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IMPACT OF HEARING AID USE ON AUDITORY PERCEPTION AND VERBAL SHORT-TERM MEMORY IN CHILDREN WITH BIMODAL STIMULATION[1]

Sanja OSTOJIĆ*[2], Ana JOTIĆ**,
Mina NIKOLIĆ*, Danica MIRIĆ**, Branka MIKIĆ**
*University of Belgrade – Faculty of Special
Education and Rehabilitation
**Clinical Center of Serbia – Clinic for Otorhinolaryngology
and Maxillofacial Surgery
University of Belgrade – Medical Faculty

Introduction: The combination of electric stimulation from cochlear implant (CI) with acoustic stimulation from hearing aid (HA), otherwise known as bimodal hearing, may provide several binaural benefits including binaural summation, binaural squelch, reduction of the head shadow effect, and improved localization. Purpose: This study investigated the influence of preoperative rehabilitation and bilateral HA use, bimodal stimulation post-implantation (CI on one ear and HA on the non-implanted ear) and hearing thresholds in the

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2 E-mail: snjostojic@gmail.com

implanted and the non-implanted ear on auditory perception and verbal short-term memory. Method: Immediate verbal memory test for Serbian language consisting of four subtests was used for auditory perception testing on 21 pre-lingually deaf children. Results: Duration of bimodal hearing proved to be significant in the terms of auditory perception and verbal short-term memory. Mid- and high-frequency amplified thresholds on the non-implanted ear were correlated with poorer perception and reproduction of monosyllables and nonsense words. Conclusion: Duration of bimodal hearing proved to be significant in the terms of auditory perception, speech reproduction and semantic ability. Patients with a unilateral cochlear implant who have measurable residual hearing in the non-implanted ear should be individually fitted with a hearing aid in that ear, to improve speech perception and maximize binaural sensitivity.

Key words: *hearing aid, bimodal stimulation, auditory perception, short term memory*

INTRODUCTION

Though possibilities for bilateral cochlear implantation are growing, it still isn't widely available. Pre-lingually deaf children with unilateral cochlear implant (CI) can use hearing aid (HA) on the contralateral ear to provide binaural stimulation, if some residual hearing is preserved in the non-implanted ear. This combination of electric stimulation from cochlear implant (CI) with acoustic stimulation from HA, otherwise known as bimodal hearing, provides binaural benefits such as binaural summation, binaural squelch, reduction of the head shadow effect, and improved localization. (Cox, DeChicchis, & Wark, 1981; Nabelek & Pickett, 1974). It was stated previously in the literature that bimodal hearing creates a significant benefit in localization of sound, speech intelligibility and perception in children, providing low-frequency information with HA and high-frequency information with CI, which is especially helpful in complex listening situations. (Litovsky, Johnstone & Godar., 2006; Ching et al., 2001; Ching et al., 2006; Schafer & Thibodeau, 2006).

Optimal Time for Auditory Stimulation and Cochlear Implantation

One of the main predictors for successful auditory perception and speech and language development is the age of implantation. According to some authors, optimal time for cochlear implantation of congenitally deaf children is within the first 3.5 years of life (Sharma & Dorman, 2006). In that time the central auditory system shows maximal plasticity and auditory stimulation

is necessary to promote its' normal maturation. Sharma, Dorman and Kral (2005), examining cortical evoked potentials, assumed that auditory development differs in deaf children deprived of sound for a short period (under 3.5 years) comparing to deaf children deprived of sound for a long period (over 7 years). Development proceeded differently in the two samples of deaf children, where children implanted within the sensitive period showed age-appropriate response, and those implanted after the age of 7 did not. Early implanted children show better results in words and sentences comprehension, word production and encoding of semantic relations (May-Mederake, 2012). This study suggested that improvements in language development after cochlear implantation at under 3.5 years of age are largely due to early auditory stimulation, and that delayed implantation would limit phonological development in that time.

The sensitivity period ends around the age of 7. After that age there is a high likelihood of de-coupling of the primary auditory cortical areas wich are likely to be de-coupled from surrounding higher-order cortex (Kral & Sharma, 2012). Secondary to sensory deprivation, cross-modal re-organization of auditory cortex happens, in which intact sensory modalities (such as vision and somatosensation) recruit cortical regions associated with deficient sensory modalities (i.e., auditory) (Sharma, Campbell & Cardon, 2014). Late-implanted subjects can detect the auditory stimulus, but the majority cannot discriminate complex sounds appropriately, resulting in compromised speech understanding and oral language learning. Any hearing stimulation prior to cochlear implantation preserves the plasticity of the central auditory pathways and leads to a more favorable speech and language development (Sharma, Nash & Dorman, 2009).

