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Cochlear implant and hearing aid: a new approach to optimizing the fitting in this bimodal situation

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Abstract More and more patients with residual hearing on the contralateral side are becoming candidates for cochlear implants (CI) surgery due to increasing CI. The major benefits of regular binaural hearing are spatial hearing, localization, and signal source discrimination in both quiet and noisy surroundings. In most of the reports, hearing aid fitting was carried out without balancing both the devices. Twelve children and eight adults with residual hearing on the non-operated side were binaurally fitted. Our fitting procedure for the hearing aid was based on the desired sensation level [i/o] method. A loudness scaling was used to adjust the loudness perception monaurally and to balance the volume of both devices. Speech audiometry in quiet and noisy surroundings was conducted both monaurally and in the bimodal mode. The fitting was modified according to the respective test results. In all children and six adults, a measurable gain and/or a subjective improvement of speech perception was achieved. Two adult patients did not accept the new fitting. In seven younger children, loudness scaling was impossible to perform because of age. This was also the case with speech audiometry for two children. A structured bimodal fitting using loudness scaling for both the cochlear implant and the hearing aid results in a subjective and objective amelioration of the patient's hearing and speech perception.

Keywords Bimodal hearing · Cochlear implant · Hearing aid · Speech perception

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Introduction

More and more patients continue to wear their hearing aid (HA) in the contralateral ear after cochlear implant surgery due to the increase in cochlear implant (CI) candidacy. The major advantage of the additional information is a bilateral auditory input enabling the patient to use binaural processing to enhance speech perception and sound localization. In addition, many patients report a better perception of music when the HA and the CI are used in this bimodal combination. This can be explained by the different frequency characteristics of both devices.

Depending on the selection of the patients, different results for speech discrimination, especially in noise, were found in patients with both CI and HA.

Most authors report that group mean was significantly higher for all [1–4] or at least some test materials or group of patients [5, 6] in the bimodal situation compared with the CI or the HA alone. However, others found no significant benefit of bilateral or bimodal input relative to a single CI [7, 8].

Most authors who reported on sound localization in the bimodal situation found that hearing improved in some patients [8], usually those with a substantial residual hearing on the HA side [9].

Until now, the fitting of the HA has mostly been done independent of the fitting of the CI. The authors report that the hearing aids were not specifically modified or optimized [1] or they provide no information about hearing aid fitting [3]. Ullauri et al. [10] suggested a protocol for fitting and optimizing cochlear implants and hearing aids using the same type of hearing aid in all children. They report on seven children who had not worn a HA before. They describe an optimization of both devices in several steps, but they do not give concrete details. Only Ching et al.

adjusted the hearing aids systematically using loudness balancing for low, medium, and high input levels [11–16].

Materials and methods

The biographical data for all patients are provided in Table 1. The subject's age ranged from 3 to 78 years. Of the 20 participants, 14 had a MEDEL device (10 with a Tempo+ processor, 4 with an Opus 2 processor), 5 had a Cochlear device (2 with Esprit 3G and 3 freedom processor), and one patient wore an Advanced Bionics Platinum Series. At the time of testing, most patients had at least 1 year of hearing experience with the CI, 4 patients (patients 7, 12, 18, 19) had only 6–12 months. All used a combination of CI and HA in their daily activities.

The fitting protocol comprises an optimization of the CI and the HA, loudness scaling (Würzburger Hörfeld, WHF [17]), speech tests in both quiet and noisy surroundings, and questionnaires for the patient, the parents and if applicable, for the teacher.

Audiometry was carried out in a sound-treated booth using a MAICO audiometer. Patients underwent speech audiometry with age and language-adapted tests. Speech audiometry in noise was conducted with two loudspeakers placed at 180° azimuth, presenting speech from the front. For all tests, the presentation level was chosen corresponding to the needs of the patient. Although in some cases, two sessions were conducted not every desirable loudness could be used with every patient. Especially speech audiometry in noise could not be conducted always, as it depended on the respective patient's ability to concentrate.

The following audiologic tests were applied:

Mainz pediatric speech discrimination tests I, II and III [18]

Göttinger pediatric speech discrimination tests I and II [19, 20]

Freiburg Numbers and Freiburg Monosyllables [21]

In all speech tests, the patients' score was determined by the percentage of correctly repeated words or in the children's tests by the percentage of correctly indicated pictures.

For loudness scaling, the WHF was used. In detail, the patient was given a touch screen to rate the loudness of narrow band noises with a middle frequency of 0.5, 1, 2 and 4 kHz. On the touch screen, seven categories from "too loud" to "not heard" were written and given as symbols for the children, but the patient could also rate between the given categories.

