedEl	1
Total	16

Inclusion and Exclusion Criteria

Articles are manufacturer differences grouped according to CI given in their fundamental front-end and back-end technologies as well as the electrodes design.

Moreover, all studies before 2005 will be excluded considering the huge technology improvement in coding strategies since then. Additionally, articles which studied the effect of stimulation rates on post-lingual adults were included. All different technologies and signal processing methodologies are categorized and separately highlighted for all CI Systems, the following CI manufacturers were included (Cochlear LTD, Advanced Bionics AB, MedEl).

Ten articles matched the inclusion and exclusion criteria. Table number two shows the remaining articles which will be studied and analyzed separately as shown.

Table 2. *Total number of research included in the review divided into CI manufacturer and sample size.*

CI Manufacturer	*Researches included*	*Total # of subjects included*
Advanced Bionics AB	2	17
Cochlear LTD	5	162
MedEl Corporation	2	32
AB, Cochlear & MedEl	1	37
Total	10	248

As mentioned in the objectives section, Arora & colleagues (2009), Balkany et al. (2007), Vandali et al. 2000; Friesen et al. 2001; Fu and Shannon 2001 found no significant correlation between CI recipients' performance and increasing the stimulation rate. On the contrary, Brill et al. 1997; Dunn, Tyler, Witt & Gantz., 2006found significant improvement in speech recognition overall when increasing the stimulation rate. This debate in research opened a room for more discussions and encouraged researchers to investigate and try to prove one hypothesis over the other.

In this review, different manufactures technologies, coding strategies, electrodes designs, test conditions, individual differences will be looked at and taken in consideration before reaching a conclusion. our hypothesis indicates that stimulation rate increasing or decreasing won't impact speech recognition and overall performance for the vast majority of CI recipients. However, for certain CI populations, the distinguishing factor may lie in altering the stimulation rate to enhance overall performance.

Throughout this review, stimulation rates will be categorized into three types shown in table 3.

Table 3. *Categories of stimulation rates*

Category	*Pulses per second*
Low stimulation rate	250-400 pps
Mid stimulation rate	500-1200 pps
High stimulation rate	>1200 pps

RESULTS

Table 5. *Summary result and the review of the above 10 articles*

	Device	Stimulation Rate pps/e compared	Results
Verschuur (2005)	MedEl	>1500-800-400	Slight & not significant better outcomes toward the mid/ high rates (800-1500)
Balkany et al (2007)	Cochlear	500-900-1200/ 1800-2400-3500	Better outcomes toward the mid rates (500-900)
Arora et al (2009)	Cochlear	250-350-500-900	Better outcomes toward mid rates (500-900)
Battmer et al (2010)	Cochlear	500-900-1200-1800-2400-3500	Slight & not significant better outcomes toward mid (500-900-1200).
Shannon et al (2011)	AB	600-1200-2400-4800	Slight & not significant better outcomes toward the higher rate (1200-2400)
Park et al (2012)	Cochlear	900-2400	Slight to significant better outcomes toward the mid rates (900)
Riss et al (2016)	MedEl	720-1200-1600	Significant better outcomes toward the higher rate (1200-1600)
Brochier et al (2017)	Cochlear	500-2400	Significant better outcomes toward the mid rates (500)
Shader et al (2018)	All	500-720-900-1200->1200	Slight & not significant better outcomes toward the mid-rate (500-720-900)
S Reynolds & R Gifford (2019)	AB	Sequential-Paired	Significant better outcomes toward the sequential stimulation which has less rate compared to paired stimulation

As shown in the table above, for both AB studies Shannon et al (2011) & S Reynolds & Gifford (2019), it was clear that mid rates sequential strategies showed better outcomes and were preferred subjectively by CI recipients. Also, the mid rates preference was evident in most if not all Cochlear studies (Balkany et al., 2007, Arora et al., 2009, Battmer at al., 2010, Park et al., 2012, Brochier at al., 2017 & Shader et al., 2018). MedEl studies were the only to show better speech perception outcomes and CI recipients' preferences toward the higher rates (Verchuur., 2005, Riss et al., 2016).

DISCUSSION

What is the Stimulation rate alternation effect on hearing performance?