These discoveries in the maturation process of auditory pathways were justified long before the use of bilateral HAs in preoperative rehabilitation period was established. For successful coding of binaural cues it is primary to have balanced activity between the two hemispheres in the auditory brainstem (Grothe, Pecka & McAlpine, 2010). If bilateral input is missing with ongoing stimulation from only one ear, inhibitory processes are not happening. This could lead to abnormal strengthening of contralateral pathways from one ear. It was established there is also a sensitive period (of 1.5 years) for bilateral auditory input in human development, to prevent permanent abnormal reorganization of the immature auditory cortex (Gordon, Wong & Papsin, 2013). Bilateral input provided later than the sensitive period, poorly restored cortical symmetry. A lack of auditory stimulation in this critical period may lead to auditory deprivation and deterioration of speech perception in the unaided ear, so early start of binaural stimulation could be crucial in establishing adequate speech and language development (Shiell, Champoux & Zatorre, 2014; Conway et al., 2011).

Auditory Perception and Verbal Short-term Memory in Preoperative and Postoperative Binaural Stimulation

The most direct indicators of phonological processing, as an auditory processing skill, would be auditory perception of words or speech production. As described by McBride-Chang (1995), assessment procedure includes (a) listening and perceiving the words that are presented orally; (b) holding the phonological representation in memory; (c) identification of the speech segment (e.g., deletion, identification); and (d) communicating the result of the performed action with a spoken response. Verbal short-term (immediate) memory is considered to be highly flexible memory and language processing system plays a crucial role in word recognition, vocabulary development, sentence comprehension and language production (Harris et al., 2013). In children who are vulnerable to speech-language delays as a result of degraded auditory input and hearing impairment, verbal short-term memory proved to be important for spoken language development (Pisoni et al., 2011). In measuring short-term memory, children with cochlear implants test below average (Pisoni & Cleary, 2003; Harris e al., 2013). Fagan and Pisoni (2010) suggest that amount of language experience is as critical for spoken word learning in deaf children with cochlear implants. In their opinion, only an accelerated rate of word learning will close the vocabulary gap for children with cochlear implants, comparing to their hearing peers. Preoperative use of HAs bilaterally ensured early exposure to speech prosody and basic language phonology in children preparing for cochlear implantation and hasted their progress. Ertmer and Jung (2012) state that the interaction between preimplant hearing experiences might have facilitated vocal development in their subjects in the early stages of assessment after cochlear implantation.

Bilateral auditory stimulation started pre-implantation, should be continued after implantation. Effects of auditory deprivation in the unaided ear were noticed a few decades ago (Gatehouse, 1992; Hurley, 1999), only to be confirmed today with findings of cortical re-organization in a form of compensatory cross-modal plasticity (Sharma et al., 2014). Consequently, this influences functional outcomes in children after unilateral cochlear implantation.

On the other hand, if bilateral cochlear implantation isn't available, stimulation can be achieved with a HA. There are clear benefits of bimodal hearing in children with unilateral cochlear implants. About 62% of children showed improvement in sound localization in binaural conditions, (Ching et al., 2006b). In children between the age of 6 and 18 using bimodal stimulation comparing to using only cochlear implant, there were significant benefits in speech perception, localization, and aural/oral function (Ching et al., 2001). This was confirmed in the study done by Looi and Radford (2001). Children with bimodal stimulation between the age of 6 and 13, had better scores in words and phonemes recognition tests, comparing to children with unilateral HA.

Effects of Thresholds in the Non-implanted Ear on Auditory Perception

Basic assumption is that bimodal users can access low-frequency acoustic information from the non-implanted ear. (Mok et al., 2006; Dorman et al., 2008). In adult population, there is a wide range of variability in reports on how the thresholds on the non-implanted ear influence auditory perception. Some studies did not establish any significant correlation between the levels of non-aided thresholds in the non-implanted ear and bimodal benefit (Luntz, Shpak & Weiss, 2005; Luntz, Yehudai & Shpak 2007; Berrettini et al., 2010). On the other hand, there are findings that aided thresholds in the non-implanted ear, rather than non-aided ones, have more influence on auditory perception (Mok et al., 2006).

