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Binaural Auditory Outcomes in Patients with Postlingual Profound Unilateral Hearing Loss: 3 Years after Cochlear Implantation

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Key Words

Asymmetric hearing loss · Binaural hearing · Cochlear implants · Profound unilateral hearing loss · Single-sided deafness · Speech perception in noise

Abstract

The value of cochlear implants (CI) in patients with profound unilateral hearing loss (UHL) and tinnitus has recently been investigated. The authors previously demonstrated the feasibility of CI in a 12-month outcome study in a prospective UHL cohort. The aim of this study was to investigate the binaural auditory outcomes in this cohort 36 months after CI surgery. The 36-month outcome was evaluated in 22 CI users with postlingual UHL and severe tinnitus. Twelve subjects had contralateral normal hearing (single-sided deafness – SSD group) and 10 subjects had a contralateral, mild to moderate hearing loss and used a hearing aid (asymmetric hearing loss – AHL group). Speech perception in noise was assessed in two listening conditions: the CI_{off} and the CI_{on} condition. The binaural summation effect (S_0N_0), binaural squelch effect (S_0N_{CI}) and the combined head shadow effect ($S_{CI}N_0$) were investigated. Subjective benefit in daily life was assessed by means of the Speech, Spatial and Qualities of Hearing Scale (SSQ). At 36 months, a significant binaural summation effect was observed for the study cohort (2.00, SD 3.82 dB; $p < 0.01$) and for the AHL subgroup (3.34, SD 5.31 dB; $p < 0.05$). This binaural effect was not significant 12 months after CI surgery. A binaural squelch effect was significant for the AHL subgroup at 12 months (2.00, SD 4.38 dB; $p < 0.05$). A significant combined head shadow and squelch effect was also noted in the spatial configuration $S_{CI}N_0$ for the study cohort (4.00, SD 5.89 dB; $p < 0.01$) and for the AHL subgroup (5.67, SD 6.66 dB; $p < 0.05$). The SSQ data show that the perceived benefit in daily life after CI surgery remains stable up to 36 months at CI_{on}. CI can significantly improve speech perception in noise in patients with UHL. The positive effects of CI_{on} speech perception in noise increase over time up to 36 months after CI surgery. Improved subjective benefit in daily life was also shown to be sustained in these patients.

Introduction

In the last few years, there has been a growing understanding and recognition of the effects of profound unilateral hearing loss (UHL) on social, educational and professional development [Wie et al., 2010]. Reduced speech perception in noise, sound localisation and quality of life are well documented problems in subjects suffering from UHL [Arndt et al., 2011; Firszt, 2012a, b; Hassepass et al., 2013; Gartrell et al., 2014].

A distinction between two UHL groups of individuals is made in the literature. Researchers have referred to patients with single-sided deafness (SSD group) in the case of the contralateral ear displaying normal hearing, which is limited to a pure-tone average ($PTA_{0.5, 1, 2 \text{ and } 4 \text{ kHz}}$) maximum of 30 dB HL via air conduction and to patients with a contralateral mild-to-moderate hearing loss as the asymmetric hearing loss group (AHL) [Arndt et al., 2011; Gartrell et al., 2014].

Specific cues that contribute to improved speech recognition in bilateral listening conditions are the head shadow effect, the binaural squelch effect and the binaural summation effect. The head shadow effect is a physical effect caused by diffraction of the signal by the head [Dillon, 2001]. For spatially separated sources, the signal-to-noise ratio (SNR) at each ear will be different due to the head shadow effect. By attending to the ear with the best SNR, speech perception improves. Patients with UHL will reduce speech reception when the poorer SNR is on the side of the functioning ear [Bronkhorst and Plomp, 1988; Dillon, 2001]. The binaural squelch effect is an improvement in speech perception in noise as a result of the addition of an acoustic input with a poorer SNR to the contralateral ear. The interaural time and level differences of spatially separated signals allow improved speech recognition [Bronkhorst and Plomp, 1988; Dubno et al., 2008]. Binaural summation occurs when speech and noise originate from the same location, and the same signal arrives at the two ears simultaneously. Binaural summation can improve the speech reception threshold (SRT) by 0.5–2 dB in normal-hearing subjects [Cox et al., 1981]. For both the binaural summation and the squelch effect to take place, central neural integration from both sides is required. The head shadow effect, on the other hand, can be seen as a monaural phenomenon that does not require any auditory integration of the two signals.

