OTOLOGY

The COVID-19 pandemic and upgrades of CI speech processors for children: part II–hearing outcomes

Anita Obrycka[1] · Artur Lorens[1] · Adam Walkowiak[1] · Elzbieta Wlodarczyk[1] · Beata Dziendziel[1] · Piotr Henryk Skarzynski[1,2,3] · Henryk Skarzynski[1]

Abstract

Purpose To gauge the benefits to children of upgrading speech processors during the COVID-19 pandemic.

Methods The study involved 297 children, aged from 7.3 to 18.0 years, whose processors were upgraded to either Nucleus 7 or Kanso 2, or to Sonnet 2 or Rondo 3. To document the benefits of the upgrades, a speech-in-noise discrimination test and Patient Reported Outcome Measures (PROMs) were used.

Results There was a significant benefit from the newer processors in terms of speech discrimination in noise. Patient Reported Outcome Measures (PROMs) indicated less hearing disability, a higher level of functioning in everyday life situations, and more satisfaction with the new speech processor in social situations.

Conclusion There is a measurable improvement in performance when the devices are upgraded to the new technology.

Keywords Cochlear implant · Pediatric · Upgrade · COVID-19

Introduction

Since the introduction of commercial CIs, spectacular advances in CI system technology have been observed. Refinement of speech processors is a continuous process, with a frequent release cycle. Manufacturers have been continually improving speech processor ergonomics as well as sound processing. In particular, they have implemented new directional microphone options and a variety of other 'front end' processing features such as digital noise reduction and automatic scene analysis.

In terms of scene analysis, the new processors supplied to patients during the current upgrade have been designed to evaluate the listening environment and automatically switch to the optimal parameters using an artificial intelligence classification system which analyzes the sound and identifies its characteristic features. The classification system separates the sound into a discrete number of classes, for example, speech, noise, quiet, or music, defined by specific audio characteristics. It then automatically adjusts the sound processing parameters according to the identified situation–selecting the appropriate front-end processing features and the best listening settings. The front-end parameters include directional microphone options, dynamic noise reduction, and wind noise reduction algorithms. Specific information on front-end processing features for the Sonnet 2 speech processor can be found in a MED-EL white paper [1] and for the Nucleus 7 Sound Processor in [2].

The aim of the present paper is to document the hearing outcomes achieved in upgraded patients. The study was designed and conducted in accordance with the principles stated in the Declaration of Helsinki.

Materials and methods

Participants

We report on 297 patients of the Institute of Physiology and Pathology of Hearing, Warsaw/Kajetany, Poland, aged from 7.3 to 18.0 years, who were provided with a new

✉ Anita Obrycka
   a.obrycka@ifps.org.pl

1   Institute of Physiology and Pathology of Hearing, ul. Mokra 17, 05-830 Kajetany, Nadarzyn, Poland

2   Heart Failure and Cardiac Rehabilitation, Department of the Medical, University of Warsaw, Warsaw, Poland

3   Institute of Sensory Organs, Kajetany, Poland

speech processor. The range of legacy processor age varied from 6.3 to 16.1 years. Esprit 3G, Freedom, Nucleus 5, and Nucleus 6 processors were upgraded to Nucleus 7 or Kanso 2, depending on the patient's preference. Similarly, Opus 2 processors were upgraded to Sonnet 2 or Rondo 3. Patient details are presented in Table 1. The upgrades were conducted during a time of peak COVID-19 in Poland according to the procedure described in separate article (The COVID-19 pandemic and upgrades of CI speech processors for children: part I—procedure of speech processor upgrade).

Table 1 Subject data

Group characteristic		
	Mean	SD
Age at upgrade (years)	12.17	2.96
Duration of speech processor use (years)	8.77	1.51
	N	%
Gender		
Female	134	45.12
Male	163	54.88
Type of HL		
Prelingual	285	95.96
Perilingual	9	3.03
Postlingual	3	1.01
Etiology		
Genetic	82	27.61
Prematurity	20	6.73
Ototoxic drugs	18	6.06
Syndromic	14	4.71
Asphyxia	10	3.37
In utero viral infection	10	3.37
Meningitis	4	1.35
Unknown	139	46.80
Additional comorbidities		
Yes	76	25.59
No	221	74.41
Implant use		
Unilateral	116	39.06
Bilateral	181	60.94
Legacy processor		
Esprit 3G	2	0.67
Freedom	23	7.74
Nucleus 5	113	38.05
Nucleus 6	9	3.03
Opus 2	150	50.51
Upgraded ear		
Right	214	72.05
Left	83	27.95
New processor		
Nucleus 7	145	48.82
Kanso 2	2	0.67
Rondo 3	19	6.40
Sonnet 2	131	44.11