Individual differences in speech recognition performance, besides audiological thresholds, could be a result of many factors. As possible reasons, some authors mention suprathreshold distortion (Summers et al., 2013; Grant & Walden, 2013), or existence of dead regions in the cochlea (Vinay & Moore, 2007). Zhang, Dorman, Gifford and Moore (2014) established that in subjects with unilateral CI and residual acoustic hearing in the non-implanted ear with cochlear dead regions, speech understanding, speech quality and music quality were best if frequencies within the dead region weren't amplified. For listeners without dead regions, speech understanding was best with full-bandwidth amplification and was reduced when amplification was not applied in audiometric threshold over 80dB hearing loss. Information about the influence of aided or non-aided thresholds in the non-implanted ear to auditory perception in pre-lingually deaf pediatric-only population are almost nonexistent.

This study investigated few hypotheses. First, that the influence of preoperative rehabilitation and bilateral HA use on auditory perception was significant. Second, that continuance of bilateral auditory stimulation post-implantation in those children, with bimodal stimulation (CI on one ear and HA on the non-implanted ear) provided better auditory perception and verbal short-term memory; and third, that hearing thresholds in the implanted and the non-implanted ear influenced performance in children included in the study.

MATERIAL AND METHODS

The study was conducted on 21 pre-lingually deaf children, from 2.7 to 10.3 years of age (32 to 124 months). In all patients unilateral cochlear implantation was done at the Clinic for Otorhinolaryngology and Maxillofacial Surgery, Clinical Center of Serbia from November 2007 to November 2012. Selection criteria were: average intellectual abilities without other impairments, presence of residual hearing in the non-implanted ear that can be amplified, use of HAs bilaterally before implantation and unilateral CI. All patients underwent multidisciplinary aural rehabilitation prior to and after cochlear implantation. Parents or caregivers of the patients gave their consent in participate to the study, and the study was approved by Institutional Ethical Board. Hearing aids used for patients were Oticon Sumo DM, Phonak Naida III and Siemens Nitro 301SP, and they were fitted according to individualized digital prescription algorithms. Pure tone audiometry was done to determine the thresholds in the implanted ear with speech processor and non-implanted ear (non-aided and aided).

Table 1 – Characteristics of the patients included in the study

Patient	Sex	Age (months)	Etiology	Ear CI	CI	HA	Age at CI (months)	Duration of rehabilitation (months)	Duration of bilateral preop. HA usage (months)	Duration of bimodal hearing, CI+HA (months)
1	female	32	Toxoplasma	left	Medel Opus I, Pulsar C.I.100	Oticon Sumo DM	20	31	17	14
2	male	34	Unknown	left	Medel RondoPulsar C.I. 100	Siemens Nitro 301SP	21	19	7	12
3	female	38	Hereditary	left	Medel RondoPulsar C.I. 100	Oticon Sumo DM	25	23	5	18
4	male	40	Unknown	right	Medel Opus I, Pulsar C.I.100	Oticon Sumo DM	17	33	10	23
5	female	43	Unknown	left	Advanced Bionic Harmony	Phonak Naida III	21	26	4	22
6	female	44	CMV	left	Advanced Bionic Harmony	Phonak Naida III	21	31	5	24
7	female	50	Hereditary	left	Medel Opus I, Pulsar C.I.100	Oticon Sumo DM	39	49	40	9
8	male	52	Cochlear hypoplasia	left	Medel RondoPulsar C.I. 100	Phonak Naida III	44	29	24	5
9	female	63	Unknown	left	Medel Opus 2Pulsar C.I. 100	Oticon Sumo DM	24	44	5	39
10	female	65	Perinatal asphyxia	left	Medel RondoPulsar C.I. 100	Siemens Nitro 301SP	41	22	7	25
11	female	68	Perinatal asphyxia	left	Medel Opus I, Pulsar C.I.100	Oticon Sumo DM	46	40	17	23
12	male	70	Unknown	left	Medel Tempo plus, Pulsar C.I.100	Phonak Naida III	39	34	5	29