Theoretically, CI users need high electrical stimulation rate to better process temporal information specially to compensate for the poor spectral information due to lower number of electrode contacts (Shannon et al., 1995; Turner et al., 1995; van Tasell et al., 1987, 1992). Also, high stimulation rates are believed to mimic the stochastic nerve firing similar to normal hearing neurons (Rubinstein et al., 1999; Wilson et al., 1997a, b; Litvak et al., 2003a-c). Kreft et al (2004), Galvin and Fu (2005) demonstrated that increasing the electrical stimulation rate will reduce the threshold detection due to neural integration and therefore increasing the electrical dynamic range for CI individuals.

However, and practically; no clear evidence or correlation have been shown between increasing the stimulation rate and better speech recognition or understanding (Brill et al., 1997, 1998ab; Friesen et al, 2005; Fu and Shannon, 2000; Holden et al., 2002; Lawson et al., 1996; Loizou et al., 2000a; Skinner, 2003; Vandali et al, 2000; Balkany et al, 2007; Arora et al, 2009).

Studying electrical stimulation rate effect on speech recognition and overall performance for CI users is extremely complicated due to several factors that interfere with the study analysis, results and conclusions. Among those factors are the fundamental CI technology differences among CI manufacturers, individual experience for CI users and etiology of hearing loss. Each CI company has its own technical features related to electrodes design, signal processing methodologies and programing parameters.

Table number 4 shows several technical features for each CI company.

Table 4. *Technical features for CI companies related to stimulation rate/ type and coding strategies*

Company	*Advanced Bionics*	*Cochlear LTD*	*MedEl Corporation*
No of electrodes	16	22	12
Type of stimulation	Sequential/ Simultaneous	Sequential	Sequential/ simultaneous
Total Stimulation Rate	83,000 pps	32,000 pps	51,000 pps
Default Coding Strategy	HiRes P	ACE	FS4
Other coding strategies	HiRes S, Optima S, Optima P, HiRes Fidelity 120, CIS, MPS	SPEAK/ CIS/ MP3000	FSP, FS4-p, HDCIS

Advanced Bionics (AB)

Shannon et al (2011), studied the effect of altering the stimulation rate and the number of active electrodes for seven post-lingual Clarion 2 implant/HiFocus electrode users. The age of participants and the years of experience were reasonably close, 33-59 years and 6-15 months respectively. Aetiology of hearing loss varied but none of the participants reported to have long term deafness, inner ear malformation or any complex aetiology to consider.

The experiments used the following different stimulation rates 600, 1200, 2400 and 4800 pps and varied the number of active electrodes for each rate from 4, 8,12 and 16. all experiments used one strategy the Continuous Interleaved Sampling (CIS) strategy (Wilson et al., 1993) regardless of the participants own strategies. Other programming parameters such as stimulation mode, pulse duration, input dynamic range, peak clipping and volume control were set to default. Thresholds (T) and Most Comfortable Levels (M) were measured behaviourally, and M levels were balanced at all active electrodes per experiment. Note that participants had several months of experience with their own Map and that they had no time to acclimatize with experimental Maps.

Recorded CNC monosyllabic word recognition and IEEE sentence recognition at 70dBA in free field were used in quiet first and second with +10 dB SNR, steady speech weighted noise was used. After administrating these measurements for each stimulation rate, participants were asked to subjectively rate sound quality of each experimental Map compared to their own Map.

In this study there were no evidence of high stimulation rate preferences over low or mid rates at all tested conditions, slight improvement was noted in noise when increasing the rate from 1200 to 2400ppse. Subjectively, all participants preferred their own Maps' sound quality over the experimental ones. This was expected given the acute nature of this study as those participants had no acclimatization period. Additionally, comparing the experimental Maps amongst each other did not show any significant improvement in speech recognition between different rates administered. When looking at altering the number of active electrodes, researchers showed clear evidence of speech recognition improvement in every condition when increasing the number of active electrodes from 4 to 8 and there was no improvement noted beyond 8 electrodes.

Susan M. Reynolds & René H. Gifford (2019), compared the outcomes of ten

Advanced Bionics experienced CI users using sequential stimulation versus paired stimulation. Although this study wasn't directed to investigate the effect of varying stimulation rates, however altering the coding strategy between paired/simultaneous and sequential stimulation will change the stimulation rate. It's known that paired stimulation leads to double the rate compared to sequential type of stimulation.