Evaluation of speech processor upgrade benefit

In order to document the benefits of upgrades, a speech-in-noise discrimination test and Patient Reported Outcome Measures (PROMs) were used. Due to COVID-19 pandemic we decided to use different assessment for each upgrade group. The processors were upgraded on 5 consecutive Saturdays, one Saturday we evaluated the advantage of microphone directionality in Sonnet 2, the other Saturday the speech processors were upgraded to Nucleus 7 or Kanso 2 there were no benefit examination as the benefit of directional microphone when upgrading to the Nucleus 7 speech processor has already been evaluated by others [3, 4]. During remaining three Saturdays we decided to use different questionnaires for each update group. The first group upgraded from the Opus 2 to the Sonnet 2 or Rondo 3 was assessed with the HISQI questionnaire. The second group, also upgraded from Opus 2 to Sonnet 2 or Rondo 3, was assessed with the APSQ. The third group, upgraded from Esprit 3G, Freedom, Nucleus 5, or Nucleus 6 to Nucleus 7 or Kanso 2, was assessed with SSQ.

Speech in noise

Speech discrimination in noise was evaluated using the Auditory Adaptive Speech Test (AAST). AAST was developed and validated by Frans Coninx (iFAP, Solingen, Germany) for estimating speech reception threshold in children over 3 years of age. The test was adapted into Polish. The test is based on an adaptive procedure implemented as an interactive PC game in multiple choice format with six alternatives. AAST is a closed-set procedure. The stimuli are trisyllabic words. In an adaptive procedure, the speech level is varied to obtain the SNR for a 50% correct score (the speech reception threshold, SRT) [5].

We decided to evaluate the advantage of microphone directionality in Sonnet 2 (compared to the one omnidirectional microphone in Opus 2), because there has been no such study in children. The AAST test was performed in an anechoic chamber, and speech was presented in front of the patients (0° azimuth) while noise was presented at the back (180° azimuth). Patients were tested in three conditions: with the old Opus 2 speech processor, with the Sonnet 2 with omnidirectional microphones, and with Sonnet 2 with natural directionality.

Patient reported outcome measures

The Hearing Implant Sound Quality Index (HISQUI19) is a 19-item questionnaire that measures the self-perceived level of ability in different everyday life situations. It estimates the implantee's ability to perform particular auditory tasks such as telephone use, distinguishing between different speakers, identifying musical sounds, and localizing sounds. Higher scores indicate a higher level of functioning [6].

The Audio Processor Satisfaction Questionnaire (APSQ) is a self-reported tool to measure an individual user's satisfaction with their hearing implant [7]. Patient satisfaction with their audio processor as measured with APSQ can be analyzed in three dimensions: (1) comfort, (2) social life, and (3) usability. The questionnaire was completed by the users themselves in case of a teenager, or in the case of younger children by their parents. Higher scores indicate more satisfaction [7].

The Speech, Spatial, and Qualities of Hearing Scale (SSQ) is designed to measure hearing disability. It measures abilities in hearing speech, spatial hearing, and other qualities of hearing and indicates how these abilities are reduced by hearing deficits. Higher scores indicate greater ability (less disability) [8].

The questionnaires were first distributed (and collected) before the speech processor upgrade. New processors were programmed with the program used by the legacy processor and an additional program (Adaptive Intelligence or SCAN, depending on manufacturer) was downloaded. At discharge from hospital, HISQI, APSQ, or SSQ questionnaires were given to the patients to take home and fill in. The questionnaires were the same as those completed before the upgrade. Two weeks later, patients were telephoned for counselling and troubleshooting, and asked to complete and return the questionnaires.