Patient	Sex	Age (months)	Etiology	Ear CI	CI	HA	Age at CI (months)	Duration of rehabilitation (months)	Duration of bilateral preop. HA usage (months)	Duration of bimodal hearing, CI+HA (months)
13	male	71	Unknown	left	Medel Opus I, Pulsar C.I.100	Oticon Sumo DM	30	55	12	43
14	male	86	Unknown	left	Medel RondoPulsar C.I. 100	Phonak Naida III	53	48	14	34
15	male	91	CMV	left	Medel Opus 2Pulsar C.I. 100	Phonak Naida III	42	60	9	51
16	female	94	Hereditary	left	Medel Tempo plus, Pulsar C.I.100	Oticon Sumo DM	57	29	9	20
17	female	99	Unknown	left	Medel RondoPulsar C.I. 100	Oticon Sumo DM	48	72	23	49
18	male	100	Unknown	left	Medel Opus 2Pulsar C.I. 100	Oticon Sumo DM	48	74	23	51
19	female	105	Hereditary	left	Medel RondoPulsar C.I. 100	Oticon Sumo DM	62	77	33	44
20	male	110	Hereditary	left	AdvancedBionic Harmony	Phonak Naida III	89	95	75	20
21	male	124	Hereditary	left	Advanced Bionic Auria	Phonak Naida III	102	101	80	21

The study was conducted on 11 female and 10 male patients, with an average age of 5.8 years (70.4 months). The youngest child involved in the study was 32 months old, and the oldest 124 months. Characteristics of the patients, side of cochlear implantation, type of CI and speech processor used, age at implantation, duration of rehabilitation, duration of bilateral hearing aids usage and duration of bimodal hearing are given in Table 1. The youngest implanted child in this study was 17 months old at the time of implantation. The earliest start of auditory stimulation with HAs was from four months of age.

Immediate verbal memory test for Serbian language was used for auditory perception testing (Vladisavljević, 1983). The test provided information about the range of auditory perception, immediate and delayed verbal memory, reproduction sequence, grammar level and semantic message realization. Choice of words was customized for patients' vocabulary level and it consisted of 4 subtests. Maximal scores on each of four subtests was 10. Total score for immediate verbal memory test represented a sum of subtest scores, with maximum value of 40. The first subtest consisted of plosive consonants (p, b, t, d, k, g) and vowels (i, e ,a, o, u) presented as 10 monosyllables (pa, ke, ba, da, ta, ga, pi, tu, do, ge). The second subtest consisted of 10 common disyllable words, consisted of plosive consonants and vocal "a", for children with poor word span (papa, tata, kaka, baba, dada, pata, baka, gada, pada, kapa). The third subtest consisted of 10 disyllable nonsense words (potu, beki, tiga, dapo, koge, gide, buki, kodu, kuto i peda). The fourth subtest consisted of 10 simple sentences, understood by children. Sentences were given in past, present and future tense. Patients were tested first with CI only, and then with bimodal stimulation (CI and HA on the non-implanted ear). The same speech therapist administered the test to all the patients individually, with "free-field" audiometry technique. Testing was done with monitored live voice testing (MLV), on the level of 60dB. Speakers were positioned 1m from the patient with 0 deg. azimuth, and testing was done on

Madsen Orbiter 922, version 2 Clinical Audiometer (Madsen Electronics, Ballerup, Denmark). The patients were asked to reproduce auditory stimulus in so called auditory – only mode, without lip reading. Only precise reproduction of each auditory stimulus was positively scored. This test was constructed to best represent the structure and dynamics of Serbian language and was validated by the Institute for Experimental Phonetics and Speech Pathology of Serbia.

Statistical analysis was performed using SSPS v20 (SPSS Inc., Chicago, IL). A p-value of less than 0.05 was considered statistically significant. Immediate verbal memory test scores were given in mean values with standard deviation. To determine the differences between scores of children tested with CI only and with bimodal stimulation Student's t test was done. Linear regression test was used to determine if age, age at implantation, early implantation (in children younger than 42 months), duration of rehabilitation, duration of bilateral hearing aids usage (preoperative rehabilitation) and duration of bimodal hearing (postoperative rehabilitation) could be predicting factors for immediate verbal memory test scores. Pearson's correlation was used to establish the relationship between the thresholds in the implanted and non-implanted ear (non-aided and aided) and Immediate verbal memory test scores.

RESULTS

Log regression test was used to determine if immediate verbal memory test scores in patients with bimodal stimulation were influenced by age, age at implantation, experience with bimodal hearing and duration of preoperative and postoperative rehabilitation (Table 2). Duration of bimodal hearing significantly influenced the scores on III and IV subtest and the total score ($p<0.05$).