The bimodal fitting was performed when the patient had a constant hearing impression with the cochlear implant and speech audiometry with the implant had stabilized.

Table 1 Biographical data of all patients

Patients	Age at examination	Sex	Etiology	Age at onset of HL	Age at CI	Implant system	Hearing aid
1	3	F	Unknown	Birth	3;09	MEDEL Opus 2	Phonak Maxx 411
2	5	F	Unknown	Birth	3;02	MEDEL Tempo+	Phonak Novo Forte E4
3	5	M	Hereditary	Birth	2;08	MEDEL Tempo+	Phonak Picoforte 3 PP-CP
4	7	F	Unknown	Birth	3;08	MEDEL Tempo+	Phonak Novo Forte E4
5	8	F	Unknown	Birth	6;02	MEDEL Opus 2	Siemens Prisma 2 D-SP
6	8	F	Unknown	Birth	7;03	Nucleus freedom	Phonak Maxx 411
7	10	F	Unknown	2;06	10;04	MEDEL Opus 2	Oticon Sumo DM
8	10	M	Unknown	1;08	4;07	MEDEL Tempo+	Oticon DF-SP
9	12	M	Hereditary	Birth	7;09	MEDEL Tempo+	Phonak Supero 412
10	13	M	Meningitis	0;08	5;08	MEDEL Tempo+	Phonak Supero 412
11	14	F	Hereditary	Birth	8;04	MEDEL Tempo+	Phonak extra 411
12	14	F	Hereditary	2;00	12;09	Nucleus ESPrit 3G	Phonak Novo Forte E4
13	17	F	Meningitis	0;11	16;04	MEDEL Tempo+	Phonak Power Maxx 411
14	17	F	Hereditary	Birth	15;08	Nucleus freedom	Phonak Novoforte E3
15	25	F	Birth complication	Birth	20;05	MEDEL Tempo+	Oticon Sumo XP
16	30	F	M. pendred	2;05	29;08	MEDEL Tempo+	Phonak SF-PP-C-L 44
17	66	F	Chronic otitis	32	65	MEDEL Opus 2	Oticon Sumo XP
18	68	F	Unknown	30	67	Nucleus freedom	Phonak Savia 311
19	71	F	Otosclerosis	20	69	Nucleus ESPrit	Phonak Novoforte E4
20	78	M	M. meniere	48	73	Advanced Bionics Platinum Series	Phonak Eleva 411

In detail, first a speech audiometry was conducted with the HA alone, then with the CI alone and finally with both the devices. Then, a loudness scaling was performed with the HA alone, with the CI alone and with both the devices. Understanding speech with the CI was evaluated at different sound pressure levels. If, for example, the patient had a better performance at lower sound pressure levels in speech audiometry or loudness scaling demonstrated an uneven slope, the CI was optimized accordingly and then loudness scaling and speech audiometry were repeated. If necessary, the above-mentioned steps were conducted several times til the patient was subjectively satisfied.

Hearing aids were programmed following the DSL [i/o] method (DSL = desired sensation level [22]), the fitting was verified in an SPL-O-gram (fit to target). Then, a speech audiometry and a loudness scaling with the hearing aid alone were conducted and the fitting of the hearing aid was optimized following the same rules as when fitting the CI, if necessary in several steps, resulting in a subjective satisfaction for the HA alone.

Then the patient was tested with both devices in speech audiometry and loudness scaling. If the results were better with only the CI or only the HA and the patient was satisfied, the fitting of both the devices remained unchanged. If the bimodal situation was not sufficient, the results of speech audiometry and the loudness scaling with the HA and with the CI were evaluated again. All adjustments of the HA were checked in an SPL-O-gram. Following the fitting procedure, a questionnaire was handed out to the patient to be returned after 4 weeks.

In the questionnaire, the patient answered questions such as:

> "How many hours a day do you use both the hearing aid and the cochlear implant?
> "How many hours a day do you use only the hearing aid?
> For seven statements such as "With both devices the localization of noises is easier for me"

the patient should indicate whether the statement was: is absolutely correct/partly correct/in this situation the additional hearing aid is not helpful/the additional hearing aid is uncomfortable in comparison with the cochlear implant alone.

Results

In most of the patients, the entire fitting procedure required 3–5 h. In patients aged between 10 and older ($n = 15$) loudness scaling was possible with the hearing aid and the cochlear implant in all patients except for 2.

Of the 12 children included, seven scored better in speech audiometry in quiet when they were fitted bilaterally. In four patients, bilateral fitting did not improve the results obtained with the unilateral better fitting. In one patient (patient 10), CI in a quiet environment provided better results at 65 dB presentation level than with a simultaneous contralateral hearing aid in place. However, with the CI alone, correct understanding of speech in noise was only 40% while bilateral fitting provided 100% comprehension. Nine children could be examined in a noisy environment, five of them scored better with bimodal fitting compared with the hearing with the better unilateral fitting. In one patient, there was no improvement and in three patients bilateral fitting resulted in poorer scores.