Statistical analysis

To evaluate the effect of microphone directionality, a repeated measured ANOVA was implemented; here, the speech-in-noise test results were used with three test conditions–Opus 2, Sonnet 2 with omnidirectional microphone, and Sonnet 2 with natural directionality–as the within-subject factor. The hypothesis of sphericity was assessed using Mauchly's test. To check which combination of variables differed significantly from the others, a post hoc pair-wise multiple comparison procedure using the Tukey test was applied.

To answer the research question of whether patients benefitted from adaptive front-end processing, the pre-upgrade and post-upgrade assessments with PROMs were compared using a Student's t test. Normal data distribution was confirmed with a Shapiro–Wilk test. All statistical analyses were performed using Statistica version 12.0. Values of $p < 0.05$ were considered statistically significant.

Results

Speech in noise

There were 36 children upgraded from Opus 2 to Sonnet 2 who were tested with AAST (children with additional disabilities or comorbidities were excluded from AAST evaluation). The age at testing in this group varied from 7.2 to 18.0 years (mean 9.9; SD 2.13). The results of AAST for three conditions are presented in Fig. 1. Results from repeated measures ANOVA showed effect of microphone directionality on speech recognition in noise ($F(2,70) = 28.05$, $p < 0.001$). Post hoc pair-wise multiple comparisons using the Tukey test showed a significant improvement of 2.69 dB ($p = 0.0001$) for Sonnet 2 with natural directionality compared to Opus 2. There was also a significant difference (2.60 dB, $p = 0.0001$) between the Sonnet 2 omnidirectional mode and the Sonnet 2 natural directionality in favor of the natural mode. There was no significant difference found for Opus 2 and Sonnet 2 omnidirectional microphone settings.

Patient-reported outcome measures

The HISQUI questionnaire was distributed to 59 children. Only pre- and post-upgrade sets which contained no more than 3 questions answered with 'not applicable' were considered for analysis. Results of children with additional comorbidities were excluded, leaving HISQUI results of 40 children aged from 7.6 to 17.2 years (mean 11.9; SD 3.18) for analysis. Results are presented in Table 2. Making use of the categorical scale of patient performance proposed by Amann and Anderson [6], after the upgrade the pre-upgrade results changed from moderate performance on average to good performance. Patient ability to perform auditory tasks increased by 5.08 points with the new processor and this difference was statistically significant (Table 2).

Another group of 60 children were asked to complete the APSQ questionnaire, and here there were 50 questionnaires of children aged from 7.6 to 18.0 (mean 11.2; SD 2.56) which were finally analyzed. The exclusion criteria for the APSQ questionnaire were the same as for HISQU. Mean post-upgrade score, compared to pre-upgrade, increased by 0.12 points for Total score, 0.09 for Comfort, 0.16 for Social life, and 0.11 for Usability. The increase in the Social life dimension was found significant. Mean pre- and post-upgrade APSQ results and pairwise comparisons are presented in Table 2.

The third group was assessed with the SSQ questionnaire which was provided to 59 children. After preliminary investigation, 27 of them were excluded based on the above-mentioned criteria, leaving 32 questionnaires of children aged from 10.1 to 17.5 (mean 14.1; SD 2.45). The post-upgrade Total score compared to pre-upgrade outcomes increased by 0.86 points and this difference was significant. Similarly, significant increases were observed for Speech hearing (1.09) and Spatial hearing (0.75). The pre–post upgrade difference