Table 2 – Linear regression of Immediate verbal memory test scores depending on age, age of implantation, duration of rehabilitation, bilateral hearing aids usage, and bimodal hearing

Test scores	Age	Age at CI	Duration of rehabilitation (months)	Duration of bilateral preop. HA usage (months)	Duration of bimodal hearing, CI+HA (months)
I subtest	-0.36	0.02	-0.14	0.25	-0.14
B coefficient (95% CI)	(-0.29 to 0.25)	(-32 to 0.35)	(-0.22 to 0.4)	(-0.15 to 0.52)	(-0.68 to 0.38)
p	0.87	0.94	0.54	0.27	0.56
II subtest	0.16	0.14	0.04	0.01	0.05
B coefficient (95% CI)	(-0.26 to 0.53)	(-0.36 to 0.64)	(-0.43-0.50)	(0.51 to 0.53)	(-0.72 to 0.88)
p	0.48	0.56	0.88	0.96	0.84
III subtest	0.4	-0.14	-0.17	0.19	**-0.6**
B coefficient (95% CI)	(-0.72 to 0.04)	(-0.67 to 0.37)	(-0.65 to 0.31)	(-0.32 to 0.75)	**(-1.7 to -0.33)**
p	0.08	0.55	0.47	0.41	**0.004***
IV subtest	-0.28	0.1	-12	0.34	**-0.69**
B coefficient (95% CI)	(-0.95-0.22)	(-42 to 26.4)	(-0.89 to 0.53)	(-18 to 1.3)	**(-2.7 to-1.05)**
p	0.21	0.65	0.60	0.13	**0.000***
Total	-0.23	0.5	-0.05	0.32	**-0.58**
B coefficient (95% CI)	(-0.51 to 0.17)	(-0.9 to 0.49)	(-0.45 to 0.37)	(-0.12 to 0.74)	**0 .006***
p	0.3	0.82	0.83	0.15	

*p<.05

There were three extremely poor performers (patients 12, 13, and 14 in Table 1). The first patient did not score at all on III and IV subtest, with scores of 50 and 60 on I and II subtest, respectively. The other two scored 50 and bellow on II, III and IV subtest.

Children with CI only scored significantly lower on all subtests (Student's t test, p>0.05). Comparing the performance of children with CI only and those with bimodal stimulation, there was a smaller difference between mean values of the first (72.8±16.5 vs. 82.9±15.5) and the second subtest (62.8±18.7 vs. 71.4±23.3), than between mean values of the third (46.7±22.4 vs. 64.8±24.2) and the fourth subtest (47.6±30.1 vs. 61.4±35.7). Also, mean value of the total score was significantly lower in children performing with CI only (57.5±19.5 vs. 71.3±20.3; Student's t test, p>0.05).

Two patients with the longest experience with HA (patients 20 and 21 in Table 1) prior to CI scored high on

Immediate verbal memory test. Scores in other patients had a wide range of variations, again with more low scores on III and IV subtest, without significant connection to the duration of experience with HA.

In patients with detectable residual hearing, the non-implanted ear was amplified with HA. Unaided and aided thresholds were determined in the non-implanted ear, as well as the thresholds in the implanted ear with processor on different frequencies, and were given in Table 3.

Table 3 – Thresholds in patients in the non-implanted ear (unaided and aided) and implanted ear)

	0,25Hz (dB HL)	0,5Hz (dB HL)	1Hz (dB HL)	2Hz (dB HL)	4Hz (dB HL)
Unaided threshold in the non-implanted ear					
Mean	86.4	95	106	111.7	102.8
Min	55	75	55	95	80
Max	105	115	120	Above 120	Above 120
Aided threshold in the non-implanted ear					
Mean	39.5	42.8	50	73.3	73.5
Min	30	30	45	45	50
Max	50	55	60	90	Above 120
Threshold in the implanted ear with processor					
Mean	33.6	33.6	33.6	33.6	33.6
Min	20	20	20	20	20
Max	50	50	50	50	50

Pearson's correlation test was used to determine correlation between Immediate verbal memory test scores in children with bimodal stimulation and thresholds in the implanted and non-implanted ear (non-aided and aided). Aided threshold in the non-implanted ear on 2000 and 4000 HZ significantly influenced I subtest scores. Significant negative correlation between II subtest and III subtest scores and aided threshold in the non-implanted ear was noticed respectively, on 250 (-0.607, p=0.004), 500 (-0.493, p=0.02) and 2000 Hz (-0.502, p=0.02) and on 1000 (-0.446, p=0.04) and 2000Hz (-0.497, p=0.02). Thresholds in implanted ear with processor and unaided threshold in the non-implanted ear did not significantly influence test scores (p<0.05). (Table 4).