Of the eight adult patients included, six scored better in speech audiometry in quiet when they were fitted bilaterally. In two patients, bilateral fitting did not improve the results obtained with the unilateral better fitting. Both adult patients examined in a noisy environment scored better with bimodal fitting compared with the hearing with the better unilateral fitting.

The results of speech audiometry with the hearing aid alone, with the cochlear implant alone and with both the devices after the fitting procedure are shown in Table 2.

Eighteen patients achieved a better fitting of both the hearing aid and the cochlear implant for their everyday life. Two patients (patients 13 and 15) did not accept the new fitting although speech audiometry showed a better understanding. Detailed information about patients′ subjective opinions is given in Table 3.

Discussion

Most studies about bimodal fitting focus on better speech perception, comparing the bimodal situation to wear the cochlear implant alone. Binaural advantages are improved speech perception, especially in noise, improved localization ability, externalization of sound, improved sound quality, and the avoidance of auditory deprivation. The underlying phenomena for binaural hearing advantages in speech perception include head–shadow effect, binaural squelch effect, and binaural redundancy. In bimodal fitting, the patient uses two types of devices. Disadvantages may include a different kind of signal offered to the central neural system, a different intensity of the signal on both the sides or different time characteristics. Because the tonotopy of the cochlea with acoustic signals differs from that of electric signals and the shapes of isoloudness curves and dynamic range may be different for both kinds of signals, the signal from one device may interfere with the signal from the other. On the other hand, the patient may profit from the advantages of both systems. A cochlear implant is inserted at the basal turn of the cochlea allowing the reception of higher frequencies than a hearing aid. In addition,

Table 2 Audiological results: unaided threshold on the HA ear, results in speech audiometry and of implementation of loudness scaling

Patients	Hearing loss on the side of the HA	Speech audiometry	Hearing aid only percent correct			Cochlear implant only percent correct			Cochlear implant and hearing aid percent correct			Loudness scaling
	Mean of 1–2–4 kHz		65 dB	dB opt	65/60 speech in noise	65 dB	dB opt	65/60 speech in noise	65 dB	dB opt	65/60 speech in noise	
1	110	MZ III	40	50		80	80		80	80		
2	112	MZ III	10	50		80	80		70	90		
		GÖ I				80	90	30	60	70	10	
3	80	MZ II	90	100	50	40	40	10	100	100	80	
4	93	GÖ II	20	60		60	70	40	70	80	40	
5	95	GÖ II	30	80		80	80	40	60	80	20	
6	110	MZ III	40	80	10	50	80	10	90	90	20	
7	115	MZ II	0	20		30	80		50	80	10	
8	90	FR W	10	35		65	70	25	65	95	10	×
9	95	GÖ II	30	50	20	70	80	20	100	100	60	×
10	95	Fr W	0	10		80	95	40	60	100	100	×
11	105	GÖ I	0	0		70	90	60	80	80	70	×
12	85	GÖ II	0	80		20	70		50	80		×
13	110	FR W	30	50		25	80	10	65	85	20	×
14	90	FR W	5	55		5	55		40	65		×
15	80	FR W	80	100	20	70	70	10	80	100	30	×
16	98	FR W	5	40		0	45		35	65		×
17	120	FR N	70			80			90			×
		FR W	50	95		80	75		50	95		×
18	110	FR N	90	90		10	90		90	90		×
		FR W	0	35		0	10		0	50		×
19	95	FR N	20			70						×
		FR W	0	5		25	55		30	70		×
20	70	FR W	15	50		10	45		5	45		×

many patients perceive a more comfortable level of hearing, especially for the perception of music.

Most groups evaluating bimodal fitting did not use special algorithms to adjust both devices. Often the fitting of the hearing aid was not controlled, but used in the fitting done by the acoustician. Luntz et al. [23] report that the adjustment of the binaural–bimodal loudness balance between the two devices was based on the patients' subjective assessment of live voice speech stimuli at the intensity of free conversation and that contralateral HAs were refitted according to the needs of each patient. However, they do not give any further information on the concrete procedure.

Mok et al. [24] asked the participants to adjust the volumes of their hearing aids to match the loudness of their cochlear implants with the voice of the tester at 60–65 dB; the volume of the CI, however, was not adjusted. Half of the participants turned up the volume of their HA during the trial and did not therefore do the tests under everyday conditions. In the other half, a regulation of the HA was not possible due to the lack of active volume control or maximum amplification already reached in the HA. In another study, both devices were programmed independently, and loudness balancing was attempted by presenting speech sound from a front loudspeaker [8].