Fig. 1 Results of speech-in-noise evaluation using AAST for Opus 2 (the legacy speech processor, left) compared to performance when upgraded to the Sonnet 2 omnidirectional microphone (Omni, centre) or the Sonnet 2 with natural directionality (Natural, right). Dots indicate mean SRT in the S0–N180 condition; whiskers show 95% confidence intervals
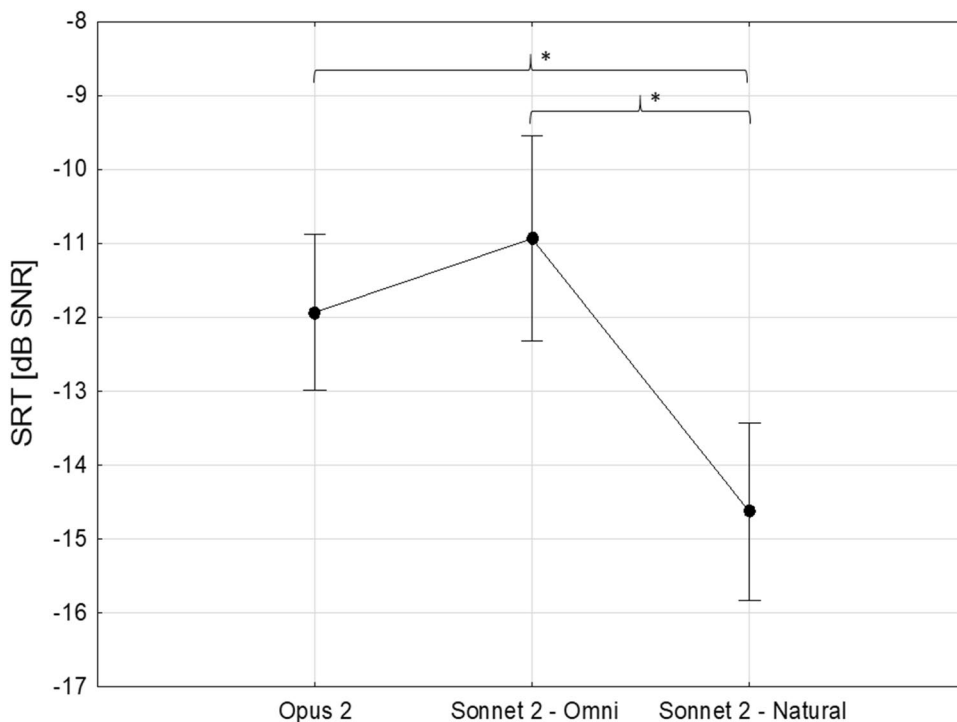
Table 2 Results of pre-upgrade and post-upgrade assessment with Patient reported outcome measures: HISQUI, APSQ, and SSQ, and pre–post pairwise comparisons

	n	Mean	SD	t test	p value
HISQUI					
Pre-upgrade	40	89.75	15.07	2.42	0.0203
Post-upgrade	40	94.83	15.45		
APSQ					
Total score					
Pre-upgrade	50	9.07	0.70	1.45	0.1534
Post-upgrade	50	9.19	0.66		
Comfort					
Pre-upgrade	50	8.98	0.89	0.63	0.5307
Post-upgrade	50	9.07	0.90		
Social life					
Pre-upgrade	50	9.07	0.79	2.05	0.0458
Post-upgrade	50	9.23	0.69		
Usability					
Pre-upgrade	50	9.15	0.85	0.89	0.3761
Post-upgrade	50	9.26	0.83		
SSQ					
Total score					
Pre-upgrade	32	5.81	1.25	3.19	0.0032
Post-upgrade	32	6.67	1.28		
Speech hearing					
Pre-upgrade	32	5.00	1.70	3.15	0.0036
Post-upgrade	32	6.09	1.81		
Spatial hearing					
Pre-upgrade	32	6.51	1.65	2.66	0.0121
Post-upgrade	32	7.26	1.61		
Qualities of hearing					
Pre-upgrade	32	6.81	1.76	1.09	0.2853
Post-upgrade	32	7.19	1.95		

of 0.38 for Qualities of hearing was not significant. The mean results for the SSQ questionnaire and the results of pairwise comparisons are provided in Table 2.

Discussion

Generally, previous upgrade studies have indicated significant benefits associated with each processor generation [2–5, 9–16]. Table 3 gives an overview of recent studies. In terms of speech perception, 10 of the 12 studies identified in Table 3 tested speech discrimination in quiet, and 5 demonstrated significant improvement after an upgrade. All studies (except one) tested speech understanding in noise, and again there was a significant benefit from the newer processors. Generally speaking, speech-in-noise outcomes reported in Table 3 are in line with the results of our study, although

direct comparisons are not possible due to methodological differences (study population, speech material, location of loudspeakers, speech processor settings). Only one previous study was done in children [3], who tested 25 experienced pediatric users of the Nucleus 5 device after upgrade to the Nucleus 6 sound processor. In the tests, speech and noise were both presented from the front. Compared with the Nucleus 5, the default Nucleus 6 program gave a significant improvement of 16.7 p.p. for monosyllabic words and 9.4 p.p. for sentences in noise. However, this improvement is difficult to compare directly to our observations–an SRT difference of 2.7 dB in our users of the Opus 2 speech processor who were upgraded to Sonnet 2.