Table 4 – Correlation of immediate verbal memory test scores and thresholds in the implanted and non-implanted ear (non-aided and aided)

Pearson's correlation		I subtest	II subtest	III subtest	IV subtest	Total
250Hz (dB)	Threshold in the implanted ear with processor	0.15	0.6	0.48	0.67	0.06
	Unaided threshold in the non-implanted ear	0.55	0.21	0.13	0.13	0.38
	Aided threshold in the non-implanted ear	0.22	**.004***	0.08	0.24	0.5
500Hz (dB)	Threshold in the implanted ear with processor	0.15	0.6	0.48	0.67	0.06
	Unaided threshold in the non-implanted ear	0.74	0.28	0.17	0.27	0.36
	Aided threshold in the non-implanted ear	0.23	**.02***	0.05	0.14	0.87
1000Hz (dB)	Threshold in the implanted ear with processor	0.15	0.6	0.48	0.67	0.06
	Unaided threshold in the non-implanted ear	0.19	0.09	0.17	0.14	0.56
	Aided threshold in the non-implanted ear	0.25	0.08	**0.04***	0.32	0.88
2000Hz (dB)	Threshold in the implanted ear with processor	0.15	0.6	0.48	0.67	0.06
	Unaided threshold in the non-implanted ear	0.3	0.21	0.19	0.32	0.6
	Aided threshold in the non-implanted ear	**0 .02***	**0.02***	**0.02***	0.17	0.68
4000Hz (dB)	Threshold in the implanted ear with processor	0.15	0.6	0.48	0.67	0.06
	Unaided threshold in the non-implanted ear	0.17	0.09	0.66	0.97	0.52
	Aided threshold in the non-implanted ear	**0 .007***	0.12	0.17	0.49	0.33

*p<.05

DISCUSSION

Auditory Perception and Verbal Short-term Memory

For children with unilateral CI with residual hearing on the non-implanted ear, amplification with HA is a valid option for achieving bilateral hearing. Bimodal stimulation, allowing combined electric and acoustic stimulation, clearly allows better speech perception comparing to CI alone (Ching et al., 2001; Dorman et al., 2008). Advantages of bimodal stimulation in verbal perception, noise, and localization of the sonorous source are already published (Litovsky et al., 2006; Ching et al., 2006a; Ching et al., 2006b) Consonants and sentence tests, as well as nonsense syllables test scores were higher in children with bimodal hearing stimulation, than in children who were CI-only and HA-only users (Ching et al., 2001; Looi & Radford, 2011). In our study, children with longer experience in wearing bilateral HAs prior to implantation were significantly better in perception of monosyllables. This closely correlates with the fact that preoperative HAs use and rehabilitation in our patients enabled first-time sound stimulation and experience with prosody of speech at a very early age. According to models of verbal language development, sound pattern learning requires a neural commitment to the acoustic properties of a native language. In children with early severe-to-profound sensorineural hearing loss who do not experience similar stimulation, development of spoken language is altered (Graf, et al., 2007). Substantial experience of listening is likely to be required before children with cochlear implants begin to understand spoken language. Acquiring basic experience and familiarity with spoken language potentially contributes to further delays in spoken word learning immediately after cochlear implantation (Fagan & Pisoni, 2010). Preoperative HAs use in our subjects also developed early skills in verbal short-term memory, which were proven to be important predictor of later vocabulary and language growth in children with CI (Kronenberger 2013).

Bimodal hearing stimulation in children allows better speech intelligibility in children, both in quiet and in noise (Lee et al., 2008, Keilmann, & et al., 2009; Mok et al., 2010). Children with longer experience with bimodal hearing after cochlear implantation in our study had better perception of nonsense words and sentences, which demands capacity for language understanding and developed short-term verbal memory. Perception and reproduction of nonsense words in the III subtest is very discriminative in terms of proper perception of sound and depicts subject's ability to manage unexpected situations in speech perception. For pre-lingually deaf children with CI this test was extremely difficult, mostly because words were out of usual speech context, without known meaning to them, so the scores significantly correlated with experience with bimodal hearing and the duration of postoperative rehabilitation. In her study, May-Mendrake (2012) established that average phonological working memory of nonsense words of the children in unilateral CI, despite early implantation, was poorer than the average of the hearing children between 4 and 5 years of age. In our study children with bimodal hearing scored better than with CI in non-sense words perception, which can be helpful in closing the gap comparing them to hearing children.