The researchers compared pure HiRes S (Sequential), which is considered a pure Continuous Interleaved Sampling CIS strategy (Wilson et al, 1993), with HiRes P (Paired) along with the latest strategy Fidelity 120, which was introduced to enhance the spectral resolution by applying simultaneous stimulation to adjacent electrodes at once. This creates current steering and imposes what is called virtual channels (Koch et al. 2007; Firszt et al. 2007). Advanced Bionics (2008) reported significant speech perception improvement in both quiet and in noise compared to the HiRes strategies.

In this study, participants were asked to use an experimental strategy or subsequent to their original strategy, they were given two weeks acclimatization period before coming back for various auditory testing as well as a subjective type of questionnaire to get their feedback on sound quality. All participants were post lingually deafened, wide age range from 25-78 years old with a wide range of CI experience from roughly 1-13 years of experience. 80% of participants used Optima S and 20% used Optima P as their default stimulation.

At the initial visit, different assessments were performed and participants results were collected. Next, five new maps given to each. Participants instructed to alternate between subsequent maps every two hours. Data logging helped to get the percentage of use for each Map. The new Maps created kept all front-end technology unchanged, however; strategies and M levels were altered and modified to reach the most comfortable levels for each participant and the pulse width was kept as low as possible to be able to reach the higher rate stimulations. These alterations to the strategies automatically had an impact on the stimulation rates.

The researchers agreed that this methodology isn't the best to monitor participants feedback given limited familiarization period, however they stated they consulted 3 CI clinicians who use CI and they provided a method that will enhance CI familiarization use for those participants. The subsequent Maps included various strategies (HiRes, Optima and Fidelity 120) with Sequential and Paired stimulation.

On the second visit, all assessments were repeated, data logging checked and questionnaires filled. Results showed a significant improvement for Sequential stimulations compared to paired stimulations for CNC word recognition and AzBio sentence recognition in both quiet and in noise. Also, significant ratings were evident toward the sequential stimulation. No effect was noted when changing strategies.

Researchers concluded the advantage of lower stimulation rates used was due to the sequential type of stimulation compared to higher (double) the stimulation rate when using a paired stimulation methodology. Researchers also did not find any decline on participants' responses for any of the auditory measures performed when using the

sequential stimulation which raises a valid argument on using the paired stimulation type as a default stimulation AB software.

Cochlear LTD

Balkany et al (2007), did a multi-centre study to investigate the hearing outcomes of CI users as a result of changing the stimulation rate. At that time Cochlear presented a new algorithm to its ACE strategy with the Freedom processor called ACE RE, which allows for faster stimulation to enhance temporal resolution. Seventy-one post lingual subjects with an age range of around 62 years enrolled in the study. None of them had any medical complications, malformation or retro cochlear lesions. Participants went through a long trail period of a minimum six months. Fifty-five participants completed the whole period and stayed in the study, while the remaining 16 dropped.

During the trial period subjects were randomly assigned to use two different strategies. One is the ACE, which includes three maps with different rates (500, 900 and 1200 pps/e) and the other was ACE RE, which also includes 3 maps of higher stimulation rates (1800, 2400 and 3500 pps/e). Subjects were blinded to both the maps order and the strategy assigned. The study design gave those newly fitted adults the opportunity to try 3 different rates in two strategies for a period (three weeks for each strategy). Then the subjects decided which map was the best for them. Based on subjects' feedback, one rate of each strategy was chosen and a further trial was assigned between the two strategies with the chosen rate.

In this study, speech assessments both in quiet and in noise were carried out in addition to participants preferences to measure the outcome of alternating stimulation rates. Participants were first asked to choose the best rate among each strategy (ACE/ ACE RE), then speech recognition was assessed to check the best of the two. Speech assessments considered were the CNC word recognition, HINT sentences in quiet and in noise, and CUNY sentences in quiet and in noise. In both assessments in noise +10 SNR was performed.

Results showed that a significant preference toward the slower (mid) rate in the ACE over the faster ACE RE. Also, speech recognition outcomes were higher for the slower rates in general. Overall, 37 out of 55 participants preferred the slower rate of ACE over the higher of ACE RE. The remaining participants showed no significant differences in favour of the higher rates. The authors concluded that higher rates failed to show improvement in speech recognition outcomes, yet this conclusion is only for the freedom device and Cochlear's signal processing strategies and can't be generalised to the other coding strategies. The author did mention that when increasing the stimulation rate to 3500 pps/e the number of maxima automatically dropped down, note that the default maxima for an ACE strategy is 8, when increasing the rate > 2400 pps/e the maxima will reduces to 6.