In two other studies [4, 10], the speech was presented from the front and the noise from the back, the same as in our study. In the first study [10], 10 experienced adult unilateral CI recipients performed a German adaptive Oldenburg sentence test in noise with the Opus 2 pre-upgrade speech processor (omnidirectional microphone mode) and the Sonnet processor (both for omnidirectional and directional microphone modes). The directional mode significantly improved SRTs by 3.7 dB compared to the legacy processor in the omnidirectional mode. This level of benefit was slightly larger than the 2.7 dB we observed in children; however, we point out that different adaptive speech tests were used in our study and CI children generally show smaller benefits compared to CI adults. Both studies suggest that users might profit from a directionality mode in noisy environments.

In the second study, the Australian Sentence Test in Noise was used to compare the performance of 105 recipients of the Nucleus 6 processor with the pre-upgrade sound processor [4], and here the upgrade improved group performance by 4.7 dB. Again, this improvement is somewhat larger than we report, but different speech materials were used. Moreover, in the study of Todorov and Galvin [4], additionally to microphone directionality, other front-end processing features such as dynamic range adjustment and noise reduction were active in the new speech processors but were not available in the pre-upgrade processors.

The benefit from a directional microphone (as was found in our current study) can be compared to the 2.3 dB SRT benefit reported by Hagen et al. [17]. Hagen and colleagues tested adults who had had at least 6 months experience with Opus 2 and tested them with their own speech processor (omnidirectional microphone mode) and the new Sonnet 2 (directional microphone mode) using the German adaptive Oldenburg sentence test in noise. Our results in children compare favorably to this result in adults, although in Hagen et al. [17] the noise was delivered from three directions: from the back and from both sides (90°, 180°, and 270° azimuth). In our study, the noise was presented from behind

Table 3 Recent studies that included assessments before and after speech processor upgrades

Study	Subjects	Upgrade	Speech in quiet test/improvement	Speech in noise test/improvement	PROM questionnaire/improvement
Biever et al. 2018 [14]	80 mostly adults	ESPRIT 3G→Nucleus 6 Freedom→Nucleus 6 Nucleus 5→Nucleus 6	CNC words/ns	AzBio/35.2 pp	SSQ comparative device use questionnaire/almost all patients preferred new processor
Dixon et al. 2019 [15]	351 adults	No data	CNC words/5-year increment of 2.85 p.p.; HINT/ns	Not tested	HUI/ns
Lorens et al. 2010 [5]	60 children	Combi 40+→Opus 2	Adaptive Auditory Speech Test/5.2 dB	Adaptive auditory speech test/0.7 dB	Visual aalogue Scale/36.1 pp for speech stimuli; 32.4 pp for music stimuli
Mauger et al. 2014 [11]	21 adults	Nucleus 5→Nucleus 6	Monosyllabic words at 50 dB/–4 pp for Scan	Sentence test (S0,N0) speech shaped noise/1.7 dB for upgrades from N5 to N6	Not tested
Mosnier et al. 2017 [13]	34 adults	AB old generation→NaidaCI Q70	Monosyllabic words/ns	Matrix/3.6 dB	APHAB/significant
Mosnier et al. 2014 [12]	35 mostly adults	ESPRIT 3G→Nucleus 5 Freedom→Nucleus 5	Monosyllabic words/11 pp for 50 dB speech level 8.1 pp for 60 dB speech level	Sentences test/22.5 pp for noise program	APHAB/significant improvement for GS, BN and RV
Mosnier et al. 2021 [9]	33 adults	ESPRIT 3G→Nucleus 6 Freedom→Nucleus 6	Matrix/6 dB	Matrix/5.3 dB	APHAB/ns
Plasmans et al. 2016 [3]	25 children	Nucleus 5→Nucleus 6	Monosyllabic words/ns	Monosyllabic words (S0, N0)/16.7 pp; Sentences (S0, N0)/9.4 pp	Not tested
Seebens and Diller 2012 [10]	45 adults	Tempo +→Opus 2	Monosyllabic words/15.8 pp Hochmair–Schulz–Moser (HSM) sentences/8 pp	Monosyllabic words/24.8 pp Hochmair–Schulz–Moser (HSM) sentences/7.6 pp	Not tested
Todorov and Galvin, 2018 [4]	105 mostly adults	ESPRIT 3G→Nucleus 6 Freedom→Nucleus 6 Nucleus 5→Nucleus 6	Not tested	Sentence test (S0, N180)/4.7 dB	Not tested
Warren et al. 2019 [2]	37 adults	Nucleus 5→Nucleus 7 Nucleus 6→Nucleus 7	CNC words/ns	Sentence test in spatially separated noise/significant improvement for upgrades from N5–N6 or N7	COSI/significant benefit in categories: hearing on the telephone, Conversation with 1 or 2 in quiet, Listening effort; Processor Comparison Questionnaire/significant level of satisfaction
Wimmer et al. 2016 [16]	10 adults	Opus 2→Sonnet	Not tested	Oldenburg sentence test (S0, N180)/3.7 dB	Not tested