Common treatment modalities for SSD consist of no treatment, a bone conduction device or a CROS (contralateral routing of signal) hearing aid. These modalities do not allow for real binaural hearing because the brain only receives and processes auditory input from one side. The cochlear implant (CI) is the only choice to restore useful hearing to a profoundly deaf ear and, therefore, the only choice in SSD individuals to restore binaural hearing. Vermeire and Van de Heyning [2009] reported 12-month post-CI outcomes in 22 subjects with UHL. A significant combined head shadow and squelch effect was noted in an SSD group. In the AHL group, the effects of a CI were larger, and a significant squelch effect of +3.8 dB, and a combined head shadow and squelch effect of

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Table 1. Subject details concerning age, duration and cause of deafness, CI type, side of implantation, contralateral PTA and use of a contralateral hearing aid (HA)

Subject No.	Age at surgery, years/months	Duration of deafness, years	Aetiology	CI type	CI ear	PTA of the non-CI ear, dB HL	HA use on non-CI ear
1	35/10	8.5	Temporal bone fracture	COMBI 40+ M	R	28	No
2	50/4	3.5	Autoimmune	COMBI 40+ M	R	69	Yes
3	67/9	10.5	Iatrogenic causes	COMBI 40+ M	L	38	Yes
4	49/3	2.5	Late posttraumatic	COMBI 40+ M	L	46	Yes
5	38/2	2.5	Labyrinthitis	COMBI 40+ M	L	15	No
6	44/8	2.5	Hydrops	COMBI 40+ M	R	49	Yes
7	41/7	20.5	Temporal bone fracture	COMBI 40+ M	L	74	Yes
8	71/7	50.5	Ototoxicity	COMBI 40+ M	L	79	Yes
9	49/3	25.5	Hemosiderosis	COMBI 40+ M	R	66	Yes
10	70/1	4	Presbyacusis	COMBI 40+ M	L	51	Yes
11	53/7	13.5	Sudden hearing loss	PULSAR CI^{100} $FLEX^{soft}$	R	10	No
12	62/6	2	Sudden hearing loss	PULSAR CI^{100} $FLEX^{soft}$	R	10	No
13	59/1	5.5	Hydrops	PULSAR CI^{100} $FLEX^{soft}$	L	25	No
14	55/5	6.5	Posttraumatic	PULSAR CI^{100} $FLEX^{soft}$	R	11	No
15	22/11	2.5	Sudden hearing loss	PULSAR CI^{100} $FLEX^{soft}$	R	15	No
16	40/8	8	Labyrinthitis	PULSAR CI^{100} $FLEX^{soft}$	R	11	No
17	64/3	2.5	Otosclerosis	PULSAR CI^{100} $FLEX^{soft}$	R	21	Yes
18	47/2	10.5	Viral cochleitis	PULSAR CI^{100} $FLEX^{soft}$	L	20	No
19	49/1	3.5	Herpes zoster	PULSAR CI^{100} $FLEX^{soft}$	L	15	No
20	49/2	1.5	Otosclerosis	PULSAR CI^{100} $FLEX^{soft}$	L	39	No
21	44/6	2.5	Posttraumatic	PULSAR CI^{100} $FLEX^{soft}$	L	6	No
22	55/7	2	Posttraumatic	PULSAR CI^{100} $FLEX^{soft}$	R	53	Yes

+6.5 dB were found. This paper reports on long-term speech perception in noise and the subjective benefit of UHL subjects 36 months after CI_{on}.