Arora et al (2009), reviewed previous studies that explored the effect of stimulation rate on speech outcomes and found that most studies compared mid (500-1200 pps/e) to high (1800-3500 pps/e) rate stimulations (Plant et al; 2007., Weber; 2007., Balkany et al; 2007.). The minimum rate explored in these

studies was 500 pps/e. In all of the mentioned studies, the results were in favour of lower rates both for speech recognition and participants preference.

Arora and her colleagues decided to investigate low to mid-rate stimulation, suggesting that lower rate will provide additional benefits to CI users such as lower power consumption and smaller size of the processor. The following four stimulation rates were selected using one strategy; ACE, (250, 350, 500 and 900 pps/e), other parameters were the same such as the stimulation mode (MP1+2) and Maxima (8), pulse width was 25µs except for those who needed loudness adjustment specially in compliance requirements cases.

The study consisted of two phases, the first phase is a 4-week take home practice for each strategy, after each trial the participant speech performance was tested. The second phase, the previous procedure was repeated for two other weeks. After that the participants were given all four stimulation rates on a separate program for another two weeks trial to compare and give their final feedback preferences in a form of questionnaire rating.

CNC word recognition in quiet and Speech Intelligibility Test SIT in quiet and in noise were used to identify the participants outcomes, a comparative questionnaire was used to identify the participants preferences.

Results showed different outcomes between the eight participants. Overall, better speech outcomes specially in noise were noted toward the mid rates 500 and 900 pps/e, no significant differences between different rates with CNC word recognition. Most subjects selected 500 pps/e as their preferred rate. However, the author did report the inconsistency between the speech outcomes and the participant's feedback. The author noted that questionnaires have lower value and less reliability when compared with speech recognition assessments due to factors like self-interpretations of questions and real time trial per rate at home in different situations.

Battmer et al (2010), did a multi-centre study, in which he presented the outcomes of three research delivered in European CI centres. Around ten CI teams participated in the three studies. The CI teams used different methods to elaborate the effect of different stimulation rates on CI24RE Nucleus freedom implant users. The author studied the outcomes of each group of the three. All participants on the three studies were post lingual, had no retro cochlear lesion or any congenital related deafness and they had full insertion electrode with one ear implanted.

Group one consisted 29 participants in Hannover and Zurich, all fitted with initially 1200 pps/e using an old processor 3G for a period of 13-33 weeks, then participants upgraded to the Freedom processor which allows for higher rates of stimulation. The experiments started with

(A) 1200 pps/e for six weeks,

(B) 500 pps/e for six weeks,

(C) 3500 pps/e for six weeks and another (C) for four weeks then (B) for four weeks and finally (A) for four weeks.

This randomized ABCCBA experiment paradigm helped reducing the learning effect along this time. The only drawback of this study as reported by the author was the initial use period when all participants started with 1200 pps/e at the initial activation and kept it

between 13-33 weeks, as this time was enough to create the familiarity with this specific rate. ACE strategy was used with Maxima 10 (default range at that time), Maxima automatically reduced when stimulation rate reached 3500 pps/e. all maps T/C levels were programmed behaviourally without considering the ECAP. Two speech assessments were used; the Freiburg monosyllabic word recognition and the Oldenburg sentence test in quiet and in noise. Results showed that 27 out of the 29 participants preferred the mid rates 500-1200 pps/e over the high rate of 3500 pps/e.

Group two consisted of 19 subjects, seven from Freiburg, four from Halberstadt, six from Kiel, and two from Antwerp. Each subject begun with one of four strategies (ACE at 900 or 2400 pps/e) or (CIS at 1200 or 3500 pps/e) and were blinded to the initial Map. After five weeks all four Maps were given to the participants for another five weeks with behaviourally optimized MAPs but this time, they were asked to indicate their preferred one. Next, they received another set of four strategies based on their preferences. These four strategies were chosen from ACE 500, 900, 1200, 1800, 2400, and 3500 pps and CIS at 1200, 2400, and 3500 pps/e. Maxima in ACE and number of electrodes in CIS were adjusted based on the rate. After about five weeks of trial, subjects indicated their final preference. Speech tests were performed for the preferred strategy and the tests were repeated about 15 weeks later.