(180° azimuth), which is considered a less difficult listening situation than used in the Hagen et al. study [17].

In addition to speech discrimination, we also used patient reported outcome measures (PROMs) as another outcome measure. There are two reasons for using PROMs. First, it isn't easily possible to test new features of front-end processing, such as scene analysis, by means of a simple speech discrimination test. During one test session, it isn't easy to simulate multiple environments and give the user time to get used to each setting. So to gauge how successful scene analysis is, we therefore recommend creating a map with these features turned on, and then let users experience the map under different common situations. The user's self-report (the PROM) then becomes an important measure of how well this new technology works. Second, one needs to recognize that there are many real-life situations, such as activity limitations and participant restrictions, which cannot be gauged by a speech discrimination test. These problems are unique and depend on personal circumstances, family situation, life-style, and so on. In such circumstances PROMs are needed in order to quantify performance. To the best of our knowledge, until now PROMs have not been used in studies of pediatric upgrades to gauge upgrade benefits. In this study, the PROM results pointed to an appreciable subjective improvement when the speech processor was upgraded to the new technology. Children or their parents reported a higher level of functioning in different everyday life situations (according to HISQUI), less hearing disability according to SSQ, and more satisfaction with new audio processor, particularly in social situations (APSQ).

Better functioning with the new speech processor (compared to the legacy processor) was indicated by a significant improvement of 5.08 points in the HISQUI score. Particularly encouraging is that the performance rating changed from moderate performance to good performance after the upgrade. The amount of functional benefit (in points) was comparable to that found previously in adults when speech processors were upgraded from Opus 2 to Sonnet. The notable difference, however, is that in adults both the pre- and post-upgraded scores were rated as "moderate performance". This suggests that the children in the current study performed better with their Opus 2 speech processors than did the adults in other studies.

It is worth noting that the mean HISQUI score found in the group of children using the Sonnet 2 unilaterally or bilaterally is better than the score reported for unilateral and bilateral CI adults, and is comparable with the mean score for single-sided deafness (SSD) CI users, Electric-Acoustic Stimulation system (EAS) users, and Vibrant Soundbridge (VSB) users [18].

To comment about a range of hearing disabilities across three domains, judgements by parents and children indicated that, compared with the legacy processor, the new Nucleus

7 processor gave better spatial hearing and speech hearing. Spatial hearing involves judgements of direction, distance, and movement. The speech hearing relates to diverse situations: noisy background conditions, reverberation, multiple voices, and the ability to ignore one voice while attending to another, following a conversation that switches quickly from one person to another, or following two speakers simultaneously [19]. Improvement in spatial hearing and in speech hearing due to the upgrade is especially encouraging, as it indicates clear advantages of the new technologies, particularly automatic scene analysis when listening in difficult acoustic conditions.