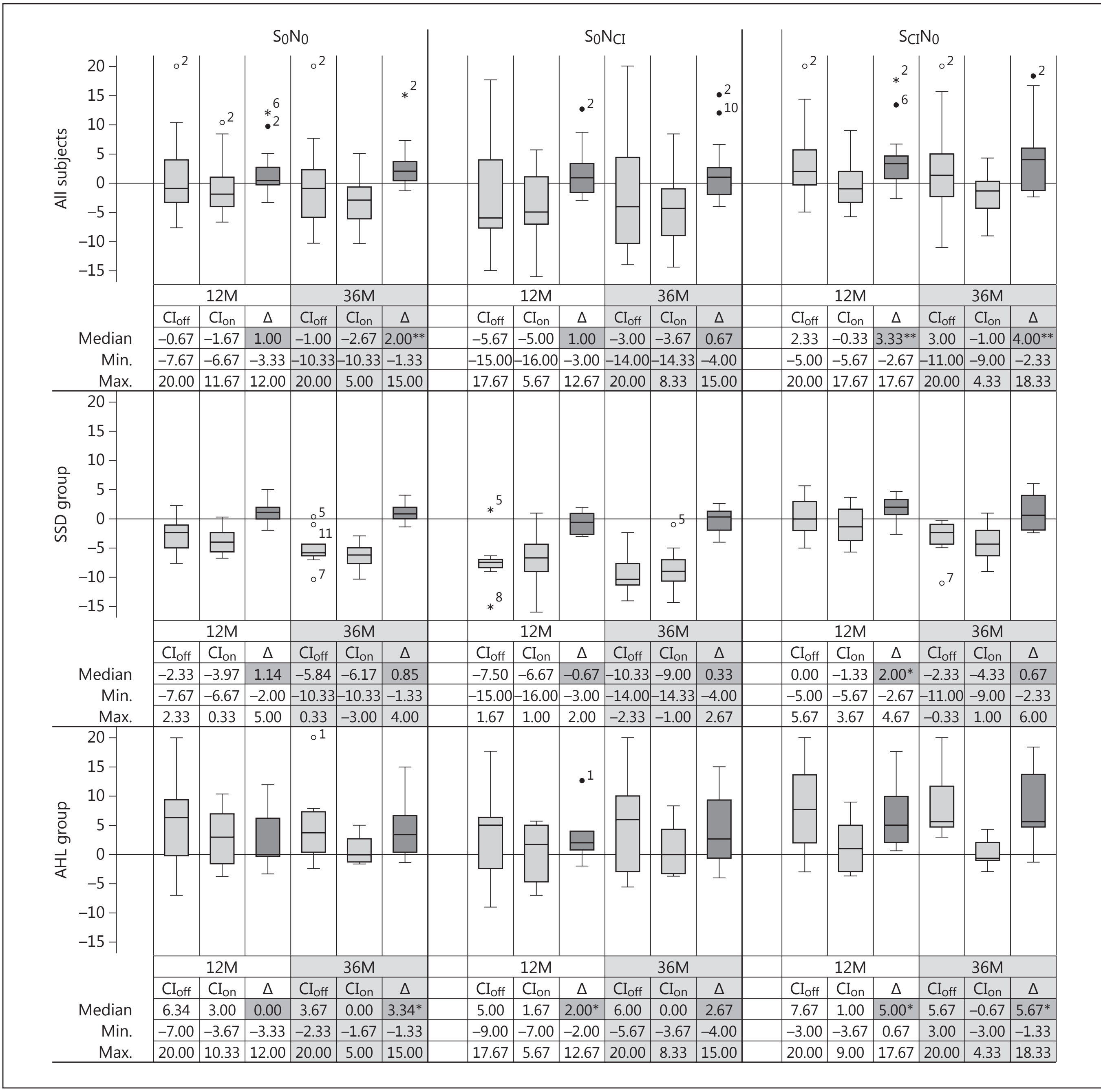
Methods

Subjects. Twenty-two patients with postlingual UHL and incapacitating tinnitus lasting less than 10 years were included in the study (table 1) [Van de Heyning et al., 2008]. The mean age of the subjects was 48 years and 8 months at the time of surgery, and average duration of deafness was 8 years and 6 months. Ten patients (S1–S10) were implanted with a MED-EL COMBI 40+ with a medium electrode and 12 patients (S11–S22) received a MED-EL PULSAR CI^{100} implant with a $FLEX^{soft}$ electrode. In all subjects, a standard surgical posterior tympanotomy for CI was performed with full electrode insertion up to the marker ring through a cochleostomy in the scala tympani. The CI fitting procedure was similar to CI fitting in bilateral deafness and subjects used continuous interleaved sampling (CIS)-based speech coding strategies in order to maximize speech recognition.