Results showed that rate has no effect on speech outcomes using monosyllabic Freiburg words recognition or Oldenburg sentences in quiet and in noise. However, participants own preferences were in favour of ACE regardless of the rate. The methodology chosen for group two avoided familiarity period that group one had with their initial Map, which is considered more reliable. However, testing only the preferred rate and strategy reported by the participants is a disadvantage as participants were not tested within different rates and/or strategies.

Group three consisted of 20 subjects, five from Barcelona, six from Las Palmas, five from Pamplona, and four from Valencia. Participants used ACE with two different rates 900 and 2400 pps/e. Maxima was adjusted between 8-12 based on user preference and Amps were adjusted based on the behavioural method in parallel to objective methods such as ECAP called NRT. Twelve weeks later a questionnaire was given and speech testing performed for the two rates. At the end of this session the speech processor was programmed at the preferred rate and participants were asked to try this Map for another twelve weeks, then participants were tested again with this preferred Map. The speech assessment used a disyllabic word recognition test in quiet and in fixed noise (+10 SNR). Results showed that after 12 weeks 18 out 20 participants preferred 900 pps/e over the 2400 pps/e, only one subject preferred the 2400 pps/e and the last subject had no preferences.

It was concluded that pulse or stimulation rate has limited effect on the speech outcomes, noting other factors that have more impact on speech outcomes such as pre implant hearing and years of deafness. However, it was noted that those CI users who had lower threshold preferred higher stimulation rates.

Park et al (2012), stated different outcomes of CI users in relation to electrical

stimulation rate alteration, either lower or higher rates. Six freedom implanted post lingual adults were recruited and informed about the aim of this research, which was to investigate the relationship between two stimulation rates (900 & 2400 pps/e) and speech outcomes. Participants aged 17 years and older where the oldest participant was 43. Only one participant aged 13 at the time of enrolment. Their CI experience ranged from 1 to 6 years. They all were programmed and tested at Hallym University Sacred Hospital. They all were programmed with two Maps (P1: 900 and P2: 2400 pps/e) with ACE strategy, MP1+2 Stimulation mode, 6-10 Maxima and 12-25μs Pulse width. T/C levels were adjusted behaviourally.

Participants were instructed to use each map for two weeks alternatively for a period of two months P1, P2, P1 and P2. Speech testing presented was done at a presentation level of 45dB HL in quiet (Korean standard Monosyllabic word lists for adults CNC), Sentences (Korean standard- sentence List for adults) in quiet and in noise. SNR started with +15 and adjusted based on scoring 70% correct. Subjective questionnaires were provided for all participants to complete. Results showed significant improvement in CNC in quiet when using the 900 pps/e for all six participants, while in sentences in noise there was a slight insignificant improvement when using the 2400 pps/e for 3 participants. Overall, subjective rating showed a preference toward the 900 pps/e for all participants when listening in quiet, noise or to media (TV/radio).

In conclusion, the authors stated that stimulation rate as a parameter can be a used to enhance CI users' speech recognition ability. However, they suggested that more prolonged research with a greater number of participants is needed to get a better understanding of the usefulness of such parameter.

Brochier et al (2017), investigated speech understanding outcomes when altering the stimulation rate (500 pps/e and 2400 pps/e) at different presentation levels (40, 50 and 60 dBA). It was hypothesized that there could be a correlation between better speech understanding and low stimulation rate at low presentation levels given the consistent correlation found between low rates and better modulation detection thresholds compared to high rates at low presentation levels (Fraser and McKay, 2012; Galvin and Fu, 2005, 2009; Green et al., 2012; Pfingst et al., 2007).

Very few research was done on the effect of stimulation rate and presentation levels together on the speech understanding outcomes. Only Park (2012) and Holden (2002) performed speech recognition tests at low presentation levels (45- and 50-dB SPL respectively). Holden did not find consistent differences in speech understanding between 1800 pps/e and 720 pps/e, but some subjects had better speech perception in noise at the higher rate for the 50 dB SPL presentation level which is goes against Park (2012) who used presentation levels of 45 dB SPL and observed consistent better outcomes on Korean sentences and phonemes with 900 pps/e compared to 2400 pps/e presented at 45 dB SPL.