More information about a reasonable fitting of both the HA and the CI was provided by Ching et al. They adjusted the hearing aid using the NAL-RP prescription as a starting point and fine-tuned the frequency response slope and gain to suit individual needs.

They used a loudness balancing test to equate the loudness of speech between ears, adjusting the loudness of speech and compression threshold. On average in children, speech perception and sound localization was significantly better in the bimodal situation compared with CI alone [15]. Some children showed significant binaural benefits in all three measures, whereas others showed benefits in one or two measures. None showed any negative effects from

Table 3 Subjective feedback

Patient	Feedback
1	Uses CI and HA regularly
2	Now has a bilateral implantation; before she wore both devices regularly
3	Parents report much better understanding of speech with HA compared to CI alone
4	Uses CI and HA regularly
5	Small subjective improvement
6	Fitting was not changed, uses CI and HA regularly
7	Behavioral disturbance, regularly requests the hearing aid
8	Hearing aid had to be programmed more loudly after loudness scaling, better gain in speech audiometry and better hearing subjectively, now has bilateral CI
9	Likes new fitting, uses HA regularly and feels unsure without HA
10	Marked subjective gain with HA, uses it regularly
11	Better acceptance of the HA after fitting
12	Better acceptance of the HA after fitting
13	Did not accept HA fitting corresponding to loudness scaling as she was used to her low frequency HA fitting
14	Gain of the hearing aid was increased, good acceptance
15	Although speech audiometry showed a better understanding, the patient didn't accept the new programming of the hearing aid, as it was too strange for her
16	Amelioration of the HA fitting, uses HA for telephone, feels helpless without HA
17	Uses both CI and HA, HA somewhat less gain than optimal in loudness scaling
18	Hears more with the CI, but does not understand better, fitting only 6 months after initializing CI
19	Good acceptance of new fitting, HA increases understanding
20	Uses both CI and HA, HA somewhat less gain than optimal in loudness scaling, hears more with CI, understands better with HA subjectively

bimodal hearing [14]. Only children who had not worn hearing aids before the trial required more gain than that prescribed by the NAL-RP. Children who had received a cochlear implant earlier in life derived greater benefits from the bimodal situation [14]. Ching et al. concluded that all recipients of a unilateral CI who have measurable residual hearing in the non-implanted ear should be fitted with a hearing aid.

Our results demonstrate that most, but not all, patients in a bimodal situation can profit from a loudness scaling-based fitting procedure (Table 3). Only in some adult patients who had been hearing aid users for a long time, the new fitting was not accepted. For example in patient 13, no success was achieved by the bimodal fitting. Since she understood quite well with the hearing aid, she preferred the fitting she was accustomed to with a high gain in the low frequencies. In her daily life, she relied mainly on the ear with the hearing aid and was not able to adapt to the new fitting which allowed a better speech understanding. On the other hand, patient 16 accepted the new fitting spontaneously and described a significant benefit in difficult communication situations. There are also patients who do not wear a hearing aid on the contralateral side although there is some residual hearing. In our experience, the variety of outcome is high and an individualized procedure is necessary. A fitting procedure based on the loudness scaling allows the objective optimization of both the CI and the HA.

Our study was limited by the lack of German tests available for speech audiometry in noise. In particular for young children, there are no tests to measure speech intelligibility in noise. At the beginning of this prospective study, two recent tests (OLSA, OLKISA) were not yet available. In our practice today, however, we use these recent tests if patients' cooperation and attention allow.

Until now, the question of whether a patient with a unilateral cochlear implant and a significant residual hearing on the contralateral side should be implanted on the second side has been a matter of debate. A review of the literature on the relative effectiveness of bimodal stimulation and bilateral cochlear implantation was done by Ching et al. [16]. They stated that no conclusions to these questions could be drawn, as data of the published studies could not be compared because of different methods of assessment, non-blinded assessments and the lack of randomized control trials. With the advances in hearing aid technology, residual hearing can be used much more efficiently than some years ago, and additionally with the extension of cochlear implant candidacy, more and more patients with greater residual hearing are candidates for a bimodal fitting.

For these reasons, the potential binaural advantages for bimodal hearing users may be underestimated in current literature. We believe that hearing aid and cochlear implant should be adjusted to complement each other without necessarily balancing loudness between both ears.

Conclusion

A structured bimodal fitting using loudness scaling for both the cochlear implant and the hearing aid mostly results in a subjective and often objective amelioration of the patient's hearing and speech perception.

Conflict of interest statement We declare that there is no conflict of interest.

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