All patients had severe to profound sensorineural UHL with $PTA_{0.5,\ 1,\ 2\ and\ 4\ kHz}$ ≥85 dB HL. The 10 SSD subjects had contralateral normal hearing limited to a PTA at maximum 30 dB HL in air conduction. The 12 subjects in the AHL subgroup had a contralateral mild to moderate hearing loss. The PTA of the non-CI ears are listed in table 1. The mean PTA was 19.5 dB HL in the SSD subgroup and 64.4 dB HL in the AHL subgroup at the 36-month follow-up. Two patients were excluded from the follow-up: S2 lost contralateral hearing due to idiopathic sudden deafness 2 years after CI, and S9 also lost contralateral hearing 2 years after CI due to hemosiderosis. The study was approved by the Ethical Committee of the Antwerp University Hospital and was in accordance with the Declaration of Helsinki and Good Clinical Practice. All patients signed an informed consent form prior to participating in the study.

Audiological Testing. All subjects were evaluated 36 months after fitting of their first CI. Speech perception in noise was determined using the LIST (Leuven Intelligibility Sentences Test) [van Wieringen and Wouters, 2008]. An adaptive procedure was used to determine the SRT. The level of the speech-weighted noise was held constant at 65 dB SPL and the level of the sentences varied in steps of 2 dB adaptively in a one-down, one-up procedure according to the subject's response. The SRT was ascertained on the basis of the level of the last six sentences of one list, including an imaginary 11th sentence. Tests were conducted in free field in an audiometric soundproof booth. Loudspeakers were at ear level and at a distance of 1 m from the listener. Three spatial speech-in-noise configurations were used: both speech and noise presented from the front (0° azimuth, S_0N_0) for measurement of binaural summation effect, speech from the front and noise from the CI side (90° azimuth, S_0N_{CI}) for measurement of the binaural squelch effect and speech presented from the CI side (90° azimuth) and noise from the front ($S_{CI}N_0$) for measurement of a combined head shadow and squelch effect. Testing was performed without the CI (CI_{off}) and with the CI activated (CI_{on}). In the S_0N_0 condition, binaural summation was investigated. In the S_0N_{CI} condition, binaural squelch was investigated. The combined head shadow and squelch effect was investigated in the $S_{CI}N_0$ condition. Patients who used a hearing aid in daily life also used it during testing.

The Speech, Spatial and Qualities of Hearing Scale (SSQ) [Gatehouse and Noble, 2004] was used to investigate subjective im-