In this study, nine post lingual CI recipients participated. Different presentation levels were used (40-, 50- and 60-dB SPL) for two stimulation rates 500 pps/e and 2400 pps/e, in two Maps using the Nucleus 6 CP910 processor. All other parameters such as pulse width, Maxima were the same for all

participants in both maps. Moreover, all front-end compression technologies and Smart Sound IQ features were disabled to have better control when changing the presentation levels specially for lower levels. Speech testing performed using CNC words, BKBs sentences in quiet and with competing noise at variant noise levels, so SNR was altered based on the sentence scores.

The results of this study showed an improvement in speech understanding in noise for those using low stimulation rates compared to higher rates. This could be due to their original Maps as 8 out of 9 participants were using a 900 pps/e and only one was using the 250 pps/e. This means all participants had better acclimatization with mid rates. This study also tried to answer is the Amplitude Modulation Detection Threshold AMDT as its thought to be better with lower presentation levels, corresponding to better speech perception. According to this study, there was no correlation between AMDT and adjusting the stimulation rates at different presentation levels.

With all Cochlear studies, the reader can note the limitation of experimenting a stimulation rate that is > 2400 pps/e, as this change in rate will reduce the number of maxima automatically by the Cochlear software, and this considered as a limitation given the reported better outcomes with increasing the number of maxima on spectral resolution hence will reflect on better speech perception outcomes (Berg et al; 2019). Also, having an acclimatization period and/or a trial period compared to no trial period reported to be an important variation that need to be looked at and controlled in future studies.

MedEI Corporation

Verschuur (2005), evaluated the effect of stimulation rate and other speech cues on speech perception outcomes for six post lingual CI recipients' adults. The used rate altered between low, mid and high for all participants who used the CIS strategy on a MedEl Combi 40+ implant except one who used the Ineraid implant.

The author reported that most studies investigated speech perception in relation to stimulation rates have revealed different outcomes. This could be due to the huge variation in test materials and conditions. Therefore, a question might be raised on speech perception outcomes with different types of speech cues along with the variation of stimulation rates.

A group of CI recipients aging between 29-73 years and a CI experience between 1-9 years were recruited. All participants were used to high rates of CIS coding strategy. The stimulation rate was lowered while all other parameters remained unchanged except for the current levels in order to match the subjective loudness preference for each participant. The number of active electrodes was between 6-12. The original high stimulation rates were between 1515-2272 pps/e. All subjects had high score BKBs sentences in quiet.

The used method was to lower the rate to 800 pps/e and then to 400 pps/e. during the use of each rate, 3 speech measures were performed. (1) Perception of synthetic speech stimuli with specific acoustic cues were varied, (2) Consonant recognition (VCV) test and (3) Measure of sentence perception (BKB), all tests were performed in quiet.

The outcomes showed that higher rate maps scored better on sentence measures. However, measures of consonant recognition and synthetic acoustic speech cues showed no changes as the rate changed. Additionally, the results of the BKB sentences showed good performance when using a mid-rate of 800 pps/e compared to the original high-rate map that each participant used previous to the experiment map since activation.

Riss et al (2016), investigated the effect of stimulation rate on speech perception outcomes in twenty-six post lingual CI recipients using two coding strategies; the High Definition HDCIS and Fine Structure FS4 designed on 2010. The fine structure coding strategy FS4 was designed to transmit more temporal information on the four most apical channels, the remaining channels can use either low 750 pps/e or higher stimulation rates up to 1600 pps/e.

It was reported that high stimulation rates for CIs allows for better temporal sampling and greater dynamic ranges by reducing the thresholds (Hong & Rubinstein, 2003). However, when looking at speech perception, results are contradicting as mentioned previously. Some studies reported better speech recognition with higher rates, but other studies found no benefit regarding speech perception. Also, the authors reported that the effects of stimulation rate on subjective sound quality have had less attention.

In this study, subject ages were between 20-81 years old, with a CI experience ranging between 4 months and 10 years. The 4 maps were created as the following:

FS4 with high rate at the non-fine structure channels, rate between 1200-1600 pps/e

a- FS4 with low rate at the non-fine structure channels, 720 pps/e
b- HDCIS with high rate at all channels 1200 1600 pps/e
c- HDCIS with low rate at all channels 720 pps/e

Note that the frequency range for the FS4 strategy is wider compared to the HDCIS. These four maps were given with no trial period. Speech testing of monosyllabic (Freiburg list) at 65 dB SPL in quiet with all four conditions was done randomly. Visual Analogue Scales (VAS) was also used to assess three aspects of sound quality: naturalness, dullness, and overall pitch. Results of this study showed significant improvement in speech perception with high rates compared to low rates for both strategies tested. Sound quality was clearer and less dull using higher rates.