Nittrouer and Chapman (2009) showed generative language advantage for children exposed to bimodal use early in life. Developed grammar comprehension, language semantics, and verbal short-term memory were needed for successful sentence perception and reproduction in IV subtest. These skills were implemented with intensive guidance and learning provided by speech therapists over time. The scores of the IV subtest were directly influenced by the duration of experience with bimodal hearing and postoperative rehabilitation, which was crucial for grammar development. Bimodal benefit in children may improve with listening experience or age (Holt et al., 2005) which is partly consistent with our results. Children learn to use CI over time in order to achieve better results in speech and language intelligibility. Post-implantation linguistic and social experiences and exposure to auditory-oral communication would significantly help obtaining those results (Wheeler et al., 2009). In our study, age of the patients was not in significant correlation to scores on the Immediate verbal memory test.

Nicolas and Geers (2006) examined how the time of hearing aid use prior to CI influenced language skills in 76 unilaterally implanted children. They established that children implanted at younger ages were those who did not receive as much benefit from a hearing aid. Duration of hearing aid use prior to cochlear implantation was not significantly associated with the language outcome, but children with better pre-implant residual hearing exhibited superior language skills after the same period of cochlear implant use to those in children with worse residual hearing.

In some studies, significantly reduced language learning was associated with the prolonged use of hearing aids prior to CI (Niparko et al., 2010). On the other hand, (Bayazit, Altınyay & Cevizci, 2015) state that children between 5 and 14 with HA use up to 12 years preimplantation improve their language skills thorough time. According to their study, patients implanted after the age of 14, and with HA use longer than 12 years reach to a plateau level after two years and hardly catch up with their peers. In our study there are three extremely poor performers, most evident in poor auditory perception and reproduction of non-sense words and sentences. According to their age and experience with bimodal listening, they did not have pre-requirements for difficulty performing, implanted under the age of 4.5, with preimplantation HA use of at least 5 month and with experience with bimodal listening above 2.5 years. We should have in mind that there is wide range of variability and individual differences in speech and language perception in cochlear implanted children (Harris et al., 2013), and that only 12-18% were high performers in terms of speech and language development (Kronenberger et al., 2013).

Thresholds in the Non-implanted Ear

There is a very limited number of the studies examining the impact of hearing thresholds in implanted and non-implanted ear on auditory perception in pediatric-only population with bimodal stimulation. The basic assumption is that CI especially provides high-frequency information. It was demonstrated that HA on the non-implanted ear helps improving the perception of the lower-frequency phonemes, allowing auditory system to integrate both signals resulting in better speech perception (Mok et al., 2006). There are few studies examining the influence of hearing thresholds on bimodal hearing benefit in adult population. It was suggested that if residual hearing was greater in the non-implanted aided ear, bimodal benefit would be greater also, which is expected (Tyler et al., 2002; Yoon, Li & Fu, 2012) Some authors (Berrettini et al., 2010) found significant correlation between unaided 1000 to 4000 Hz threshold and speech perception in bimodal stimulation in pre-lingually deaf adults . On the other hand, there are studies that found no significant correlation between unaided thresholds in the non-implanted ear and bimodal benefit (Luntz et al., 2005; Luntz et al., 2007). Other authors support the claim that aided thresholds in the non-implanted ear, rather than non-aided ones, could be related to bimodal benefit (Jang et al., 2014). Mok et al. (2006) established that poorer thresholds at 1000 and 2000 Hz were correlated to greater bimodal benefit, but did not find any significant correlation between aided thresholds in the low frequencies and bimodal benefit. It was suggested that mid- to high-frequency information provided by the HA might interfere with information provided by the CI, giving an adverse effect on bimodal hearing. There are, however, basic differences between adults and children in cases of bimodal stimulation. Most of the studies involve post-lingually deaf adults. In pre-lingually deaf children, bimodal hearing proved to be essential for bilateral stimulation of central auditory cortex, achieving timely speech development and communication. In preoperative rehabilitation HA were used for introducing sound stimulation for the first time, hearing the tones in the low-frequencies and learning the prosody of speech. In postoperative period, HA was used in the non-implanted ear to continue bilateral sound stimulation and to provide better reception of low-frequency sounds. In our study significant negative correlation was noted between I, II and III subtest scores and aided thresholds in the non-implanted ear. Mid-frequency and high-frequency amplified thresholds were significant in poorer understanding and repeating monosyllables and nonsense words. Some studies state that bimodal hearing provides betted localization of sound, but not necessarily better speech perception (Jang et al., 2014), which could be the case in our study. Also, we have to keep in mind that children involved in the study had severe to profound sensorineural hearing loss bilaterally, so the gain of HA on high frequencies could be debatable. The proven existence of dead regions in cochlea, which is quite common in these patients, could be another possible reason. There are studies in adults (Zhang et al., 2014) which confirm that in patients with unilateral CI with cochlear dead regions, after amplification was applied for frequencies within the dead regions, speech understanding and speech quality was significantly better. This could be the subject of further investigation in children with bimodal stimulation.