Group		S_0N_0 12M CI_{off}	S_0N_0 12M CI_{on}	S_0N_0 12M Δ	S_0N_0 36M CI_{off}	S_0N_0 36M CI_{on}	S_0N_0 36M Δ	S_0N_{CI} 12M CI_{off}	S_0N_{CI} 12M CI_{on}	S_0N_{CI} 12M Δ	S_0N_{CI} 36M CI_{off}	S_0N_{CI} 36M CI_{on}	S_0N_{CI} 36M Δ	$S_{CI}N_0$ 12M CI_{off}	$S_{CI}N_0$ 12M CI_{on}	$S_{CI}N_0$ 12M Δ	$S_{CI}N_0$ 36M CI_{off}	$S_{CI}N_0$ 36M CI_{on}	$S_{CI}N_0$ 36M Δ
All subjects	Median	–0.67	–1.67	1.00	–1.00	–2.67	2.00**	–5.67	–5.00	1.00	–3.00	–3.67	0.67	2.33	–0.33	3.33**	3.00	–1.00	4.00**
	Min.	–7.67	–6.67	–3.33	–10.33	–10.33	–1.33	–15.00	–16.00	–3.00	–14.00	–14.33	–4.00	–5.00	–5.67	–2.67	–11.00	–9.00	–2.33
	Max.	20.00	11.67	12.00	20.00	5.00	15.00	17.67	5.67	12.67	20.00	8.33	15.00	20.00	17.67	17.67	20.00	4.33	18.33
SSD group	Median	–2.33	–3.97	1.14	–5.84	–6.17	0.85	–7.50	–6.67	–0.67	–10.33	–9.00	0.33	0.00	–1.33	2.00*	–2.33	–4.33	0.67
	Min.	–7.67	–6.67	–2.00	–10.33	–10.33	–1.33	–15.00	–16.00	–3.00	–14.00	–14.33	–4.00	–5.00	–5.67	–2.67	–11.00	–9.00	–2.33
	Max.	2.33	0.33	5.00	0.33	–3.00	4.00	1.67	1.00	2.00	–2.33	–1.00	2.67	5.67	3.67	4.67	–0.33	1.00	6.00
AHL group	Median	6.34	3.00	0.00	3.67	0.00	3.34*	5.00	1.67	2.00*	6.00	0.00	2.67	7.67	1.00	5.00*	5.67	–0.67	5.67*
	Min.	–7.00	–3.67	–3.33	–2.33	–1.67	–1.33	–9.00	–7.00	–2.00	–5.67	–3.67	–4.00	–3.00	–3.67	0.67	3.00	–3.00	–1.33
	Max.	20.00	10.33	12.00	20.00	5.00	15.00	17.67	5.67	12.67	20.00	8.33	15.00	20.00	9.00	17.67	20.00	4.33	18.33

Fig. 1. SRT (in dB SNR) for all subjects, the SSD subgroup and the AHL subgroup in CI_{on} and CI_{off} conditions for the spatial speech configurations S_0N_0, S_0N_{CI} and $S_{CI}N_0$ 12 months (12M) and 36 months (36M) after cochlear implantation. *$p < 0.05$; **$p < 0.01$.

provement in hearing capabilities after CI. This questionnaire consists of 50 questions divided into three subsections rating speech, spatial and sound qualities. Scores on the SSQ give an idea of the performance of hearing-impaired people in daily life. All subjects completed the questionnaire before, and 12 and 36 months after CI surgery.

Statistical Analysis. Because of the small sample size, a Wilcoxon signed-rank test was used to assess whether speech reception results changed with CI for each spatial configuration within the two subject groups. To detect differences between the SSD and AHL groups, unpaired t tests were performed. Statistically significant differences ($p < 0.01$ or $p < 0.05$) are displayed in the graphs,

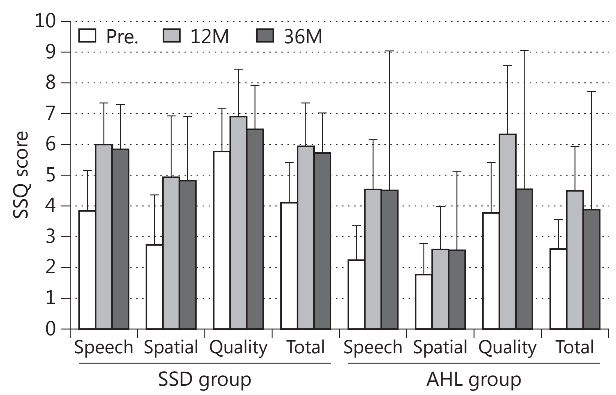


Fig. 2. SSQ total and subscale scores and standard deviations for the SSD subgroup and AHL subgroups before implantation (Pre.), and 12 months (12M) and 36 months (36M) after fitting the first CI.

and for post hoc analysis the Bonferroni correction was applied. Statistical analysis of the SSQ questionnaire was performed with repeated-measure ANOVA.

Results

Box plots of the speech-in-noise test results for the two listening conditions and the three spatial configurations (S_0N_0, S_0N_{CI} and $S_{CI}N_0$) for all subjects, and the SSD and AHL subgroups are shown in figure 1. Median, minimum and maximum values are shown in the tables included in figure 1.