SSQ scores in the present study were similar to those reported by Lovett et al. [20] in a pediatric population. When compared to adult data, children upgraded to the Nucleus 7 scored better than unilateral CI recipients and performed comparably to bilaterally implanted adults–except for the SSQ section "qualities of hearing", where children outperformed adults using the previous generation of processors with no automatic scene analysis [21]. Considering that our study group included both unilateral and bilateral children, this tends to suggest that children made good use of the additional advantages provided by the automatic scene analysis built in to their new speech processors. Moreover, in terms of the SSQ total score, children upgraded to processors with automatic scene analysis had a mean score of 6.67, higher than the 5.8 achieved by adults upgraded to processors lacking automatic scene analysis [17].

Turning to the children's satisfaction with their new speech processors, the APSQ results indicate a very high level of satisfaction. APSQ is a relatively new questionnaire in the field of hearing implants and there are no prior studies using it on CI recipients. The children's satisfaction with the upgrade speech processors, as measured by APSQ, was 9.19 points, higher than the level of satisfaction (mean score of 8.8 points) from users of bone conduction implants and their audio processors [22]. For the comfort subscale, the mean score was 9.07, for the social life subscale 9.23, and for the usability subscale it was 9.26. These scores are higher than the mean scores from the validity study, which were 8.0, 8.2, and 9.0, respectively.

The absence of any observed benefit in terms of APSQ total score can be attributed to a ceiling effect. The group mean score was already 9.07 with the Opus 2 pre-upgrade speech processor (on a scale with a maximum of 10 points) and increased to 9.19 with the Sonnet 2. In one APSQ validation study already mentioned [7], the APSQ results had a tendency towards a ceiling effect and failed to show any difference between devices. In the current study, the rationale of using APSQ was simply to document whether children were satisfied with their new processor. Nevertheless, despite the ceiling effect, in the current study a significant improvement was seen on the social life subscale. This finding is

encouraging, as it indicates that the new speech processor can play an important role in the children's social life by substantially diminishing limitations in activity or restrictions on participation. This is directly reflected by the responses to items 10 and 13 on the social life subscale, which addresses participation in cultural activities and group conversations. This correlates with the improvement in speech-in-noise discrimination seen with the Sonnet 2 speech processor, demonstrating that such new technologies as directional microphones can improve children's auditory performance in difficult acoustic environments. This is important, as the impairments to CI children's ability to understand speech in noisy environments are well documented.

Conclusion

In terms of speech perception we have been able to demonstrate the real benefit from a directional modes implemented in the new speech processors. In addition to speech discrimination, Patient Reported Outcome Measures (PROMs) indicated less hearing disability, a higher level of functioning in everyday life situations, and more satisfaction with the new speech processor in social situations.

We have demonstrated that children obtain a significant improvement in performance when their speech processor is upgraded to the new technology, with new front-end features such as directional microphones, noise reduction algorithms, and scene analysis systems.

Declarations

References

1. MED-EL (2019) Automatic sound management 3.0 with the SONNET 2 Audio Processor

2. Warren CD, Nel E, Boyd PJ (2019) Controlled comparative clinical trial of hearing benefit outcomes for users of the Cochlear™ Nucleus® 7 Sound Processor with mobile connectivity. Cochlear Implants Int 20:116–126. https://doi.org/10.1080/14670100.2019.1572984

3. Plasmans A, Rushbrooke E, Moran M et al (2016) A multicentre clinical evaluation of paediatric cochlear implant users upgrading to the Nucleus® 6 system. Int J Pediatr Otorhinolaryngol 83:193–199. https://doi.org/10.1016/j.ijporl.2016.02.004

4. Todorov MJ, Galvin KL (2018) Benefits of upgrading to the Nucleus® 6 sound processor for a wider clinical population. Cochlear Implants Int 19:210–215. https://doi.org/10.1080/14670100.2018.1452584

5. Lorens A, Zgoda M, Obrycka A, Skarzynski H (2010) Fine structure processing improves speech perception as well as objective and subjective benefits in pediatric MED-EL COMBI 40+ users. Int J Pediatr Otorhinolaryngol 74:1372–1378. https://doi.org/10.1016/j.ijporl.2010.09.005

6. Amann E, Anderson I (2014) Development and validation of a questionnaire for hearing implant users to self-assess their auditory abilities in everyday communication situations: the Hearing Implant Sound Quality Index (HISQUI19). Acta Otolaryngol 134:915–923. https://doi.org/10.3109/00016489.2014.909604