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Shader et al (2018), investigated whether using a non-default stimulation rate; particularly lower rates would improve speech perception for post lingual CI adult recipients. Also, whether low rate is potentially preferred for older > 65 years old CI recipients.

This study recruited 37 subjects, aged between 22-87 years old. 40 ears were tested as 3 of the 37 are bilateral recipients. Subjects had at least one year of CI experience, and they all passed a screening test of dementia designed by (Teng and Chui 1987). Participants were divided into two groups as follows:

(1) Cochlear group (32 subjects), and (2) Advanced Bionics/MedEl group (5 subjects).

Maps were programmed and T/C levels were measured individually for the following rates: 500, 720, 900, 1200 and occasionally >1200 pps/e in case the recipient's original map was programmed at a higher rate. Participants used an experimental processor similar to their own. The main parameters remained unchanged. Noise reduction compressions were turned off while keeping the same other front-end technology on. AzBio and a Perceptually Robust English Sentence Test Open-set (PRESTO) sentence materials were introduced at a level of 65 dB SPL in quiet and with +10 SNR used as a measure of speech perception. Only a 5-minute familiarization period was assigned before testing for each experimental map, in which subjects listened to an audio book during these 5 minutes.

There is slight evidence that lower rate could improve speech perception with increased age, 85 years old subject showed some improvement when altering the rate from 900 pps/e default to 500 pps/e. however, a significant decline in speech understanding was associated with increased age and more complicated testing materials such as the PRESTO sentences, especially in the presence of competing noise.

In general, this study showed that the best performance of subjects was recorded using their default rate, however; some improvements were noticed when altering away from the default rate. One important limitation of this experiment mentioned by the author is the limited trial period (only 5 minutes).

CONCLUSION

Going back to our question, if faster stimulation rate for a CI recipient really results in better hearing performance. In fact, results of the above review are conflicting, more researchers suggest the mid rates over the high ones. Therefore, more research studies are needed to better understand the effect of a faster rate on the speech perception outcomes, controlled focused methods are required to avoid all possible limitations which have been seen in several studies such as and not limited to, period of trial, test conditions and materials, subjects' variations in relation to CI experience, aetiology of deafness and history of hearing, type of the device and technology embedded as well as electrodes design.

Looking at the above reviewed studies, stimulation rate alteration to (lower or higher rates) is not correlated with significant improvements on speech perception outcomes. Most researchers and experienced clinicians prefer to use the default stimulation rate recommended by each manufacturer due to certain features related to the electrode designs and its technicalities and electronics.

How much faster stimulation rate can be provided? What are the consequences that a CI clinician should expect when changing the rate in the Map parameters and on the patient perception?

It was reported that very fast stimulation rate creates several electrical stimulation downsides, most importantly interaction/interference, the high channels compliance which leads to lower battery life, loudness summation which might cause loudness discomfort.

According to the previously mentioned insights, the following tips are suggested when dealing with the stimulation rates:

1- Its highly recommended to start the CI programming with the default setting suggested by the manufacturers, however several authors recommended not to use the HiRes P from AB and to use the HiRes Optima S instead due to lower power consumption and also to reduce the channels interaction (S Reynolds & R Gifford., 2019; J Wolf & E Schafer., 2015 book).
2- In cases of uncertainty and inability or failure to achieve the expected speech perception outcomes, its recommended to provide the CI recipient with extra programs with different stimulation rates, particularly lower rates in the following reported cases:

a- Auditory Neuropathy Spectrum Disorder (Pelosi et al., 2012; Paterson et al., 2005)
b- Cochlear aplasia and common cavity (Pelosi et al., 2012; Paterson et al., 2005)
c- Elderly CI population (Shader et al., 2018)
d- Adults reporting difficulty to wear the processor consistently during the day due to reported headaches, fatigue, or tinnitus.
e- Adults reporting poor sound quality or ongoing echo that does not resolve with usual programming adjustment.

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