The binaural summation effect that is calculated as the difference between the SRT in CI_{on} and CI_{off} in the S_0N_0 condition was significant after 36 months for the study cohort (2.00, SD 3.82 dB) and for the AHL subgroup (3.34, SD 5.31 dB). No significant binaural summation effect was found 12 months after CI surgery in the SSD and AHL subgroups, and after 36 months for the SSD subgroup only.

A significant squelch effect was only established after 12 months for the AHL subgroup (2.00, SD 4.38 dB). This binaural squelch effect was calculated as the difference between CI_{on} and CI_{off} SRT in the S_0N_{CI} condition.

A combined head shadow and squelch effect, calculated as the difference in SRT between CI_{on} and CI_{off} in $S_{CI}N_0$ condition, was significant for the study cohort after 12 months (3.33, SD 4.50 dB) and 36 months (4.00, SD 5.89 dB). This effect was also significant for the SSD subgroup after 12 months (2.00, SD 2.09 dB) and for the AHL subgroup after 12 months (5.00, SD 6.05 dB) and 36 months (5.67, SD 6.66 dB).

Results of the SSQ questionnaire are shown in figure 2. For the SSD subgroup, the SSQ total score and for the speech and spatial subsections significantly increased up to 36 months after implantation (speech: $p = 0.0058$; spatial: $p = 0.013$; qualities: $p = 0.10$; total: $p = 0.0047$). For the AHL subgroup, the SSQ total score and for the speech subsection significantly improved up to 36 months after implantation compared to before CI surgery (speech: $p = 0.042$; spatial: $p = 0.42$; qualities: $p = 0.70$; total: $p = 0.017$). No significant correlations were found between speech reception in noise and scores on the SSQ questionnaire.

Discussion

The present data demonstrate that the average speech perception in noise improves in patients with acquired UHL in the CI_{on} condition compared to the CI_{off} condition. The results of this study show that the restoration of binaural effects is possible following CI treatment in patients with UHL and normal hearing (SSD group)/moderate hearing loss in the contralateral ear (AHL group).

However, the ability to use binaural inputs takes several years of CI use. This is in line with the findings of studies in bilateral CI showing that several years of CI use are necessary to fully take advantage of binaural cues available from the second implant [Eapen et al., 2009]. These authors found that the binaural squelch effect continues to develop for up to 4 years of bilateral CI use. It was suggested that this was due to the need for greater cortical integration of inputs. Similarly, a considerable amount of time seems to be necessary for the integration of electric input via the CI when normal auditory input is available from the other ear.

Although no significant summation effect was seen in the data collected 12 months after cochlear implantation [Ramos et al., 2012; Gartrell et al., 2014], a significant summation effect was present 36 months after CI in our series. Therefore, binaural processing strategies may develop with continued use of the implant over time, indicating the importance of long-term follow-up studies of binaural evaluation.

In the spatial configuration $S_{CI}N_0$, we can calculate a combination of the head shadow and squelch effect when listening in the CI_{on} condition as compared to listening in the CI_{off} condition. The addition of the CI resulted in a significant improvement in speech perception in noise.

The results of improved speech perception in noise over time with the CI compared to acoustic hearing only are also reflected by the improved SSQ scores. In the SSD subgroup, a benefit in daily life was shown for speech understanding and for spatial hearing. In the AHL subgroup, a significant improvement in the speech subscale was noted. The speech subscale assesses how well a person can understand speech in quiet and noisy situations, the ratings for which would be expected to be linked to the audiometric results for speech reception tests in noise. For the quality subscale, no significant difference was found between scores before and 36 months after implantation. However, no significant correlations between SSQ scores and speech perception in noise were found. This may be due to a relatively small variation in SSQ scores after 36 months and to the small size of the study group. This also shows that the SSQ and speech in noise tests each measure different aspects of hearing with the CI.

In other studies on CI patients with UHL, results were comparable to those found in this study. Arndt et al. [2011] reported improved speech perception in noise and sound localisation in CI-treated SSD cases 6 months after implantation and suggested that the improvements were due to restored binaural hearing. The benefits of CI also outweighed the benefits obtained through treatment with CROS or bone conduction devices.