7. Billinger-Finke M, Bräcker T, Weber A et al (2020) Development and validation of the audio processor satisfaction questionnaire (APSQ) for hearing implant users. Int J Audiol 59:392–397. https://doi.org/10.1080/14992027.2019.1697830

8. Noble W, Jensen NS, Naylor G et al (2013) A short form of the speech, spatial and qualities of hearing scale suitable for clinical use: the SSQ12. Int J Audiol 52:409–412. https://doi.org/10.3109/14992027.2013.781278

9. Mosnier I, Sterkers O, Nguyen Y, Lahlou G (2021) Benefits in noise from sound processor upgrade in thirty-three cochlear implant users for more than 20 years. Eur Arch Oto-Rhino-Laryngol 278:827–831. https://doi.org/10.1007/s00405-020-06144-y

10. Wimmer W, Weder S, Caversaccio M, Kompis M (2016) Speech intelligibility in noise with a pinna effect imitating cochlear implant processor. Otol Neurotol 37:19–23. https://doi.org/10.1097/MAO.0000000000000866

11. Seebens Y, Diller G (2012) Improvements in speech perception after the upgrade from the TEMPO+ to the OPUS 2 audio processor. Orl 74:6–11. https://doi.org/10.1159/000333124

12. Mauger SJ, Warren CD, Knight MR et al (2014) Clinical evaluation of the Nucleus® 6 cochlear implant system: performance improvements with SmartSound iQ. Int J Audiol 53:564–576. https://doi.org/10.3109/14992027.2014.895431

13. Mosnier I, Marx M, Venail F et al (2014) Benefits from upgrade to the CP810TM sound processor for Nucleus® 24 cochlear implant recipients. Eur Arch Oto-Rhino-Laryngol 271:49–57. https://doi.org/10.1007/s00405-013-2381-8

14. Mosnier I, Mathias N, Flament J et al (2017) Benefit of the Ultra-Zoom beamforming technology in noise in cochlear implant users.

Eur Arch Oto-Rhino-Laryngol 274:3335–3342. https://doi.org/10.1007/s00405-017-4651-3

15. Biever A, Gilden J, Zwolan T et al (2018) Upgrade to nucleus 6 in previous generation cochleä sound processor recipients. J Am Acad Audiol 29:802–813. https://doi.org/10.3766/jaaa.17016

16. Dixon PR, Shipp D, Smilsky K et al (2019) Association of speech processor technology and speech recognition outcomes in adult cochlear implant users. Otol Neurotol 40:595–601. https://doi.org/10.1097/MAO.0000000000002172

17. Hagen R, Radeloff A, Stark T et al (2020) Microphone directionality and wind noise reduction enhance speech perception in users of the MED-EL SONNET audio processor. Cochlear Implants Int 21:53–65. https://doi.org/10.1080/14670100.2019.1664529

18. Bräcker T, Hellmiss S, Batsoulis C et al (2019) Introducing real-life listening features into the clinical test environment: part II: measuring the hearing performance and evaluating the listening effort of individuals with a hearing implant. Cochlear Implants Int 20:165–175. https://doi.org/10.1080/14670100.2019.1579980

19. Gatehouse S, Noble W (2004) The speech, spatial and qualities of hearing scale (SSQ). Int J Audiol 43:85–99

20. Lovett RES, Kitterick PT, Hewitt CE, Summerfield AQ (2010) Bilateral or unilateral cochlear implantation for deaf children: an observational study. Arch Dis Child 95:107–112. https://doi.org/10.1136/adc.2009.160325

21. Smulders YE, Van Zon A, Stegeman I et al (2016) Comparison of bilateral and unilateral cochlear implantation in adults a randomized clinical trial. JAMA Otolaryngol Head Neck Surg 142:249–256. https://doi.org/10.1001/jamaoto.2015.3305

22. Hundertpfund J, Meyer JE, Ovari A (2020) Patient-reported long-term benefit with an active transcutaneous bone-conduction device. PLoS ONE 15:1–15. https://doi.org/10.1371/journal.pone.0241247