Limitations of the Study

There are few limitations to this study. Immediate verbal memory test is highly specific for Serbian language, and though highly sensitive in testing auditory perception, immediate verbal memory, grammar level and language semantics, it is not widely applicable out of Serbian speaking area. Age at the moment of testing was a limiting factor. Tests like Digit Span Forward (DSF) and Digit Span Backward (DSB), could not be applied in children under six years age, because of the test complexity and the subject's inability to understand the given task. Also, the results were influenced by the small sample and heterogeneity of subjects in terms of different duration of bimodal stimulation and ages of cochlear implantation. Normal hearing control group was not included in the study, because the study focused on assessing auditory perception changing with the duration of bimodal stimulation. Further research with larger samples would be necessary.

Scores on Immediate verbal memory test depended on the duration of bimodal stimulation, but were at the same time highly individual, thus suggesting that development of speech and language skills over time is a dynamic multifactorial process that develops outside a definite timeframe.

CONCLUSION

Results of our study indicate there was a benefit of bimodal stimulation in pre-lingually deaf children with unilateral cochlear implants in auditory perception and short-term memory. Duration of bimodal hearing proved to be significant in the terms of auditory perception, speech reproduction and semantic ability. Mid-frequency and high-frequency amplified thresholds on the non-implanted ear were correlated with poorer perception and reproduction of monosyllables and nonsense words.

Patients with a unilateral CI who have measurable residual hearing in the non-implanted ear should be individually fitted with an HA in that ear, to improve speech perception and maximize binaural sensitivity. Bimodal stimulation should be considered, if bilateral cochlear implantation is not available in pre-lingually deaf children.

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UTICAJ SLUŠNIH POMAGALA NA AUDITIVNU PERCEPCIJU I NEPOSREDNO VERBALNO PAMĆENJE KOD DECE SA BIMODALNOM STIMULACIJOM

Sanja Ostojić*, Ana Jotić**, Mina Nikolić*, Danica Mirić**, Branka Mikić**
**Univerzitet u Beogradu – Fakultet za specijalnu edukaciju i rehabilitaciju*
***Klinički centar Srbije – Klinika za otorinolaringologiju i maksilofacijalnu hirurgiju i Univerzitet u Beogradu – Medicinski fakultet*

Summary

Kombinacija električne stimulacije kohlearnog implanta (KI) i akustične stimulacije slušnog pomagala (SP), poznata kao bimodalni sluh, može imati razne binauralne prednosti koje uključuju binauralnu stimulaciju, binauralno sažimanje, redukciju eho efekta i unapređenje lokalizacije izvora zvuka. Cilj: U ovom istraživanju je ispitan uticaj preoperativne rehabilitacije i upotrebe bilateralnog slušnog pomagala, bimodalne stimulacije nakon implantacije (KI na jednom uhu i SP na neimplantiranom uhu) i pragova sluha u implantiranom i neimplantiranom uhu na auditivnu percepciju i verbalno kratkotrajno pamćenje. Metod: Za ispitivanje auditivne percepcije kod dvadeset jednog prelingvalno gluvog deteta korišćen je Test za ispitivanje verbalnog pamćenja za srpski jezik, koji se sastoji od četiri podtesta. Rezultati: Pokazalo se da je trajanje bimodalnog sluha značajno kod auditivne percepcije i verbalnog kratkotrajnog pamćenja. Povećani pragovi srednje i visoke frekvencije na neimplantiranom uhu bili su u korelaciji sa slabijom percepcijom i reprodukcijom jednosložnih i besmislenih reči. Zaključak: Pokazalo se da je trajanje bimodalnog sluha značajno za auditivnu percepciju, reprodukciju govora i semantičku sposobnost. Pacijentima sa unilateralnim kohlearnim implantom, sa merljivim rezidualnim sluhom na neimplantiranom uhu, trebalo bi ugraditi slušno pomagalo u to uho, kako bi se poboljšala percepcija govora i maksimizovala binauralna osetljivost.

Ključne reči: slušno pomagalo, bimodalna stimulacija, auditivna percepcija, kratkotrajno pamćenje

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