Buechner et al. [2010] reported on 5 subjects with SSD and ipsilateral tinnitus 12 months after cochlear implantation. In these subjects, CI surgery did not improve speech perception when the noise was presented from the front or the side of the CI, but only improved in the spatial configuration of noise on the normal-hearing side and speech from the front (S_0N_{AH}, head shadow effect). In our SSD group, no significant benefit of CI could be detected in the S_0N_0 and S_0N_{CI} configurations at 12 months, too. In the S_0N_{AH} condition, 4 of 9 subjects showed an improvement in speech perception when the CI was added and 2 subjects had a slightly negative effect [Vermeire and Van de Heyning, 2009].

Another observation is the recently documented influence of tinnitus in the unilateral deaf ear on speech perception in the contralateral normal-hearing ear [Mertens et al., 2013]. The presence of tinnitus can elevate speech perception thresholds in the opposite ear when the implant is switched off, which may confound the ideological performance of the patient in the CI_{off} condition.

Our patient population used their CI constantly. The tinnitus relief resulting from CI stimulation was probably an important motivating/driving factor for constant/daily CI use [Van de Heyning et al., 2008; Punte et al., 2011]. This reinforcement to wear a CI may have an influence on the speech reception results obtained with a CI in SSD patients. All patients, both those with normal hearing and those with a moderate hearing loss in one ear, experienced a subjective benefit after CI surgery, as evaluated by the SSQ questionnaire. Of note, self-rating of hearing capabilities using the SSQ is low in unilateral deaf patients, particularly in the unaided condition. This indicates that the experienced handicap caused by UHL is substantial, which has also been reported in the previous literature.

The underlying neural correlate of enhanced speech-in-noise recognition in the binaural stimulation mode with electric and acoustic inputs is still under debate and has been recently investigated by different researchers. Most evidence points to central integration at the higher auditory integration centres of the primary and secondary auditory cortex [Rohl et al., 2011; Straka et al., 2013]. Signals, whether acoustically or electrically evoked, from the auditory nerve follow mainly a crossed pathway, but an ipsilateral route exists, too. The signals from both sides may also integrate at the brainstem level and may as well independently be conveyed in different layers in the same tracts and nuclei [Straka et al., 2013].

The main cortical theory implies that it is not just a mean summation of stimuli but rather the integration and better processing of the information [Goycoolea et al., 2011]. Moreover, this may be different for threshold and suprathreshold functions. For directional hearing, merging of input from both sides occurs at the superior olivary nuclei [Grothe et al., 2010; van der Heijden et al., 2013]. Theoretical models, however, focus on threshold recognition at the brainstem level [Heil, 2014]. Theoretical and experimental models imply that the acoustic nerve information is similar from the acoustic and the electric stimulated side.

Schoof et al. [2013] could not demonstrate binaural unmasking based on interaural time differences and only weak, inconsistent, overall spatial release from masking in a similar condition, where the CI used an envelope feature extraction algorithm. In this experiment, fine-structure analysis for frequencies under 1,500 Hz were used. Whether this is characteristic of summation effects has not yet to be proven.

In this series of patients, all subjects had acquired unilateral deafness. It is unknown whether and when plastic changes can occur after prolonged periods of differentiation, which occurs for example in congenital unilateral deafness [Kral et al., 2015]. However, there is a risk that in some UHL cases where auditory deprivation is experienced for more than 10 years, the potential for binaural hearing advantages to develop may be absent.

The cortical integration theory for enhanced binaural speech recognition also supports the importance of long-term auditory rehabilitation training and explains the observation that enhanced speech recognition ability in noise is demonstrated only after long periods of CI experience of up to 3 years, as shown in our series of UHL patients.

Conclusion

CI can significantly improve speech perception ability in noise for patients with UHL. The positive effects of CI on speech perception in noise increase over time, up to 36 months after implantation. The improvement in the subjective benefit of hearing ability in daily life was also shown to be sustained in these patients over time.

Disclosure Statement

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